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PHYSICS EDUCATION AND IDENTITY DEVELOPMENT: THE “PERSONAL-
EPISTEMOLOGICAL CONSONANCE/DISSONANCE” CONSTRUCT

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Thesis' overview

The present thesis aims to report on my three-year study of the connections that can be established between physics—considered in terms of its content, methods, practices, and values (what is usually regarded as the epistemology of a discipline)—and physics students' identity development. The thesis is divided into four parts, comprising a total of six chapters.

Part 1 constitutes the theoretical core of the work. In the first Chapter of this part is introduced the central focus of the research, which is identity development through science education. A general overview of past and current research in the literature is provided, aiming to present how this theme has been studied and to identify the blind spots that will be addressed in the following chapters. A germinal theoretical construct is then suggested, grounded in selected frameworks from the science education literature, aimed at better exploring the identified blind spot. Research questions are formulated to guide the development of the theoretical construct through the subsequent case studies.

This part also includes a description of the H2020 FEDORA project and the general context within which the following case studies were conceived and implemented (Chapter 2). The FEDORA project (September 2020 - August 2023) was coordinated by the Physics Education Research Group of the University of Bologna and included five further partners: the University of Oxford, the University of Helsinki, Kaunas Technology University, FormicaBlu, and Teach the Future.

Parts 2 and 3 discuss three case studies (classroom implementations) whose data analyses contributed to the refinement of the research questions and, consequently, the reflection on the theoretical construct. This thesis aims indeed to establish a data-driven argumentation, informed by case studies, rather than relying solely on theoretical speculation.

Part 2 specifically contains the study of two classroom activities conducted by the same two teachers (Paola Fantini and Sara Moresco) within an upper secondary school in Rimini, Italy. The first activity took place between October 2020 and May 2021, while the second occurred between March and June 2023. These two projects are part of a broader set of activities developed within the FEDORA project. Chapters 3 and 4 outline respectively the design of the two activities (“Physics of Clouds” and “Kairòs”) within the context of the project, discussing their design, presenting data analysis and related outcomes, and examining their contributions to the research questions and the theoretical construct.

Part 3 is devoted to the final case study, an orientation course for upper secondary students designed in collaboration with Lorenzo Miani and under the supervision of Prof. Levrini. The course centred on scientific uncertainties, climate change, and future studies, is also framed within the FEDORA project and builds upon its framework. Therefore, it is also grounded in and informed by the empirical outcomes from the previous case studies and by studies conducted by Lorenzo Miani in his PhD project. The course was designed to contribute to our research projects and took place between November and December 2023, with further interviews conducted until January 2024. In Chapter 5, the course design is introduced, connecting it to both the FEDORA project and the outcomes from Chapters 3 and 4. There is also a discussion of the multiple data analyses conducted, which led to the preparation of three research papers (two submitted and one in progress).

Finally, **Part 4** (Conclusions) gathers the outcomes from the three case studies and illustrates how the theoretical construct has been faced through these studies.

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Chapter 1

Introduction

This chapter establishes the foundational context for this dissertation, positioning the research within the broader academic discourse on identity in science education. Indeed, the goal is to elucidate why identity has emerged as a crucial area of focus within education research but also to highlight a blindspot identified within the research literature.

In Section 1 is introduced the critical role that identity plays in science education; there, is also argued that certain conventional teaching practices risk hindering students' development as both individuals and informed citizens. Section 2 presents a review of the increasing strand of research around identity in science education, discussing also other aspects that can help illustrate the growing interest in this topic as the foundation of a dedicated SIG¹ in the most important European Research Association in Science Education (ESERA). The review is organized around a range of diverse approaches, including socio-constructivist, narrative, and discursive frameworks. For each, the relevant theoretical underpinnings are introduced. The review is structured chronologically, tracing the evolution of identity frameworks in science education research over time to demonstrate how each successive approach has built on or diverged from previous ones. While not exhaustive, the review seeks to capture the diverse interpretations of identity within the field and the various methodologies employed.

Section 3.1 is devoted to a critical analysis of the review and to identifying both limitations and a specific blindspot, which will be the core of the whole research. This part can be thought of as the part *destruens* of the chapter, where I critically deconstruct the limitations of existing research and identify a weak point that sets the premises of the research focus. In Sections 3.2 and 4 is introduced the idea of an initial “theoretical construct” to better capture and study the blindspot identified. This will be grounded on existing literature frameworks properly selected from the science education literature (Section 3.2). Finally, in Section 4.1 are formulated the Research Questions that guide the reflection around the theoretical framework in the subsequent chapters. Together, Sections 3.2, 4, and the following Chapters (besides Chapter 2) constitute the *pars construens* of the dissertation, where I build the theoretical and empirical foundation for this study.

¹ SIG means Special Interest Group. Usually Research Associations (such as ESERA) are divided into subgroups focusing on a particular theme (here identity).

1. Why research about identity in science education?

Identity was not the central point of the research when I first started my master's thesis and then my PhD research. What got my attention was instead a point raised by Svein Sjøberg in a UNESCO report about the challenges in science and technology education in the European context (Sjøberg, 2001). In framing the problem of enrolment in science and technology careers, he enumerates a set of possible reasons, and one important focus is on the kind of science which is taught at school: *“Many studies show that pupils perceive school science as lacking relevance. It is often described as dull, authoritarian, abstract and theoretical. The curriculum is often overcrowded with unfamiliar concepts and laws. It leaves little room for enjoyment, curiosity and a search for personal meaning and significance”* (Sjøberg, 2001; p. 209).

School science is often perceived as lacking relevance, with little space for students to explore personal meaning (for now we can interpret relevance as the “value for the individual” - later it will be specified as a more stringent meaning). This perception is supported by various studies which show that rigid teaching methods discourage student engagement and lead to feelings of alienation (Hamm et al., 2020; De Zuani Cassina, 2022). The problem seems to be the rigidity and normativity imposed by the school science which prevents students from sharing and developing opinions.

Nonetheless, the traditional values of the scientific enterprise as objectivity, neutrality, disinterestedness and rationality have long since been questioned by new strands of research within the scientific disciplines themselves. Theories such as quantum mechanics or complex systems have led indeed to a profound reconceptualization of the epistemological foundations of physics (Wigner, 1976; Bishop, 2011), which more or less naively has been revoiced by general media. As a consequence, students perceive a clash between science (as they experience in daily life) and school science (what they learn at school). The de-humanized science curriculum detached from real-world issues contributes then to student disengagement. For instance, research has shown that when students are not encouraged to relate scientific concepts to their personal lives and societal challenges like climate change, they struggle to see the relevance of the subject and lose interest in pursuing further studies in science (McKenzie et al., 2024; Ulriksen et al., 2014). Even if science is pointing to consider more and more non-quantifiable aspects, such as the inclusion of “reflexive uncertainty” in climate studies (Shepherd, 2019), schools are still rooted in values of objectivity, neutrality, disinterestedness, that *“may seem to justify an absence of ethical considerations and a lack of empathy with, and concern for, the social implications of science. [...] In these circumstances, science comes to be perceived as ‘cold’, uncaring and lacking a human face”* (Sjøberg, 2001; p. 211).

The coldness Sjøberg describes then very rarely allows for the development of students’ opinions and feelings, hence resulting in a school subject poorly relevant. It is noteworthy that since 2001, few steps have been taken to improve the relevance of school science, by reforming curricula and introducing topics closer to everyday life, such as climate change, even though much effort seems to be needed (McKenzie et al., 2024). As I attend and work with schools, speaking and interviewing students (De Zuani Cassina, 2022), I keep having this sensation of dualism between humanities and STEM concerning a relevance discourse (Levrini, 2015). Scientific disciplines still have a hard time creating the conditions for students’

self-expression, imposing a strong normativity which also betrays the very nature of science itself, based on the argumentation of opinions.

There are at least two major reasons that prevent us, as science educators, from neglecting the problem.

The first reason is that as long as STEM subjects are perceived as strongly normative, we are going to lose all those students who do not fit with this setting or those who do not accept to bear this load (Ulriksen et al., 2014). Thus, there is still a high rate of drop-out from STEM majors at the University level (Hamm et al., 2020), which increases difficulties in enrolment.

The second - and in my opinion - more important reason is about the possible consequences for those who keep studying science in such conditions. If the science class is not welcoming opinions, ideas and self-expression in general, students may still accept to participate in the lesson but to the detriment of themselves as people, to their sense of self and ways of reasoning which are inhibited. Hence, when they attend classes, they are somehow forced to “leave themselves out of the room” with the consequence of being one person from 8 am to 1 pm during lecture hours and being who they are the rest of the time (De Zuani Cassina, 2022). Studying in environments which do not leave space for personal meaning (Sjøberg, 2001) can induce people to split into two parts.

Generally, the issue can be framed as a problem of relevance. With this term, I exploit the work of Stuckey and colleagues (2013). The authors identified three types of relevance for science education, respectively individual, societal and vocational:

*"The relevance of science education for the **individual** encompasses matching the learners' curiosity and interests, providing students with necessary and useful skills for coping with their everyday lives today and in the future, and contributing to the development of intellectual skills."*

*"The relevance of science education from the **societal** viewpoint focuses on preparation of pupils for self-determination and a responsibly led life in society by understanding the interdependence and interaction of science and society, developing skills for societal participation and competencies for contributing to society's sustainable development."*

*"The relevance of science education in the **vocational** dimension is composed of offering orientation for future professions and careers, preparation for further academic or vocational training, and opening up formal career chances (e.g., by having sufficient coursework and achievements to enter into any given higher education programme of study). (Stuckey et al., 2013; p. 18).*

Within this framework, the issues mentioned so far can be interpreted as a lack of societal and individual relevance. Indeed, STEM subjects are usually recognized as valuable for future career opportunities and there is a shared awareness of their value in the job market. The problem is rather starting to consider how physics taught in formal contexts may become something needed for self-determination and the development of citizenship skills (societal relevance) as well as something which could provide necessary instruments to cope with ordinary life (individual relevance).

The objective then could be to look for strategies to regenerate science education at school, so that it could appear also individually and socially relevant to students and provide useful tools for their trajectories as people embedded in a socio-cultural environment.

An individual trajectory in a social context is commonly recognized by scholars as an “identity trajectory” (Gee, 2001; Carlone and Johnson, 2007; Gonsalves, 2018; etc.). In this sense, I claim here the interpretation of promoting societal and individual relevance for science education as a way to support students’ identity development.

The objective then is to investigate how the regeneration of science education can become a support for students’ identity development. Before elaborating on possible strategies, the first step requires outlining the huge amount of research about identity in science education. This will be the content of the following Section.

2. Identity in the science education research: a review

2.1 General picture

This second section presents a historical overview of how the concept of identity within the science education community has been addressed over the last 40 years. I will mention the most relevant frameworks and approaches and describe the present situation of the research community.

The interest in identity in science education started around the late 1990s when scholars began to increasingly recognize the importance of individuals' issues to their engagement in scientific learning experiences (Calabrese Barton, 1998; Richmond and Kurth, 1999; Brickhouse, 2000). The concern around the interaction between identity issues and scientific learning increased and research has begun to address especially how identity features can enhance or obstacle the learning process in scientific communities (Brickhouse et al., 2001; Gilbert and Yerrick, 2001; Russell et al., 2005; etc.).

As time went by, a proper field of research was developed under the name of "science identity" and is now one of the most trending strands of research within the science education community. In their recent review "The identity turn in science education research: a critical review of methodologies in a consolidating field", Danielsson and colleagues summarize science identity research as *"regarding the interplay between agency and structure in young people's educational choices, achievements, and aspirations, including how different social categories (such as gender and ethnicity) intersect with students' experiences of the science disciplines"* (Danielsson et al., 2023, p.2). Despite the attempt to define the strand, the authors recognize that identity in science education has been inquired so far with an increasing number of approaches, both on a theoretical and a methodological dimension. For example, we have witnessed a growing interest in other figures' identities as teachers, and professionals, besides the most common perspective on students' identities. Thus, due to the huge number of different contributions, the boundaries of the science identity field are still not that clear (Levin et al., 2017). As reported in Danielsson and colleagues' review, between 2000 and 2004 only 13 empirical papers on students' identity were published (considering the most important journals of science education), and were mainly small-scale, qualitative studies, focusing on the individuals rather than the social constructs around them (Danielsson et al., 2023). Then, from approximately 2011 onwards there was a steep increase in the publications, with an average number of publications per year which recently reached 80-90 papers (see Figure 1).

Among the papers examined in the review, the authors were able to recognize three clusters:

- **macro-psychological studies** (36 out of 198 reviewed): these studies conceive identity as a personal trait enacted in contexts, even though the focus is more on the individuals.
- **macro-sociological studies** (15 out of 198): these studies shift their attention from individuals to the contexts, conceiving identity as shaped by social structures.
- **micro-interpretive studies** (146 out of 198): these studies are positioned halfway, considering both individuals and the social structures they inhabit as mutually defining an identity trajectory.

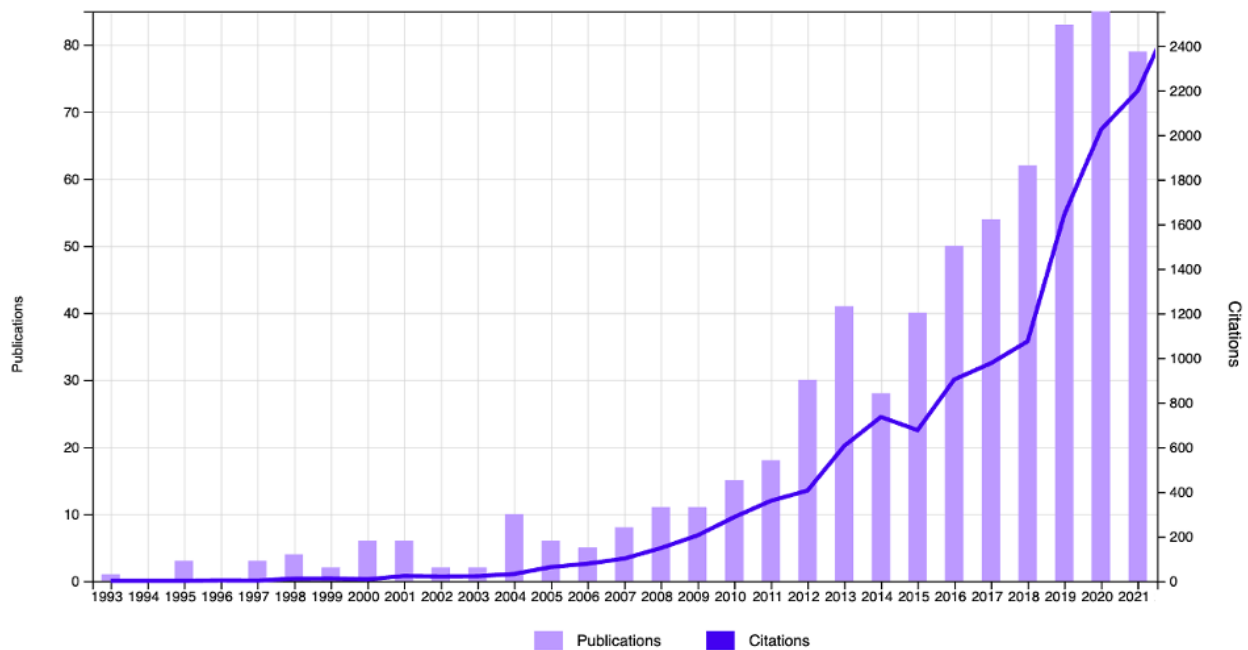


Figure 1: Logical query on Web of Science ("identity" AND ("stem" OR "science" OR "physics" OR ...)), then filtered within Science Education literature.

Micro-interpretive studies are the most common also because they do not force to primarily consider just individuals or just the contexts but rather let more open the set of possible approaches.

Nonetheless what emerges is that identity became a major line of research among scholars in science education, as also mentioned in the introduction of the recent handbook edited by Holmegaard and Archer, named "Science Identities: Theory, method and research" (2023): *"the point here is that the field shifted quickly, from "don't do it" to "everyone's doing it, and maybe you should, too". Identity, about two decades ago, quickly catapulted to one of the field's hot topics"* (Carlone, 2022; p. 3).

The handbook was born as a consequence of the creation of a Special Interest Group (SIG5) on "science identities", among the SIGs of the ESERA Conference (European Science Education Research Association²), the largest science education association in Europe. The authors grasped the hype around identity within conferences and journals and *"felt there was a clear value and need to bring together and support what we perceived to be a steadily growing field of innovative work using the concept of science identity"* (Holmegaard and Archer, 2022; p. 5). As they say, the objective was to offer *"a rich and stimulating "smorgasbord" of ways of thinking about, understanding and researching topics of identity about science and STEM"* (Holmegaard and Archer, 2022; p. 6). SIG 5³ has since its foundation promoted meetings, discussions, webinars, and writing and reading clubs. The huge attendance at its symposium at the last ESERA Conference in Cappadocia, Turkey (August 2023) and the ever-increasing number of SIG 5 members show again the wide interest in the topic.

Nonetheless, despite the wide interest and the vast amount of research produced and being produced, Danielsson and colleagues point out noteworthy deficiencies. As a conclusion for their review, they

² <https://www.esera.org/>

³ <https://eserasig.wixsite.com/identity>

formulate three final claims concerning the status of science identity research: i) methodological homogeneity and blank spots; ii) underconceptualisation of science identity idea; iii) (the need for) scaling up and scaling down to inform policy and practice.

I will briefly summarize each of the three issues.

- Methodological homogeneity and blank spots: the majority of the studies identified in their review are small-scale and qualitative studies, mainly with an ethnographic or anthropological approach. This homogeneity could probably hinder seeing “the affordances offered by other approaches” (Danielsson et al., 2022). Furthermore, blank spots can be addressed in the research, mostly dominated by intersectional studies centred around the connection (in science) among gender, race, religion, and social class on the one hand, and identity on the other hand.
- An underconceptualisation of science identity: since identity is a word of common language, it should be deeply conceptualized when taken within the research realm. Indeed, “*while identity is often theorised as a perspective [...] it is frequently also used in a looser sense to describe an empirical phenomenon*” (Danielsson et al., 2023; p.20) and in general is taken for granted and not punctually described, or operationalized. Hence, “*there is now a need to fully operationalise perspectives on identity [...] (to) serve the purpose of not losing the analytical sharpness of the work, avoiding the danger of turning ‘identity’ into nothing more than a ‘buzz word’*” (Danielsson et al., 2023; p.20).
- Scaling up and scaling down to inform policy and practice: since most of the studies are small-scale qualitative, there’s a need to think about the ways and the extent to which these studies can scale up and consider how they can be implemented in different contexts, or with a larger number of participants. At the same time, researchers should strive to find approaches which can be scaled down from large and quantitative studies and inform the practice of teachers.

Finding solutions to address the deficiencies identified by Danielsson and colleagues should be of interest to all the researchers involved in the field of science identity. For what concerns this dissertation, the first deficiency is considered, stressing the urgent need to establish research which considers aspects other than only the social ones, when studying the connection between science and identity.

In the next section, I first outline the fundamental perspectives developed in the last 30 years on science identity to secondly introduce the blank spot at the basis of the PhD project. The criterion used for this review part is to proceed in chronological order, except theories which are extensions or revisions of other previous ones, which have been grouped with the original theory they come from.

2.2 Community of Practice legacy

In the early 1990s, Etienne Wenger and Jean Lave theorized the “community of practice” framework, initially within the company domain (Lave and Wenger, 1991; Wenger, 1998), even though the framework rapidly became a reference for other domains, as science education (Mega et al., 2020).

Communities of practice are groups of people that share a practice, such as people working in the same office, a family, a group of peers, a sports team, a scout group, an orchestra, etc. An orchestra, for example, is made by players who play together, following some rules (being tuned, playing at the same

tempo, respecting the dynamics of musical volume...), and they have different tools (the musical instruments, the sheets, the music stands, the dresses) and different roles (director, soloist, percussionist, and so on). This is just a simple example that still makes clear some important features of a community of practice. The most important is that a community of practice necessarily stands upon the practice. A further feature is that the practice is carried on by the actions of members and by the means of a repertoire, that is either concrete (the object of the practice, such as the stands) or even abstract as the rules, the roles, the habits (Wenger, 1998).

The strength of the concept in catching group dynamics has widened its range of application up to the field of education, and then science education. Indeed, many authors started to consider classrooms as communities of practice, so using CoP to read dynamics within science learning (Brickhouse & Potter, 2001; Tan & Calabrese Barton, 2008; Irving & Sayre, 2014). But what is the reference to identity in the community of practice theory?

In CoP, learning the practice is outlined as a process of becoming a member of the community. As Shanahan (2009) argues, *“individuals learn about the community of practice and what is expected of its members. These expectations are internalised and the individual can make choices to act in a way that will gain them membership in the community”* (p. 57). The attention is devoted to the individual process of internalisation of the community's possible roles and norms; the internalisation is what is called identity (development) within the CoP framework. As it can be seen, this identity is strictly entrenched with the practice, and with the mutual relation with the other community members. In the CoP conceptualization of identity, the unit of analysis is the individual, which by negotiating the meaning of the practice with the other members is also negotiating the experiences of the self (Wenger, 1998).

The framework of “community of practice” and its conception of identity as a trajectory to inner forms of community participation mediated by practice has been extensively mutated by science education researchers (Carlone, 2004; Furman & Calabrese Barton, 2006; Rahm, 2002; Tan & Calabrese Barton 2008; etc.). One interesting work is the one by Nasir and Hand (Nasir & Hand, 2008), which dealt with the idea of practice-linked identity. In their work, the authors analyzed why students felt more aware of their role and the repertoire while playing basketball rather than while doing math. In their conceptualization of practice-linked identity, they used CoP's interpretation of identity construction as the learning of roles and norms, hence an identity inextricably entrenched with the practice. To address their question Nasir and Hand investigated what are the specific mechanisms that make two disciplines, such as maths and basketball, so different in the development of practice-linked-identities. From the analysis of interviews made with students and fieldwork observations, it emerged that the gap perceived by the students between themselves and math, as opposed to the feelings linked to basketball experience, can be explained as the absence of three fundamental features in the educational structure: access to the domain, integral roles, opportunity for self-expression (N. S. Nasir & Hand, 2008). In the authors' idea, the lack of these aspects inhibits the establishment of a math-linked identity.

Hyater-Adams and colleagues (2018) combined CoP with the framework of “racialized identity” coming from the work of Nasir in math education. Through this merging, they ended up with a new theoretical construct named “Critical Physics Identity”. This framework has been discussed in its potentiality to disclose the impact of racial identity for the subsequent formation of a physics-identity. This can provide insights into how racial or religious minority communities are marginalized, *“in order to push the field of physics forward into a more inclusive and equitable future”* (Hyater-Adams et al., 2018, p. 17).

Fracchiolla and colleagues exploited instead CoP framework as an analytical tool to study how informal physics programs can support science identity development. In their studies, they interpreted the features of informal physics programs as features of a community of practice such as negotiation of experiences, community membership, competence of a repertoire, etc. (Fracchiolla et al., 2020). The studies show that a structured community engagement supports the transition of participants from novices to more central, competent members of the physics community (Fracchiolla et al., 2020; Prefontaine et al., 2021).

These represent just a set of examples showing the influence of the “community of practice” theory on studying and inquiring about identity development in science education.

2.3 Discursive approach

Besides the community of practice, other foundational ideas theorizing around the nature of identity have been developed starting from the late 90s, among a vast production of case studies testing the efficacy of such theories as analytical instruments.

James Paul Gee’s influential work conceptualizes identity through a discursive approach. He defines identity as “being recognized as a certain ‘kind of person’ in a given context” (Gee, 2001, p. 99), emphasizing that identity is socially legitimized. According to Gee, identities emerge through ways of behaving, interacting, valuing, thinking, believing, speaking, and even reading and writing—elements that are accepted within specific groups (Gee, 2015, p. 3).

Central to Gee’s theory is the concept of D/discourses. Discourse (lowercase “d”) refers to connected stretches of talk or writing, whereas Discourse (uppercase “D”) represents a broader social practice—patterns of language, behavior, and interaction that allow individuals to be recognized as a particular kind of person (Gee, 2001, p. 110). Discourses (uppercase) shape identity by positioning individuals within social categories, such as particular kinds of professionals, cultural groups, or social roles (Gee, 2015, p. 3). While Discourses are fundamental in shaping identity, Gee also acknowledges a core identity—a sense of self that persists across different contexts. He explains that individuals develop a unique trajectory through Discursive space, shaped by their recurring experiences and interactions. Identity is not static; rather, it evolves as individuals interpret and narrate their experiences within Discourses (Gee, 2001, p. 111). In this sense, narrativization plays a crucial role in identity construction, allowing individuals to shape the meaning of their own trajectories rather than being passively defined by social structures.

This perspective bears similarities to Wenger’s Community of Practice (CoP) theory, particularly in viewing identity as a dynamic trajectory formed through social interaction. However, while Wenger focuses on the role of practice in shaping identity, Gee’s analysis is primarily historical and discursive, emphasizing how language and recognition shape one’s sense of self.

Gee further argues that language is essential for constructing identity: “I work out my identity [...] by making sense of what it means to be a man or a woman of a certain sort [...] But I cannot make sense of anything or interpret anything without a language or other sort of representational system” (Gee, 2001, p. 112). This underscores the inextricable link between discourse, interpretation, and self-concept.

The centrality of the discourse in the making of identity has been recognized by many following scholars in science education. For instance, Tan and Calabrese Barton (2008) argued that “*the act of authoring an*

identity is necessitated via a constant state of dialogism, where “sentient beings exist in a state of being ‘addressed’ and in the process of ‘answering’” (p.569).

In the following section, I discuss how Gee’s discursive approach has been recalled and modified by scholars in science education.

2.4 Narrative approach

The discursive approach has been seminal in the development of science identity research. Gee’s framework has been recalled by many scholars, sometimes also to develop a new discursive approach in contraposition to Gee’s (Brown, 2004; Sfard & Prusak, 2005; etc.).

The fundamental difference between the approach of Gee and the one by Brown, for instance, is the locus of control of the Discourse. Even though Gee speaks about “own narrativization” done by individuals, still this is a second interpretive step following the first formulation of Discourse done by the others. The Discourse conceptualized by Gee is mainly owned by the others.

According to Brown instead, the Discourse⁴ is the one done by the individual. Indeed, in his work Brown analyzed the scientific Discourse displayed by students, which allowed them to develop agency in the community of learners, hence to develop identity in line with the identities available in the community or in opposition to those. In the specific, the author recognized four kinds of approaches to the Discourses: *opposition status, maintenance status, incorporation status and proficiency status* (2004). These correspond to markers within a continuum where the two edges (opposition and proficiency) represent the two possible attitudes: using and interiorizing the *scientific discourse practices* as a way to develop an identity within science (proficiency status) or on the opposite refusing the scientific discourse to develop an identity detached from science (opposition status) and from the scientific normative identities (Furman & Calabrese-Barton, 2006).

Another notable work grounded on *Discourse* and again opposed to Gee is the one by Sfard and Prusak (Sfard & Prusak, 2005). In their work, the authors inquire about the potential of a *narrative approach* to identity and check the extent of its analytical efficacy for educational research. The objective is to find an operational way to study the impact of sociocultural context on students’ identity development.

The interest in the social-contexts impact was quite unusual back at that time (now largely cleared), as the review by Shanahan shows (Shanahan, 2009). In her literature review about identity in science education research, Shanahan creates a taxonomy of the papers published until 2007 and analyzes them by borrowing the Personality and Social Structure Perspective (PSSP) of Cotè and Levine (2002). According to PSSP, the study of identity can be framed within a triangular metrics - *personality, social structure and interaction*: i) for Social Structures they consider groups and societies that create social roles and pressures; ii) for Interaction they consider the daily patterns of contact between individuals within which they form unique identities; iii) for Personality they consider self-concepts and self-perceptions (Cotè & Levine, 2002). Nonetheless, the authors state that it is the “*transition between these levels that represent how individuals make sense of their lives, themselves and the situations in which they live; it is in these articulations that identity resides*” (Shanahan, 2009; see Figure 2 below).

⁴ Even though Brown and Sfard do not adopt the capital letter for Discourse, I will keep here the same notation used by Gee to refer to that connotation previously introduced.

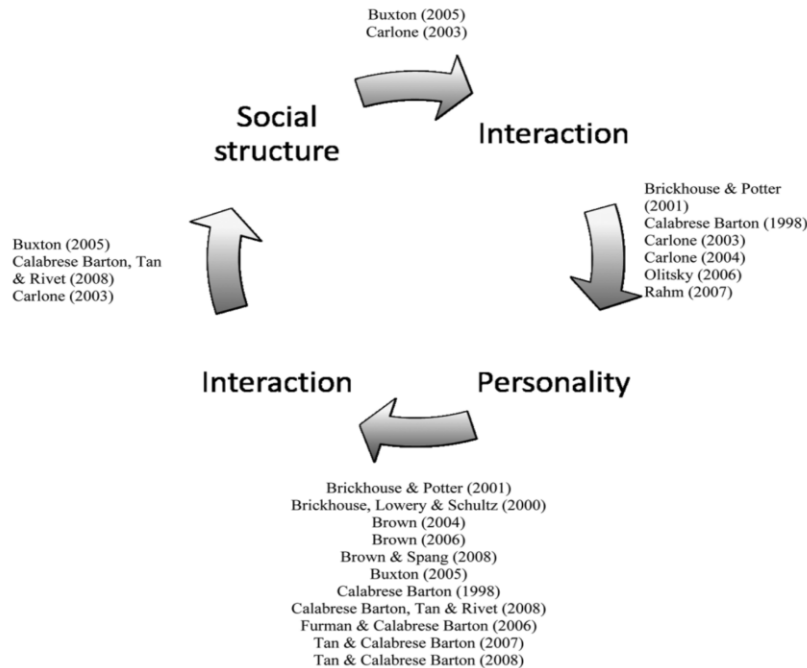


Figure 2: The papers reviewed by Shanahan and mapped in the PSSP metrics (from Shanahan, 2009; p. 56).

Shanahan, by placing the different papers reviewed in the transitions between the three poles, notes that most of the research focused only on the transitions between *personality* and *interaction* and vice versa. In this sense they tend to be micro-sociological studies, as we consider social structure as the macro-pole and personality as the micro-pole (interaction can be thought here as a mesoscale). The paper by Sfard and Prusak was instead framing identity including also the social structure dimension.

Coming back to Sfard and Prusak's work, they explicitly critique references to identity such as "who one is" or "being a certain kind of person" which are used in previous definitions of identity (Gee, 2001). As they report, *"these sentences seem to be saying that there is a thing beyond one's actions that stays the same when the actions go on, and also that there is a thing beyond discourse that remains unchanged whoever is talking about it. Such an essentialist vision of identity is as untenable as it is harmful"* (Sfard & Prusak, 2005; p.9). The authors reject any nuance of immobility of identity as the Gee "core" one, which maintains independently from the actions or Discourses. Even sharing the discursive approach promoted by Gee, they bring it to the very edge of the spectrum. In their approach, the Discourse shifts from being the representation of identities to being the ontological substance of identity: no identity can be thought of as extra-discursive. As they say, *"In concert with the vision of identifying as a discursive activity, we suggest that identities may be defined as collections of stories about persons or, more specifically, as those narratives about individuals that are reifying, endorsable and significant [...] Rather than viewing identities as entities residing in the world itself, our narrative definition presents them as discursive counterparts of one's lived experiences"* (Sfard & Prusak, 2005; p.14).

They further distinguish between two possible reifications of the narratives: *actual* and *designated identities*. Actual identities are sentences related to true facts in the present, statements such as "I am a good driver, I have an average IQ". Designated identities are stories which narrate eventual projections in the future, which have a reasonable probability to occur, such as "I want to be a musician" or "The next summer I will have a next job". Designated identities could sound quite strange, and resemble more desires or aspirations than identities. Still, as Sfard and Prusak precisely point out, *"The scenarios that*

constitute designated identities are not necessarily desired, but are always perceived as binding” (Sfard & Prusak, 2005; p. 16). Such identities are usually not consequence of a deliberate and rational choice but driven by sociocultural origins or deep convictions, gaining more concreteness and stability than ordinary desires.

As evidenced, the position of Sfard and Prusak strongly emphasizes the Discourse as the only variable of interest in studying identity, refusing to accept identitarian features as given or shaped beyond Discourses. Also, the authors highlighted how narratives that individuals construct are influenced by the broader cultural narratives and the social structures in which they are embedded, affirming the importance of socio-cultural aspects.

The importance of narratives for identity development highlighted by Sfard is witnessed by many following studies in science education. For instance, Harper and Kayumova found out how identity construction is particularly influenced by narratives shaped by personal experiences and societal expectations, for students from marginalized backgrounds (2022). Examining multilingual Black and Brown girls, they highlighted the strong intersection between race and language for science identity construction. Similarly, Ibourk and colleagues (2022) used Sfard's framework in conjunction with intersectionality theory to explore how students of colour construct and navigate their identities. Through a narrative approach, these studies underscored the complexities of identity formation for students who must reconcile personal narratives with the dominant narratives and discourses of science.

Teachers' identities have been extensively studied too with the narrative framework (Carlone et al., 2010; Melville and Bartley, 2013). For instance, Melville and Bartley (2013) focused on how science teachers constitute their professional identities in ways that resist and challenge the prevailing educational discourses, using narratives to articulate their experiences and emotions within the educational system.

Besides the differences with CoP, the narrative approach developed by Sfard has both become a common interpretation of identity and an operational tool to study identity development. The next section illustrates another approach which originated properly to establish an analytical instrument to frame identity construction in science.

2.5 Operational-analytical approach

So far, we have seen diverse frameworks, highlighting respectively the community practices or the discourses. Identity has been indicated as the trajectories of learning that individuals perform within a community of people (Lave & Wenger, 1991; Nasir et al., 2008), as the interiorization of the discourse which others made about ourselves (Gee, 2001), as the substance of the discourses relating us (Sfard & Prusak, 2005). By recalling also the PSSP framework, identity is an evolving trajectory with a constant tension between the individual and the others, which happens within a social structure (PSSP). Regardless of the approach chosen, there is a shared consensus on the importance of the others and the context for identity work.

As Shanahan comments, science identity can be positioned in an 'agency-structure dialectic', *“From a structural perspective, identity is defined by the requirements, norms and expectations imposed on*

individuals as a result of their membership and position within a social group [...]" (Shanahan, 2009; p. 45). A dualism in which the individual tries to advocate his role and agency within the social structure.

Indeed, Brickhouse and Potter (2001) claim that identities are the ways in which the individual is participating in the social contexts but are also the interpretation which the others make of such participation. Also for Calabrese-Barton (1998), identity is referred to as "who we think we must be to engage in science" (p.1). In these and other following works (Avraamidou, 2021), identity construction in science learning is conceived as the appropriation and interiorization of the roles and memberships available within the community where the trajectory is performed. If the community is the science class, then specific kinds of identity will be the ones to fit in. Elsewhere (Carlone, 2004) Carlone described this imposition from the social structures, saying that *"the promoted science identities may not be socially available, achievable, or interesting to all participants. Thus, these alternative, 'inappropriate' identities may become marginalised within the community"* (Carlone, 2004; p.396).

But the focus can be shifted also to the agency pole of the aforementioned dialectic: *"Studying identity from an agential point of view means attending to the ways in which individuals construct identity rather than act in accordance with an imposed identity"* (Shanahan, 2009; p. 45). This was the case of Brown mentioned above with individuals defining their discourses. According to the agency-structure dialectic, identity is intertwined with agency in the sense that "acting" allows the construction of the self, but also the construction of the self creates space of agency.

By including agency, all these studies contribute to establishing a feature of "dynamicity" for identity. Whatever conceptualization is used indeed, identity is not something given but rather is *never fully formed*, always negotiated within structures which set the interaction with others. This has been taken almost for granted in all the following studies.

The framework presented in this section takes the premises from the reflections elaborated in previous approaches (community of practice, discursive, narrative) but focuses more on methodological aspects. At its creation the authors laid questions such as "What could be the role of studying identity? Can we use identity as an analytical instrument?"

Heidi Carlone, in the introduction to the handbook edited by Holmegaard and Archer, reports: *"About 20 years ago, I had interests in studying the short- and long-term impacts of elementary teachers' pedagogical practices on students' science identities. I consulted with a senior colleague in the field, and he said, 'Good ideas. But don't call it identity! That construct is too hard to operationalize'"* (Carlone, 2023). In her view, identity has always been an operational tool, something to construct and then use for other purposes, not something to define for its sake. If we recall the paper by Gee, titled "Identity as an Analytic Lens for Research in Education", he claims: *"There are, of course, other terms in circulation for what I am calling 'identity' (e.g., the term subjectivity) and 'core identity' (e.g., some people reserve the term identity for 'core identity'). I do not think it is important what terms we use. Rather, what is important for me here is to show how the notion of identity, in the sense I have defined it, can be used as an analytic tool for studying important issues of theory and practice in education"* (Gee, 2001, p. 100). Also, if we recall the work of Sfard and Prusak, they were studying identity to find tools *"for fathoming the mechanism through which the wider community, with its distinct cultural-discursive traditions, impinges on its members' learning"* (Sfard & Prusak, 2005; p.20).

The objective to develop identity as an operational lens was then shared by Carlone and Johnson when they published their seminal paper two years after receiving that warning about operationalization. Their work: "Understanding the science experiences of successful women of color: Science identity as an

analytic lens” (2007), became over the years a reference paper for studies concerning identity in science education.

In the paper, the authors wanted to construct a tool to analyze three longitudinal experiences of black women who sought a career in science. The goal of making identity an operational lens was:

- to see what people are marginalized and why in science experiences.
- to see the trajectories from peripheral to central participation of students in the practices of science. Here authors explicitly recall the use of *community of practice* theory to describe the process of newcomers joining the process of learning.
- to see what kind of science practices are enacted or generally what kind of image is delivered to students, hence what kind of science identities are promoted and what kind of identities are rejected.

Taking from these premises and capitalizing on the tension between the individual and others that previous works unveiled, they asked themselves: *“How would we describe a person who has a strong science identity?”*. Hence their answer was: *“She is competent; she demonstrates meaningful knowledge and understanding of science content and is motivated to understand the world scientifically. She also has the requisite skills to perform for others her competence with scientific practices (e.g., uses of scientific tools, fluency with all forms of scientific talk and ways of acting, and interacting in various formal and informal scientific settings). Further, she recognizes herself, and gets recognized by others, as a “science person.” Our model captures these aspects of science identity in three interrelated dimensions: competence; performance; and recognition”* (Carlone & Johnson, 2007, p. 1190).

Science identity here is argued to evolve through iterative proofs of *competence* that are *recognized* by the other members of the community (classmates, colleagues, chiefs, students), through the evaluation of *performances* (Figure 3).

The authors interpret competence as the ability to use scientific practices and scientific languages and display this as a performance. But even if this happens, still there can be situations where individuals do not feel strong science identities, since they lack recognition from the other members of the community. Indeed, *“we can envision someone who might be very competent in her understanding of science content and may be able to adequately perform scientific practices, but, for one reason or another, may not recognize herself or get recognized by others as a science person”* (Carlone & Johnson, 2007, p. 1191).

The role of recognition hence is crucial in allowing science identities. In this regard, Avraamidou (2021) explored the ways in which people get/do not get their recognition, building on Carlone and Johnson’s framework but also framing the study within intersectionality⁵ (Collins et al., 2021).

⁵ Intersectionality is a framework which analyze individuals as placed at the intersection of many identities; this approach can be related to previous ideas coming from CoP framework and Multiple Worlds theory (Phelan et al., 1991). Indeed, individuals can be unpacked in their multiple identities, as they cross from one community of practice (Wenger) or world (Phelan) to another: a scientist has his/her science-identity which is displayed and recognized at work, but could be also a Latin person (ethnic-identity) as well as be a parent (institution identity according to Gee), and so on. Hence people find themselves dealing with what is named “nexus of multimembership”, according to CoP (Lave & Wenger, 1991). The possible strategies which people adopt to cross the boundaries which can be present between these memberships are strictly connected to their identity development. In fact, as framed in the theory of Phelan, there could be many kinds of boundary crossing between the communities, which have an impact on the ways people manage their multiple identities (identity here is interpreted as a sense of belonging): i) congruent worlds -> smooth transition; ii) different worlds -> boundary

Avraamidou analyzed the stories of three women within the physics academic community: a native to Northwestern Europe late-career white woman and two immigrant women in Northwestern Europe, one being an undergraduate student of color and the other being an early-career Muslim woman. By her discussion it emerges that recognition is a spectrum rather than a dichotomy feature (yes/no), it comes from many sources (family, peers, college, colleagues), lasts all the life and is strongly politically and socially connotated so it reflects eventual discriminations according to gender, ethnicity, classes, etc. (Avraamidou, 2021). The analysis indeed shows that *“Collectively, the three life-histories tell stories of otherness, persistence, hope, and failure and they elucidate the kinds of identities that are deemed “in-place” and “out-of-place” in physics. They showcase how the three women authored multiple identities that simply co-existed for them, while for others were seen as conflicting and caused misrecognition”* (Avraamidou, 2021; p. 28).

Hence, she concludes that *“we need to conceptualize recognition as action which implies more than “seeing as” and requires action on what we recognize”* (Avraamidou, 2021, p.33). Recognition seems crucial for allowing identity construction, hence it must be explored in its complexity and a reflection on who recognizes and what is recognized is of capital value.

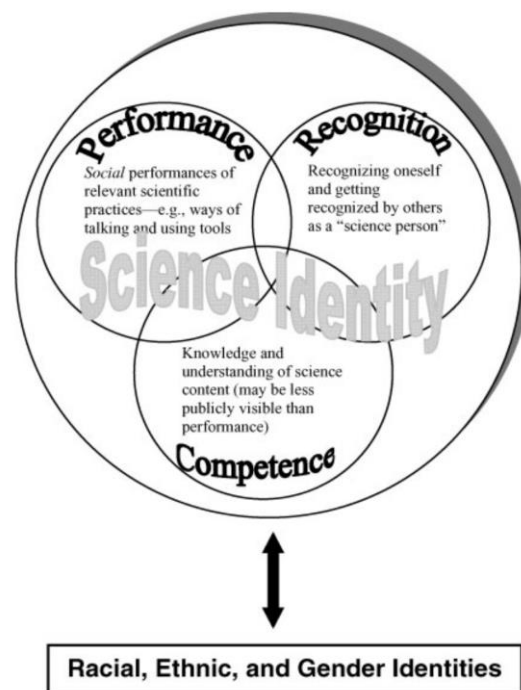


Figure 3: The three intertwined dimensions defining science identity within the Carlone and Johnson framework: performance, recognition and competence. These are connected to racial, ethnic and gender identities as the authors acknowledge their impact on science identity, even though they claim for further specific studies (from Carlone & Johnson, 2007; p. 1191).

crossing managed; iii) different worlds -> boundary crossing hazardous; iv) borders impenetrable -> boundary crossing insurmountable (Phelan et al., 1991). According to the similarity of values and norms between the communities, shifting from one to the other can be smooth but sometimes it is so hard that borders become *insurmountable* (Phelan et al., 1991).

It takes the premises from Carlone and Johnsons's framework also the research about physics identity carried on by Hazari and colleagues over the last fifteen years.

The authors designed a framework of physics-identity drawing from Carlone's one, but added interest as a fourth marker, *"Looking more specifically at the development of physics identity, we built on the aforementioned research to propose that it is influenced by students' perceptions of how they are recognized (or not) by others with respect to physics (recognition factor), their interest in physics (interest factor), their beliefs in their ability to perform physics-related tasks (performance factor), and their beliefs in their ability to comprehend physics content (competence factor)"* (Potvin & Hazari, 2013; p.282).

They explicitly added interest to the previous framework as a crucial element in determining individuals' decision of what kind of student to be (Hazari et al., 2010).

In the following works, they explored quantitative⁶ correlations among the markers through multiple regression techniques (Hazari et al., 2015; Hazari et al., 2022) and structural equation modelling (Hazari et al., 2020), to see if general correlations could be found across diverse settings. These studies revealed a variety of aspects related to identity construction in physics learning contexts as: i) the impossibility of generalizing claims about the direction and extent of correlation between the markers in promoting/inhibiting identity construction, without considering and analyzing each context (Hazari et al., 2020); ii) the strong impact of teachers cues for both affective and cognitive engagement of students (Hazari et al., 2015); iii) the positive impact of informal activities such as participating in STEM competitions and talking science with friends and family with respect to physics identity development, even though they could at the same time reinforce inequalities exclusion in physics identification (Hazari et al., 2022).

It is interesting to see how these studies exploiting markers such as recognition, competence, performance and interest most of the time disclosed episodes of exclusion within physics learning contexts. The main reasons provoking exclusion, according to these and other studies (Gonsalves & Danielsson, 2020; Carlone, 2004; Wang, 2018) which could be positioned in the transition between *personality* and *social structure* (taking the PSSP perspective), are gender and ethnicity. As a consequence, they were able to reveal *"the unique cultural characteristics of physics in comparison to other scientific fields, namely being the most male-dominated and the least ethnically and religiously diverse STEM field"* (Avraamidou, 2021, p. 4).

⁶ It is a key feature of the Hazari group to work only with quantitative methods, unlike the qualitative nature of most of the studies about science identity.

3. Discussion of frameworks and identification of a blindspot

In the previous section, the literature produced over the last 30 years about identity in science education has been outlined. While presenting the diverse frameworks I aimed to enhance the differences but also some similarities. In particular, we have now reached a full consensus about the dynamic feature of identity. Even though Gee's perspective, still popular among some authors, argues for what he calls "core identity", still he considered the one's sense of self as "*never fully formed or always potentially changing*" (Gee, 2000; p.111). Furthermore, individuals' identities - or as they say their "trajectories" - have been acknowledged as fundamentally oriented, shaped or even created (Sfard & Prusak, 2005) by external inputs, in terms of the interaction with others, with the social contexts and structures, with the repertoires and practices of groups of belonging, the interaction between groups of belonging, etc. The studies mentioned form a quite detailed frame of the possible ways in which scientific contexts create the condition for individuals' science identity developments.

It has been also argued the crucial role that scientific social and political structures have in allowing people's recognition within the scientific community, considering their gender, ethnicity, social class or religion. However, this seems to be not all of the story.

The impact of social and political features of scientific disciplines on science identity development is certainly decisive but it does not include other variables which can be equally important. Many studies discussing the impact of physics socio-political structures dominated by inequality on the identity development, do not examine in what sense these identities are physics identities rather than mathematics or biology identities. The point I am trying to sustain is that by taking into consideration only the socio-political aspects which are common to many scientific disciplines we are not able to distinguish between a physics identity or a chemistry identity. This can be considered a provocative way to claim that the specificity of disciplines, which could instead allow us to distinguish between physics and chemistry identity, relies also on the epistemological dimension. This positioning shift could allow to answer a simple yet deep question such as "What makes these science identities scientific?", or more specifically "What makes this physics identity physicist?".

One of the few examples studying the interaction between epistemological aspects and identity construction is represented by the theoretical framework of *appropriation* developed by Levrini and colleagues (2015). Taking the premises by questioning how scientific disciplinary learning is integrated with students' identity formation, they borrowed from linguistics the term "appropriation" as disciplinary grounded learning but also involving "*a reflexive process of transforming scientific discourse in a way that is authentic and personal*" (Levrini et al., 2015; p.93). Through the analysis of data collected within a classroom intervention on thermodynamics conducted in an Italian upper-secondary school, the authors were able to operationally define appropriation and check its effectiveness in recognizing the presence of a reflexive kind of learning.

They ended up with a set of five markers defining appropriation:

- a) the disciplinary discourse of the student expresses an *idiosyncratic idea*: this idea is genuinely produced by the student, is different from others' ideas and is not taken by the teacher.
- b) the discourse (around the idiosyncratic idea) is *disciplinary grounded* in the sense that it respects the languages, the logic and the knowledge of the discipline

- c) the discourse is *thick* as it involves multiple dimensions like “a metacognitive one [what learning physics means for me] and an epistemological one [what image of physics makes sense to me]” (Levrini et al., 2015; p. 118).
- d) the discourse is *non-incident* as it is displayed on many occasions and is coherent with a personal story beyond the single episode
- e) the discourse is a *carrier of social relationships* in the sense that positions the student within the class, providing a sort of role or nickname according to the idiosyncratic idea (“the one who likes philosophical aspects”, “the one who likes the computational issues”, etc.).

The design principles at the basis of the activity - *multiperspectiveness, multidimensionality and longitudinality* - were able to present a more open and personally relevant discipline to students which they used to position themselves and develop their identity (Levrini et al., 2015). The relevance of the study is then to illustrate how contents and not only educational practices can promote identity work, when dealt with in a specific way.

This example is notable as it approaches the link between learning science and identity construction from a perspective which relates more to the epistemological aspects than issues such as the socio-political ones. I use here the term *epistemological* instead of *epistemic* (coherently with the authors), to illustrate a reflective process involving the knowledge content. Physics in this sense offers a rich set of examples to clarify the point. Physicist for instance produced two bold and contrasting theories such as General Relativity and Quantum Mechanics, both valid. This is an epistemic issue, elements of knowledge. However, they spent (and still spend) much time to discuss around those theories as they suggest profound diversities in terms of methods and - most importantly - values. How the community of scientists engages and reacts to these epistemic elements is an *epistemological question*.

The idea of Levrini and colleagues is that *appropriating* a content is a deep learning process which triggers reflections similar to those that scientist may do in front of a new theory: “To what extent do we accept this? What values does it bring? Does the image conveyed by the theory make sense to me? Etc.”. In this sense, the example of appropriation’s marker C (“what image of physics makes sense to me”) is precisely *epistemological*. Learning the diverse images of physics would have been an *epistemic issue*, whereas asking what images make sense to me is an *epistemological issue*.

Thus, it is immediate to consider that are the epistemological aspects rather than the epistemic which matter for the identity development. It is indeed the kind of engagement and interpretation of the knowledge content that informs how that content may support or not a growth of the self.

Besides the lack of studies focusing on the role of epistemological aspects, another point seems to have been overlooked by research. There is a notable and growing interest in intersectional studies examining how other identities such as ethnic or religious ones impact science identity formation. Still, we cannot say that the opposite direction is under attention. The frameworks mainly used to work with identity, using for instance constructs as recognition, do not allow to “flip the direction” of the research and thereby they heavily condition the research itself.

Based on this and the previous issue (lack of attention to epistemological aspects) I then call for a new perspective on identity construction within science education. This perspective should entail:

- a **“flip of direction”**: from how other identities impact science identity to how science impacts non-scientific forms of identity.
- a **zoom-in** to the epistemological aspects: besides the role of socio-political aspects of science we should inquire about the impact of epistemological aspects on identity construction. In particular, we could ask ourselves about possible ways of dealing with content and the consequent impact on identity construction.

In light of this suggested positioning, in the next section I recall the theoretical frameworks needed to formulate the theoretical perspective. Thus, an initial version of a theoretical construct and approach is presented in detail. According to the intention to test the theoretical construct and the approach formulated, the Research Questions that guided the case studies of the thesis are finally introduced.

3.2 Building a perspective with frameworks

This Section discusses in three separate subsections the details of the theoretical frameworks used to define the theoretical perspective around identity mentioned, and which informed its following refinement.

3.2.1 FRA wheel

Previously, I claimed the need for a “flip of direction” and the need to pay attention to the intersection between scientific epistemological aspects and identity construction. In doing so, I separated the epistemological aspects from the socio-political ones, implicitly assuming the FRA for the Nature of Science framework (Erduran & Dagher, 2014).

FRA stands for “Family Resemblance Approach”, a concept originating from Wittgenstein (1958). Family resemblance was conceived as a way to overcome the difficulties of defining concepts. Instead of providing a definition Wittgenstein suggested considering concepts for the similar categories they share with analogous concepts; these categories create a “family” of related characteristics, where no single characteristic is common to all similar concepts, but each one shares some traits with other ones.

This elastic approach was mutated by Irzik and Nola (2011) to address the nature of scientific disciplines (NOS). Such a perspective of the Nature of Science positioned itself over the last years in opposition to the “consensus view” (Lederman et al., 2002). Rather than providing a set of foundational features to define if a discipline is scientific or not, the FRA entails scientific disciplines by including the aspects commonly agreed as scientific between observers, contexts, etc. This approach is powerful since it is broad and elastic enough to gather not only the commonalities but also the specific features that are present across scientific disciplines without cutting down some of them. In projecting FRA into NOS, Irzik and Nola extended the dimensions usually included in the NOS perspective to embed both the cognitive-epistemic and social-institutional dimensions of science (2011). In recalling the FRA to NOS approach, Erduran and Dagher further extended the framework, introducing categories like “social organizations and interactions,” “political power structures,” and “financial systems” to capture the broader social dynamics influencing science (2014). The Reconceptualization of FRA-to-NOS (RFN) of Erduran and Dagher capitalized on the perspective of science education research including the new categories for a more

comprehensive understanding of the nature of science (NOS) in education. Furthermore, Erduran and Dagher highlighted the operational character of RFN by creating a visual tool to help teachers and learners engage with the complex dimensions of science in more organized and meaningful ways (see Figure 4).

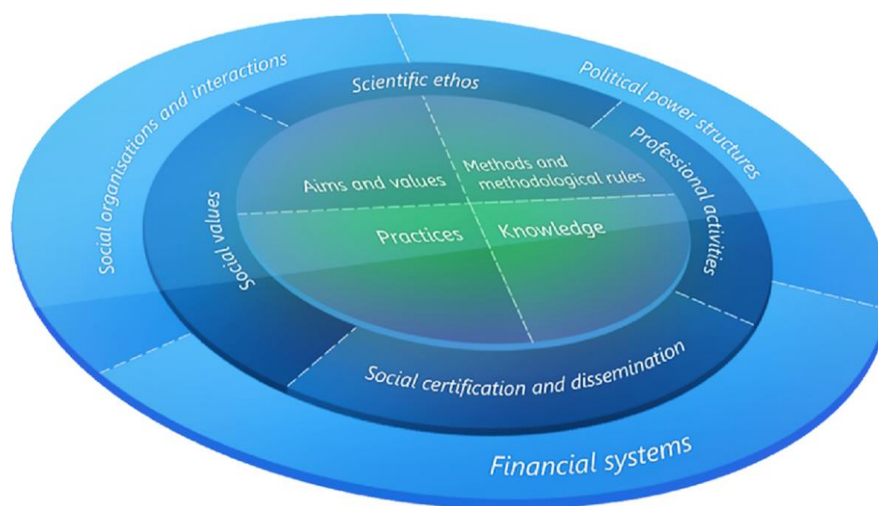


Figure 4: The FRA wheel suggested by Erduran and Dagher, representing the dimensions of scientific disciplines (from Erduran & Dagher, 2014; p. 28).

The result of this extension is the FRA wheel, which has become a common reference for studies around NOS in science education.

The wheel is formed by two major parts: the inner core stands for the cognitive epistemic features of scientific disciplines, whereas the outer circle of the wheel stands for their socio-cultural, political and financial ones. The cognitive-epistemic core includes scientific knowledge, methods and methodological rules and practices, such as observation, experimentation, and argumentation. It also covers the aims and values of science, such as accuracy, consistency, and objectivity, which guide scientific inquiry. The socio-cultural circle highlights how societal norms, ethics, and values influence science. It also includes the processes by which scientific knowledge is validated and disseminated, such as peer review and publication. It is important to notice that these are *epistemic* elements and not *epistemological issues*. The epistemological side here could be a reflection around these epistemic features (a reflection on the contents, the practices, the values and methods).

The outer political-economic circle instead embeds the political structures as well as the financial systems to emphasize how political contexts and funding sources can influence scientific research in its scopes and applications.

The RFN approach has been widely applied to national curriculum analysis, showing how NOS can be more comprehensively integrated into science curricula (Kaya & Erduran, 2016; Yeh et al., 2019; Cheung, 2020; Caramaschi et al., 2022; Mork et al., 2022; etc.). The FRA framework therefore has been used as an analytical tool but also as a conceptual guide for developing science curricula that reflect the complex interrelations of features within scientific disciplines (Erduran & Dagher, 2014).

The reason why I took this framework as a reference is that for the first time clearly distinguishes between the different nuances of science. The separation into cognitive-epistemic, socio-cultural and political-economic macro-areas provides a comprehensive view of the multiple aspects of scientific disciplines. Even though all the areas are mutually connected, still this visual tool allows to mainly focus for example on cognitive-epistemic features. In this way, I am quite confident of the possibility of inquiring about the specific impact of epistemological scientific issues on students' identity development, without considering that much also the social, cultural and political issues.

3.2.2 Working with contents: the Model of Educational Reconstruction

In the previous section, I evidenced the efficacy of RFN (Reconceptualized FRA to NOS) in distinguishing between cognitive-epistemic and socio-institutional parts of scientific disciplines. Still, cognitive-epistemic elements such as knowledge, methods, etc., are not neutral items. It is indeed crucial to acknowledge the (many) ways we can deal with them and "model" their shape for desired outcomes. In this sense, as I claimed many times so far, the intention is to work for a kind of scientific education based on contents which could offer an image of science as open for self-positioning and hopefully personally relevant for students. Thus, the question is what approaches can be helpful for this objective.

The Model of Educational Reconstruction, elaborated by Duit and colleagues (Duit et al., 2012) seems to be a good candidate in this sense. It was elaborated upon the legacy of Didaktik and Bildung, an educational perspective widespread across German-speaking countries since the beginning of the 70s (Klafki, 1995). In the specific, "*Bildung is viewed as a process (which) denotes the formation of the learner as a whole person [...]*" while "*Didaktik is based on the notion of Bildung (and) concerns the analytical process of transposing human knowledge like domain-specific knowledge into knowledge for schooling that contributes to the above formation (Bildung) of young people*" (Duit et al., 2012; p.16). Consistently, the authors call for an education where "*science content is not viewed as 'given' but has to undergo certain reconstruction processes [...] (and) to be transformed into a content structure for instruction*" (p.18). The MER approach articulates into three steps:

- 1) **Clarification and analysis of science content:** This step focuses on analyzing the structure of scientific knowledge from both scientific and educational perspectives. This means also identifying the epistemological features embedded in a scientific concept.
- 2) **Research on teaching and learning:** this step demands studying students' preconceptions, interests, attitudes, and learning difficulties as well as examining the features of the instruction context.
- 3) **Design and evaluation of teaching and learning environments:** this step involves the development of instructional materials, learning activities, and teaching sequences that are informed by the clarified science content and the findings from research on teaching and learning.

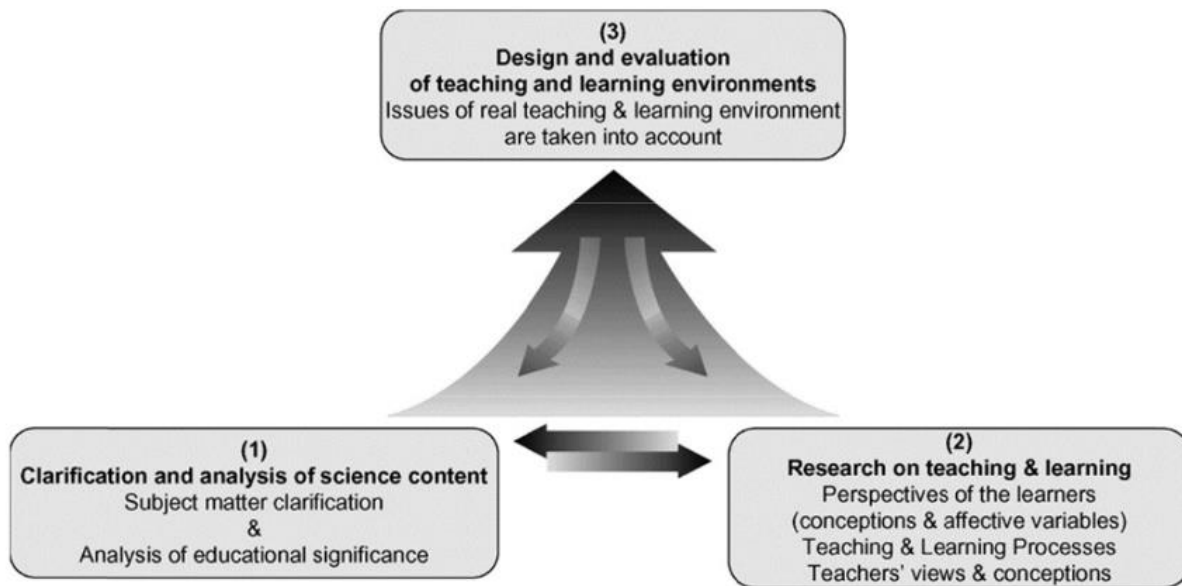


Figure 5: The three iterative steps of MER (from Duit et al., 2012; p. 30).

The design process is iterative and recursive, ensuring that the instructional materials are continuously refined based on feedback from classroom practice.

Since its formulation, the Model of Educational Reconstruction has been exploited in different ways within science education research, such as:

- to investigate students' conceptions of a variety of subjects matter such as AI (Vo et al., 2024), glaciers (Felzmann, 2014), prismatic images (Grusche, 2017), etc.
- to design classroom implementations around diverse topics such as thermodynamics (Levrini et al., 2015), nanoscience (Stavrou et al., 2018), solid-state chemistry (Nursaadah et al., 2019), etc.
- to reflect on science exhibition design (Laherto, 2013).

Concerning the development of my theoretical perspective, the MER approach is a good example of the epistemological depth of scientific contents and how much this may impact science learning. Furthermore, the iterative scheme of MER suggests a way to construct a local teaching implementation based on science epistemological aspects but also in agreement with students' views, conceptions, perspectives and capabilities.

3.2.3 Epistemic emotions

At the end of Section 3.1, I proposed a “flip of direction”, demanding the need for new perspectives studying the impact of science epistemological aspects on students' identity construction. As it is clear I am insisting on the direction that goes from science (considered in its cognitive-epistemological features) toward individuals' identity development. This is driven by the belief that learning is not a neutral experience, and we should pay attention to the consequences that the contents we teach may have for our students, on a personal level. This impact may involve both cognitive issues (how students are informed in their thinking) and affective ones (what feelings are activated by the content learning). This is because learning itself is both a cognitive and affective engagement process (Morshead, 1965).

To refine the theoretical construct objective of the research, it seems crucial then to introduce a framework able to describe the affective response to content learning experience. The choice is thus to include the framework of “epistemic emotion” (Jaber & Hammer, 2016a; 2016b), studying the emotions felt during the learning process. They are indeed named “epistemic” as they emerged in the process of knowledge (from Greek *episteme*) construction, evaluation, and critique.

Epistemic emotions or feelings should be first distinguished from ordinary emotions and feelings. Emotions, broadly understood, have been conceptualized from various perspectives. For instance, some scholars view emotions as internal feelings experienced in response to external stimuli (psychodynamic approach) (Zembylas, 2007), whereas others conceptualize emotions as socially and communicatively constructed experiences (socio-constructivist approach) (Schutz & DeCuir, 2002). An intermediate position is the one by Scherer who entails both a “*dynamic, continuously fluctuating nature of emotion processes and the existence of discrete language labels referring to steady states*” (Scherer, 2000, p.75). To him, emotions are “episodes of synchronization in a nonlinear dynamic system”, where a continuous evolving affect state (socio-constructivist) sometimes locks itself in static structures (psychodynamic) which have been defined with labels (anger, joy, etc.).

When emotions are triggered by the epistemic process they can instead be defined “epistemic emotions”: “*what distinguishes epistemic affect from more general descriptions of affect is the notion that such affective experiences are directly related to the pursuit of knowledge construction [...] and are experienced in the epistemic work of constructing and critiquing knowledge*” (Davidson et al., 2020; p.4).

As Arango-Muñoz and Michaelian (2014) discuss, epistemic emotions are not peripheral but central to the cognitive processes involved in learning and scientific inquiry, and they are related to learners’ awareness of their mental capacities and processes. Examples of these emotions are surprise, curiosity, joy, confusion, anxiety, frustration, and boredom (Muis et al., 2018), even though other authors consider also confidence, uncertainty, difficulty, etc., as epistemic emotions (Arango-Muñoz & Michaelian, 2014). Without entering into the huge debate of what affect state can be considered or not epistemic emotions (not the scope here), it is noteworthy to recall the centrality of these emotions in the scientific experience, for both learners and professionals. As Sansone (2009) reports, when learners engage in sense-making—interpreting data, constructing hypotheses, or critiquing theories—these activities are necessarily accompanied by epistemic emotions which shape the learning process. In this sense emerges that epistemic emotions in science are not *goal-defined* but rather *experience-defined*, as they are not emotions toward science but rather emotions emerging when dealing with scientific knowledge construction.

Given this, epistemic emotions are a crucial element of the interaction between students and the cognitive-epistemic part of science, as they are “*affective dynamics entangled with the conceptual and epistemological substance of science*” (Jaber et al., 2016). We should then carefully consider the role of epistemic emotions which are not just byproducts of the learning process but rather are central to how students engage with and internalize scientific knowledge.

Hence, the traces of epistemic emotions will have a central role in the development and refinement of my theoretical construct, as proxies to better understand students’ relationship with the “conceptual-epistemological substance of science” (Jaber et al., 2016).

4. Developing a theoretical construct

Section 3.1 introduced a blindspot in the current literature about science identity which I claim deserves to be investigated: the impact of epistemological aspects of science disciplines on students' identity work.

The identification of this blindspot required frameworks upon which developing a theoretical perspective able to investigate this impact. Thus, Sections 3.2.1, 3.2.2 and 3.2.3 introduced the three theoretical frameworks used to articulate the original positioning: RFN (Reconceptualized FRA to NOS), MER (Model of Educational Reconstruction) and epistemic emotions. These frameworks respectively allowed me to distinguish between cognitive-epistemic and socio-political dimensions within scientific disciplines, to identify a strategy by which it is possible to foster the epistemological richness of science in creating learning activities which provide space for students' visions, ideas and identities, and to study the affective answer to epistemological issues raised during the content learning.

With these frameworks in mind, I will inquire how designing learning activities based on specific physics epistemological aspects which create room for students' ideas and idiosyncratic positions, can foster - via⁷ the emergence of epistemic emotions - students' identity development beyond the boundaries of the discipline.

Through the empirical case studies presented in the next Chapters, I will try to find a name for this whole process (theoretical construct) and try to make it more operational. I will start by assuming the potential presence of this unidirectional link between epistemology and identity development and then consider possible conditions of its activation/inhibition.

The consolidation and refinement of this theoretical perspective will be guided by Research Questions which will be addressed and extended along the Chapters, based on the results of data analysis.

4.1 Research Questions

Here is the first set of RQs.

There is a broader Research Question related to the characterization of the theoretical construct,

RQ: *What elements may characterize a theoretical construct connecting physics epistemology and identity development?*

which required the creation of three strands to address.

The first strand concerns the *methods* and entails RQ I:

RQ I: *What methods and analytical lenses can be used to identify the connection between physics epistemology and identity development?*

The second strand concerns the contents and entails RQ II:

⁷ This is an hypothesis to check.

RQ II: *What physics contents can inhibit or activate the link between epistemology and identity?*

The last strand is related to the role of epistemic emotions, grounded around RQ III:

RQ III: *What role do epistemic emotions play in the activation of this link?*

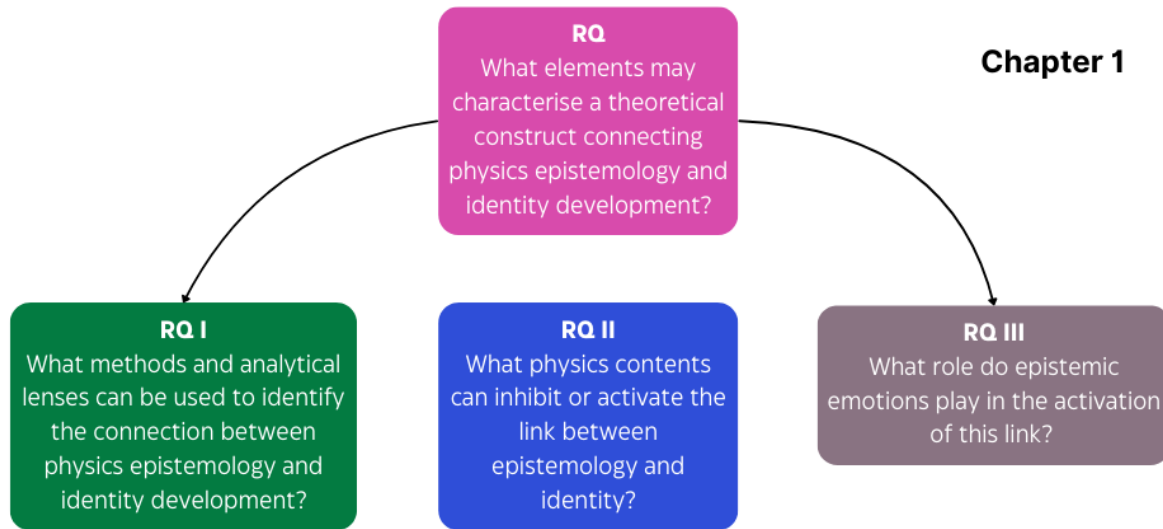


Figure 6: The structure of the three strands (I, II and III) into which the general Research Question has been unfolded. Each strand has its own color to facilitate the differentiation in their development. The scheme will be recalled in Chapters 3,4 and 5 and expanded according to results emerged in those Chapters.

The three RQs corresponding to the strands define the structure of the research presented in the dissertation and will be developed in the following Chapters. The broader Research Question (*What elements may characterize a theoretical construct connecting physics epistemology and identity development?*) will be answered at the end of the thesis (Chapter 6), in light of the contributions provided by each strand over the three case studies.

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Chapter 2

Introduction

In the first Chapter, the theme of the research has been introduced and the supporting Research Questions that will be addressed have been formulated.

This Chapter aims to contextualise the three studies of Chapters 3, 4 and 5 within a bigger framework. Those studies are activities done within the framework of the H2020 FEDORA Project (<https://www.fedora-project.eu/>), a European Horizon project coordinated by the Bologna PER Group. The project completely funded my scholarship and funded the realisation of the activities presented in the next chapters.

In the first Section are outlined the project premises while in the second Section are illustrated the project objective, namely to develop a pedagogical data-driven model for science educators, proposing a future-oriented science education to “enable creative thinking, foresight and active hope” (from FEDORA website). In the third Section are discussed the project outcomes, in terms of the theoretical frameworks produced and the recommendations developed. Finally in the Conclusion is sketched the relationship of my research with the diverse parts of the project.

This Chapter is a re-elaboration of a research paper published in September 2023 by the Frontiers in Education journal: “Enhancing relevance and authenticity in school science: design of two prototypical activities within the FEDORA project” (De Zuani Cassina, D’Orto, Fantini, Tasquier and Levrini, 2023).

1. Premises

In the modern era, which sociologist Hartmut Rosa refers to as the “society of acceleration” (Rosa, 2009), the pace of scientific and technological advancement has become so fast that many societal institutions find increasingly difficult to adapt to these rapid transformations. Artificial intelligence, quantum technologies, cryptography, and mobility are just examples of challenges that have been transforming rapidly in the last few years and have a great impact on society (European Commission, 2021). In addition, the present post-modern society is featured with the giant challenge of climate change which unfolds in poly-crisis such as geopolitical instabilities, forced migrations, and biodiversity loss (IPCC, 2023).

In this panorama, science education is considered of fundamental importance, hence policymakers and science education researchers are trying to push for schools to play an intermediary role between students and the most demanding present-day challenges, to promote an educational curriculum that could help to make sense of society and its development as well as to develop a sense of agency. Signs of this intent can be found in many recent reports by research commissions. For instance, the European Commission in the “Council Recommendation on Learning for Environmental Sustainability” (2021) highlights the *“role of education in empowering people for environmental sustainability [...] Schools, universities and other education and training institutions will become places where sustainability is not only taught but also actively practiced”* (p. 8). Also, the 2021/C 66/01 Resolution of the Council of the European Union shared some recommendations which aim to foster *“creative approaches in green education [...] and promoting educational concepts, such as Education for Sustainable Development and Global Citizenship Education, in order to empower citizens to contribute to sustainable development”* (p. 21).

Along the same lines, many “competence frameworks”, released in recent years, aim to map the skills needed to face such kinds of challenges. For instance, in 2022 the European Commission launched the GreenComp, the European sustainability competence framework, in order *“to improve and develop the knowledge, skills and attitudes to live, work and act in a sustainable manner”* (Bianchi et al., 2022). In particular, the GreenComp identified four areas crucial for the promotion of sustainability competencies: “embodying sustainability values”, “embracing complexity in sustainability”, “envisioning sustainable future” and “acting for sustainability”. These four areas each focus on different aspects (recognising the values, supporting a systemic view, being projected towards the possible futures, take action to reach sustainability) and could be a starting point for educational approaches (Laherto et al., 2023).

The European Commission also launched the Digital Competence Framework for Citizens – DigComp (Vuorikari et al., 2022), which aims to foster students’ ability to solve problems by creatively using digital technologies, since *“in a growing technological world, these skills become part of their citizenship training to participate in the digital society where they will live”* (Pedró et al., 2019). These competence frameworks point out a way to develop skills that will soon be required as citizens’ skills, and push for education and science education to “create the room” for their inclusion.

Besides the competence frameworks launched by the European Commission, further approaches have been outlined to promote general awareness and engagement with the current challenges, by using art as a means for science communication and public engagement. “STEAM (Science, Technology, Engineering, Arts and Mathematics) education” is an approach advocating the need and relevance of including Art & Design in teaching/communicating STEM subjects (Yakman, 2008). It has been adopted

and developed, for example, by Science Gallery (SG), an international university network of galleries set up to “ignite creativity and discovery where science and art collide” (<https://sciencegallery.org/>). SG locates creativity at the core of both scientific and artistic discovery, and its vision conceives “a world where creativity knows no boundary”. From the SG perspective, some of those boundaries are represented by siloed disciplines and outdated curricula that lack a future-proofing approach. By fostering interdisciplinary collaborations among researchers, artists and industries, Science Gallery produces expositions, workshops, events and learning programmes⁸. Hence, the Science Gallery Network and more generally the STEAM approach can be considered an example of how merging arts with STEM education can be fruitful in improving student engagement, creativity and problem-solving skills (Liao, 2016); in addition, such an approach can create a connection with social/political issues that can help STEM disciplines and STEM education leading the strong innovation this century requires (Maeda, 2013). STEAM research indeed showed how such an approach could help to improve the learning satisfaction and motivation of students towards sustainability issues (Hsiao and Su, 2021; Kim et al., 2017) and more specifically Climate Change issues (Jacobson et al., 2016).

Nonetheless, despite the urgency and importance of aligning school curricula with societal needs, formal educational systems are struggling to reposition themselves concerning current challenges and related policy recommendations. Concerning sustainability education, only two years ago almost half of national curricula worldwide still do not refer explicitly to climate change issues (UNESCO, 2021a). As the OECD revealed, “*societal and environmental changes are happening rapidly, and technologies are developing at an unprecedented pace, but education systems are relatively slow to adapt*” (OECD, 2019). On top of this Rousell and Cutter-Mackenzie-Knowles add that the traditional school education around climate change lacks focus on social, political and ethical dimensions crucial to promoting a comprehensive perspective on Climate Change (Rousell & Cutter-Mackenzie-Knowles, 2019).

As for AI instead, even though both the policy-makers and scholars are pushing for the inclusion of AI teaching in both lower and higher education, still the development of AI curricula is late in coming. In 2021, UNESCO reported that only 11 governments have implemented K-12 AI curricula in their countries, due both to the difficulty of creating space in the curriculum and the need for teachers’ education around AI in terms of knowledge, practices and values (UNESCO, 2021b). In addition to this, much research is evidencing how AI is not only a new tool students should learn to use. Indeed, teaching AI should not be flattened to its technical aspects, even though they can be misleading and we should pay attention as educators (Polverini and Gregorcic, 2024). We should also recognize that the AI revolution is changing the way knowledge is produced and by who, which is a demanding yet not trivial aspect to include in AI education (Erduran and Levirini, 2024; Barelli et al., 2024).

Therefore, two gaps within formal science education seem to progressively emerge between what students experience at school and what they experience in everyday life outside school.

On the one hand, doing science at school is perceived as something strongly different from the common image of doing science within scientific communities (a distance on the level of *practice*). Hence, the larger this gap is perceived by students, the more the authenticity (Kapon, 2016; Kapon et al., 2018) of school scientific practices is questioned. Specifically, we frame authenticity by borrowing from Kapon (2016): authenticity in the sense of letting learners explore scientific ideas and questions in a community-like class setting (Calabrese-Barton, 1998; Miller et al., 2018; Stroupe, 2014; Windschitl et al., 2012) or the

⁸ Information about Science Gallery Network mission and values are declared in the section “What Science Gallery does” of their website (<https://sciencegallery.org/what-sg-does>) and in their internal (for network members only) toolkit (<https://toolkit.sciencegallery.org/about-science-gallery/our-mission-values/>).

authenticity of making students and teachers interact with science practices and activities (Houseal et al., 2013; Wormstead et al., 2002).

On the other hand, as already said, topics related to challenges such as climate change and sustainability or artificial intelligence do not find space within every school's scientific curriculum, and this could increase the gap between school and society (here the gap is at the level of *topics*). Scientific themes tackled in class sometimes appear disconnected and far removed from present-day challenges and this establishes a mismatch between the relevance of science within and outside school. The mismatch inhibits a kind of learning that is personally meaningful and relevant for students (Kapon, 2016). We frame "meaningful and relevant" learning by elaborating on the concept of relevance as introduced within the first Chapter by Stuckey (Stuckey et al., 2013).

As it is evident from science education literature, a lack of personal relevance for science education (for example in terms of practices and topics) could be at least not effective in promoting science identity development, if not an obstacle in certain cases. Indeed, scientific disciplinary identity is fostered when the practices enacted by the individuals are recognised as relevant for the community of practice (Wenger, 1998); if the practices and topics that find space in class are different from those which make sense in "real" scientific communities (Windschitl et al., 2012) students have little chance of feeling like participants in "science-construction" and thereby developing a scientific identity. Hence, engagement, interest and identification with STEM disciplines decrease (Hazari et al., 2010; Potvin and Hazari, 2014). Therefore, as I claimed in the first chapter, relevance affects also an identity development which is not only encapsulated within the scientific dimension. As it will be clear in the next sections and chapters, students can find a chance to develop as people (beyond discourse about future career choices or disciplinary identities) if they can participate and express themselves within scientific activities which they recognize as personally relevant (De Zuani & Levrini, 2024).

Thus, emerges a profound misalignment between a society that runs faster and faster (Rosa, 2009) and presents students with more and more new challenges to face and on the other hand a science education which could be of tremendous importance for developing the necessary skills to cope with such challenges but still encounters diverse limitations to its effectiveness. To name a few: the clash between a strongly disciplinary-based instruction which is at odds with the multifaceted nature of issues such as AI or climate change; the presence of outdated topics at school along with the lack of space for current challenging topics; the unpreparedness of teachers around relatively new topics, etc. Hence, to conclude, a re-configuration towards future-oriented curricula is advocated in terms of current challenging topics and related competencies (OECD, 2019; Pedró et al., 2019). Additionally, I claim that there is a need to include schools in this debate that is mainly carried on by science education scholars and policymakers to design principles which could map the debate to a more practical level, and lead to specific instructional activities and learning modules (De Zuani et al., 2023).

2. FEDORA and its objectives

The FEDORA project (<https://www.fedora-project.eu/>) started in 2020, as part of the Horizon 2020 programme and ended in August 2023. It included a network of experts at the nexus of science education, science communication and society:

- University of Bologna (leader of the project and coordinating WP4 and WP7)
- University of Helsinki (coordinating WP3)
- University of Oxford (coordinating WP5)
- Kaunas University of Technology (coordinating WP1)
- Formicablu (science communication agency coordinating WP2 and WP6)

WP1-6 indicate the “Work Packages”, the work units in which the project has been divided.

1. WP1 refers to the analysis of Blindspot 1 (interdisciplinarity), with the objective of aligning science teaching/learning in formal contexts with the modus operandi of R&I;
2. WP2 refers to the analysis of Blindspot 2 (new languages), with the objective of exploring new languages, narratives and arts in science education;
3. WP3 refers to the analysis of Blindspot 3 (futures), with the objective of futurizing science education;
4. WP4 refers to the development of a pedagogical model based on the analysis of the three blindspots;
5. WP5 refers to the political dimension, with the objective of engaging policymakers and offering them guidelines;
6. WP6 refers to the communication and dissemination of FEDORA in its making;
7. WP7 refers to project management.

The project had the general aim of developing a future-oriented model for both formal and informal science education, which can equip youngsters with the thinking, foresight and action competencies needed to grapple with societal challenges. The intention was to foster a change in the view on schooling and the role of science education in addressing societal challenges and the science-society gap, as well as to support proactive and anticipatory policymaking on this issue.

To that end, FEDORA worked on three forms of misalignment (blindspots) identified between the educational system and society: i) a clash between the hyper-specialised organization of teaching in disciplines and the inter-multi-transdisciplinary character of present-society challenges; ii) a mismatch between the formalised disciplinary languages and the need for new languages to enhance the capacity to talk about contemporary challenges; iii) the discrepancy between atemporal teaching approaches and the need to support students to construct visions of the future by empowering actions in the present.

The three mismatches have then been re-formulated into three research pillars addressed by the first three working packages (WPs) of the project: interdisciplinarity (WP1), search for new languages (WP2), and future-oriented education (WP3). These pillars represent the basis for the development of related educational frameworks for regenerating science education. For instance, the first blindspot makes evident the need to push an interdisciplinary science education; hence, this is set as a grounding pillar and then a selection of the “materials” (theoretical frameworks) useful to frame interdisciplinarity is done. This process led to clarifying the FEDORA perspective for each of its grounding pillars (shown in the following lines).

2.1 Pillars

Interdisciplinarity

First of all, it is noteworthy to clarify the difference between interdisciplinarity, multidisciplinary and transdisciplinarity. The three approaches are quite similar, yet they differ according to the kind of connections among the disciplines involved. Interdisciplinary approaches **integrate** ideas, instruments and perspectives from diverse disciplines to explain specific phenomena, as the classical integration of physics with mathematics (see for instance the birth of Special Relativity as discussed by Miani, 2022). Multidisciplinary approaches **justapose** the ideas and perspectives of diverse disciplines, without integrating them (Ashby & Exter, 2019). Finally, transdisciplinary approaches “*encourages the creation of new or shared conceptual frameworks, both in terms of methodology and theory that transcend fields and integrate disciplinary perspectives*” (Pucetaite et al., 2023). In this sense, transdisciplinarity overcomes the very nature of the disciplines involved towards the formation of a brand-new paradigm.



Figure 1: A visual interpretation of multi/inter/transdisciplinarity from FEDORA images (<https://www.fedora-project.eu/interdisciplinarity/>).

The construction of the first pillar, hence the construction of what kind of interdisciplinarity FEDORA promotes, stands mainly upon two theoretical frameworks. The first one is the “FRA to NOS Reconceptualisation” framework (Erduran and Dagher, 2014), presented in Chapter 1. The “FRA to NOS” framework has been used to reflect on the epistemic core of a discipline and in class, it is recommended for designing activities aimed at providing students with a foothold vocabulary to articulate a comparison of the epistemic cores of disciplines (Satanassi et al., 2023). The educational potential of the epistemic core is that it provides examples of reasoning’s structures, rigour’s criteria, and explication of principles, and dealing with these features might train students’ “sense-making” skills (Tasquier, Levrini, Barelli, Branchetti et al., 2022).

The second framework is the meta-theory of boundary objects and mechanisms elaborated by Akkerman and Bakker (2011). In their work, the authors discuss the different figures that populate boundaries (boundary people, boundary objects) and the possible boundary-crossing mechanisms (identification, reflection, coordination, transformation). In FEDORA, the conceptual richness of this “boundary metaphor” has been used to model interdisciplinarity and its “paradoxical” nature: boundaries both separate and connect. Interdisciplinarity means to blur and redefine disciplinary identities (which are themselves a compound of inner dimensions) and requires managing the equilibrium between “sense-

making skills” - systems, critical and analytical thinking- and “strange-making skills” (Bol & de Wolf, 2023) - creative, imaginative and anticipatory thinking (Levrini et al., 2023; Pucetaite & Rauleckas, 2023).

New languages

The second pillar (search for new languages) elaborates on the concepts of engagement and innovation (Troncoso et al., 2023) to explore possible ways for regenerating languages in science education. Engagement, in science education, is considered as a cognitive and emotional experience that results in a change of attitude. Furthermore, a language is considered innovative if it presents connections between science and other domains of knowledge, *“which can inspire a cognitive journey towards something not obvious at first but that becomes essential and personally relevant once touched upon”* (Tasquier et al., 2022b). In this sense, the STEAM approach is an example of how those non-obvious cognitive links between different domains of knowledge (scientific and artistic ways of making sense of the world) can be explored and fostered.

Hence a new language as a combination of symbols to convey a message to someone, which in this case has been combined with interdisciplinarity and the future, becoming a new practice to imagine the future, a medium to stimulate radical imagination and *“tools for crossing boundaries and inhabiting these frontier zones”* (Levrini et al., 2023).

Future

The third pillar (future-oriented education) reflects the ambition to adapt “future thinking” to science education (Branchetti et al., 2018; Carter & Smith, 2003; Jones et al., 2012; Levrini, Tasquier, Barelli, Laherto, et al. 2021; Paige & Lloyd, 2016). In this case, the pillar builds upon four main ideas resulting from an interaction between the analysis of the research literature and the empirical exploration of some case studies related to the issue of futurizing science education. Particularly, the FEDORA approach interconnects research in a variety of domains: future studies, youth studies, science and technology studies, and educational studies on agency, as well as societally oriented approaches to science education, such as the SSI (socioscientific issues) and STSE (science, technology, society, environment) strands. The four main ideas are:

- **Two-track thinking:** personal futures are often perceived by students as positive and in one’s own hands, on the other side global futures are perceived as gloomy and beyond their control (Cook, 2015; Rubin, 2013). This leads to a polarization between individual and collective, and the creation of “safe bubbles” (Levrini et al., 2021a);
- **The five dimensions of the Future Consciousness framework** (Ahvenharju et al., 2018): these can be thought of as scaffolding principles for future thinking processes. Such dimensions (time perspective, agency beliefs, openness to alternatives, systems perception, concern for others) represent the prior conditions that allow future-oriented thinking and behaviour to take place;
- **The involvement of time:** using a temporal perspective to frame the concept of agency, following the work of Emirbayer and Mische (Emirbayer et al., 1998). In this case, the “chordal triad of agency” will be used to foster students in the creation of future scenarios (possible future, probable future, preferable future);
- **Evidence technology:** highlight the role of technology and its nuanced and complex function in future thinking, since technology has been shown as one of the main sources of transformation of the present into the future (Bishop & Hines, 2012).

3. FEDORA's outcomes

3.1 Frameworks and Recommendations

The three research pillars of FEDORA (interdisciplinarity, the search for new languages and a future-oriented science education) have been the basis for the formulation of three frameworks, the final research findings of the project. Based on the analysis of the misalignments done within WP1-2-3, the frameworks pointed out the main related issues and elaborated specific recommendations for science educators.

The frameworks are respectively:

- FR1: Framework for aligning science teaching/learning in formal contexts with the modus operandi of R&I: new inter-multi-transdisciplinary forms of knowledge organization for co-teaching and open-schooling (Pucetaite & Rauleckas, 2023),
- FR2: Framework for aligning science education with society: the search for new languages and narratives to enhance imagination and the capacity to talk about contemporary challenges (Troncoso et al., 2023)
- FR3: Framework to Futurize Science Education (Rasa et al., 2023)

Each framework contains respectively recommendations aimed at providing teachers and educators with practical inputs to answer the following questions (Levrini et al., 2023; Tasquier, Levrini, Barelli, Caramaschi et al., 2023):

1. How can we model inter-multi-transdisciplinarity and design “boundary spaces” in formal and informal educational contexts? What institutional, epistemological, cultural, and emotional barriers can interdisciplinarity encounter?
2. How to create innovative ways to communicate, foster and imagine?
3. How do young people perceive their personal and global futures? How do they imagine the role of science and technology in those futures? How can science education foster students' future thinking and agency?

FR1

The FEDORA elaboration on the first pillar resulted in recommendations divided into three dimensions according to diverse stakeholders. At the political level, governance and institutional processes need to include qualitative criteria in staffing, performance assessment, and workload allocations to prioritize the sustainability of interdisciplinary courses; also, they should focus on the importance and societal impact of research over mere “ease of evaluation” (Levrini et al., 2023).

At the community level, human resource practices must be updated to incorporate the previously revisited qualitative criteria and there should be an emphasis on collaboration and co-ownership of interdisciplinary courses among educators. This can be supported by developing materials and case studies to enhance institutional changes.

At the individual level, the concept of the “disciplinary nomad” should be encouraged as a way to practice interdisciplinarity. Institutions should facilitate the development of a common interdisciplinary language

rather than emphasizing only the different disciplinary approaches. In this sense, creating a “third space,” free of disciplinary symbols, is a suggested way to enable interdisciplinarity.

In general, the FR1 suggests to:

- Balancing sense-making skills like critical thinking with strange-making skills such as creative thinking
- Encouraging students to take intellectual risks and embrace scientific uncertainty to be able to face complex issues
- Differentiating the curriculum to make different types of knowledge accessible to learners.

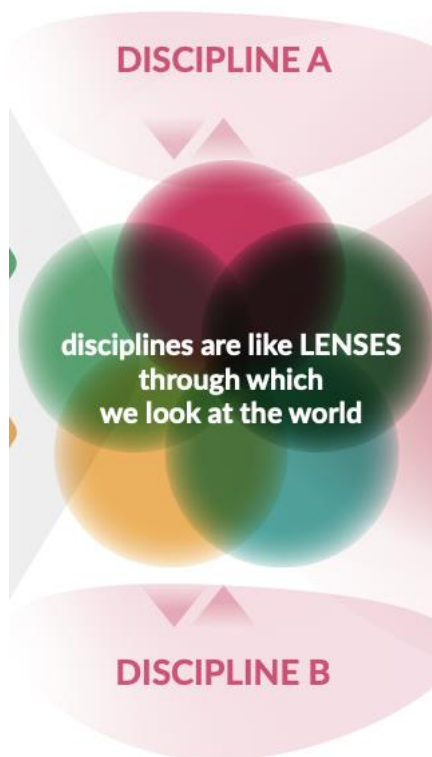


Figure 2: The disciplines merging suggested by FR1 (From “Pathways for a future-oriented science education A handbook from the FEDORA project”, Levrini et al., 2023; p. 6).

FR2

The FEDORA elaboration on the second pillar resulted in 4 kinds of languages “to navigate unexplored territories and possible futures, and convey actions in our uncertain times”: i) the languages for adaptation; ii) the languages for foraging futures; iii) the languages for uncharted territories; iv) the languages for interdependencies.

Besides these four languages, eight related recommendations have been produced, suggesting the creation of experimental spaces beyond disciplinary boundaries to encourage innovation and change as well as immersive experiences exploiting various languages, such as theatre and music. According to FR2, this could help address complex issues like global health and climate change, also by involving diverse roles and viewpoints.

Also, FR2 promotes "tri-dimensional" thinking which overcomes binary perspectives and supports interdisciplinary identities. Thus, lessons should be student-centred, encouraging peer-to-peer exchanges

and inverted classes. Inclusive programs are then necessary to enhance teachers' collaborative strategies, considering student diversity to appreciate different capacities.

Therefore, it is crucial to bridge formal and informal education with value-laden real-life issues, inviting experts and using current sources, to make education relevant (Stuckey, 2013). In addition, using traditional and digital tools bridges gaps between teachers and students, emphasizing sociability and relationships in knowledge building. Ongoing education and capacity building are crucial, as fostering creativity and transformative potential requires continuous training, and integrating future thinking into formal and informal school learning.

FR3

The FEDORA elaboration on the third misalignment (based on empirical studies and desk research across the countries of the partners) made evident nine issues grouped into three main groups:

- Students' problems in perceiving their future: students often feel powerless and detached regarding their future, struggling with static, deterministic views and a lack of agency (Angheloiu et al., 2020; Rasa et al., 2022).
- Students' difficulties in connecting the future with scientific and technological knowledge: their narratives about the future are frequently simplistic and lack imagination, often influenced by polarized thinking and superficial technological utopias or dystopias (Rasa et al., 2022; Rubin, 2013).
- Issues related to educational design: absence of explicit future concepts in curricula (Ahvenharju et al., 2018; Carrington et al., 2010) and a lack of metacognitive skills to articulate future thinking (Bol & de Wolf, 2022).

The empirical and theoretical-driven reflection around these issues ended up in 14 recommendations (see Figure 3).

They generally aim to: include future topics in curricula as well as in teacher education programs, and foster future-scaffolding skills (Levrini, Tasquier, Branchetti & Barelli, 2019; Levrini, Tasquier, Barelli, Laherto et al., 2021) by addressing ongoing trends in science and highlighting the role of humans in their development, develop interdisciplinary projects, use collective group work and deconstruct school space-time rituals to stimulate students' expression and imagination of future images (see Figure below for details). The intention is to disclose tools to let students connect with and find agency within their personal and global futures as well as provide a broad and deep perspective about how to overcome the idea of one future as prescriptive, unidirectional and imposed from above (Rasa et al., 2023). These recommendations have been summarised and reported within the FEDORA "Future Manifesto" (Bol et al., 2023).

To wrap up, the recommendations that emerged by FR1-2-3 represented the synthesis of the FEDORA project's findings and insights, targeted to policymakers, researchers in science education, curricula developers, teacher educators and teachers and have been conceived as conceptual tools to imagine and design interdisciplinary, future-oriented, engaging, relevant, and meaningful science learning experiences for learners of different ages and backgrounds (Bol et al, 2023; Pucetaite and Rauleckas, 2023; Rasa et al., 2023; Tasquier, Levrini, Barelli, Branchetti et al., 2022; Troncoso et al., 2023).

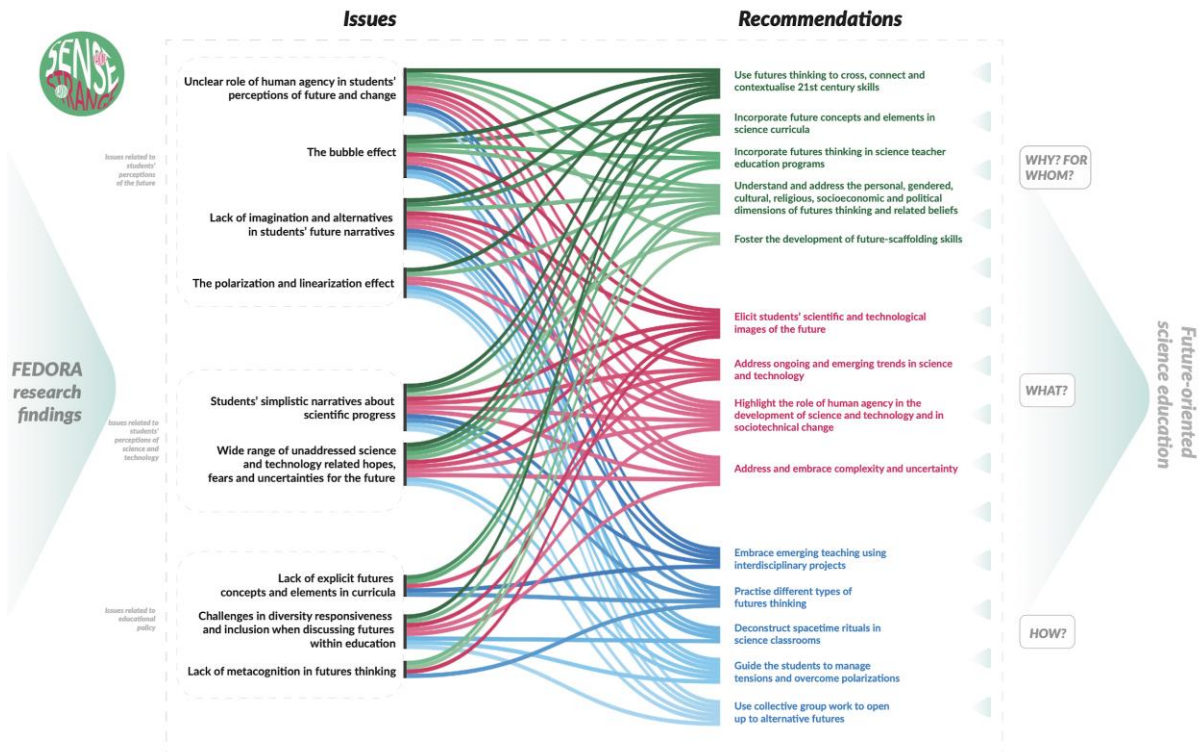


Figure 3: On the left are the nine research issues, organized in the three macro-categories. On the right the recommendations each one linked to one or more informing issues, organized into three dimensions: a general one (why? for whom?), one concerning the contents (what?) and one concerning the pedagogical solutions (how?). (From “Pathways for a future-oriented science education A handbook from the FEDORA project”, Levrini et al., 2023; p. 10).

3.1 Open-schooling

Open-schooling is a structural feature of the FEDORA project, inspired by a previous European Project - SEAS (<https://www.seas.uio.no/>) - in which the Bologna PER Group was involved.

Open-schooling represents the ambition asked for by the European Commission to create experiences “*in which schools collaborate with community actors outside the school for the wellbeing of the community*” (Tasquier & Jornet, 2023). The bottom-line idea is to break down the barriers which separate schools and society which creates the aforementioned “gap”, and let students engage in a more relevant kind of teaching. In particular the “openness” has been interpreted in FEDORA as a demand for action at the content level, at the level of interaction among stakeholders and at the level of institutional transformation.

Nonetheless, open-schooling networks were crucial in the definition and refinement of the three theoretical frameworks. Indeed, three networks (based respectively around Helsinki, Oxford and Bologna) contributed to the design and implementation of local activities that took the premises from the initial versions of recommendations but to test and refine them.

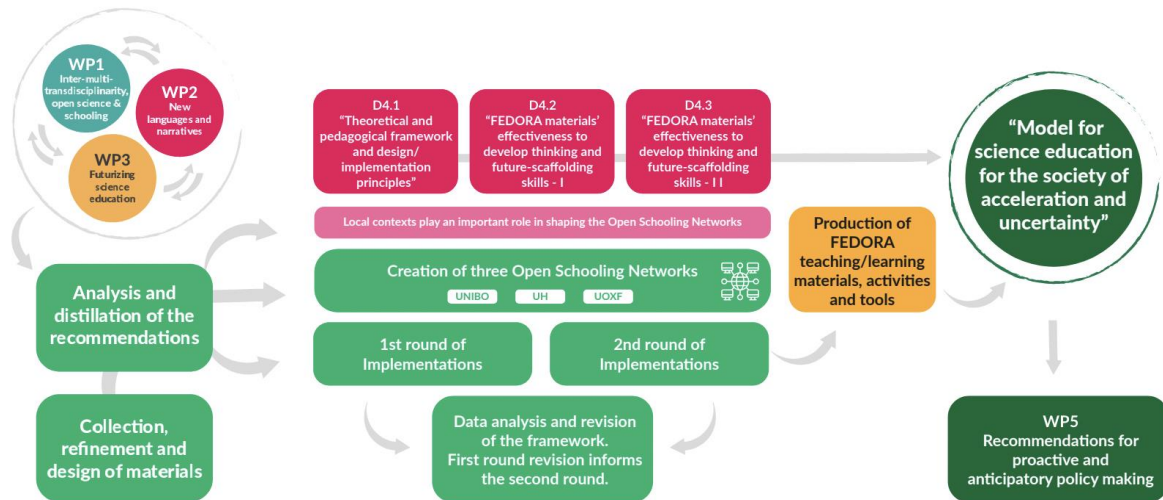


Figure 4: An overview of the process that led from the research analysis around the three misalignments towards the creation of the final educational model for the society of acceleration (the work of coordinating all the processes was the task of WP4, led by the University of Bologna).

From the analysis of the initial recommendations a first version of the theoretical frameworks was produced to be used in the three Open-Schooling Networks; this led to the creation of a first round of implementations whose analysis led to a second round of implementations and a final revision of the frameworks, besides the teaching/learning materials (Levrini et al., 2023).

Two rounds of activities have been implemented between 2022 and 2023, for a total of 18 implementations involving more than 300 students, 50 teachers, 40 researchers and *“a variety of other stakeholders in a diverse set of learning environments, both formal, non-formal and informal, including schools, universities, teaching-learning centres, and museums”* (Levrini et al., 2023; p.10). For each activity, some recommendations from the three frameworks were taken as starting points and then mapped into *“Design Principles”* to fit with the local context and topics addressed (the process is illustrated in Figure 5).

The meaning of open-schooling networks is to create a shared space for reflection, in which teachers bring their own disciplinary expertise and accept to re-generate the subject matter (Tasquier & Jornet, 2023) by intertwining with other teachers, other disciplines, other practices and knowledge. This *“trading zone”* is representative of the crucial interest of involving schools in a debate which too often is only left to academics and policymakers. This could be beneficial for pushing schools to engage in the challenges illustrated in the European reports but also for documenting what practical obstacles and difficulties may arise in diverse contexts.

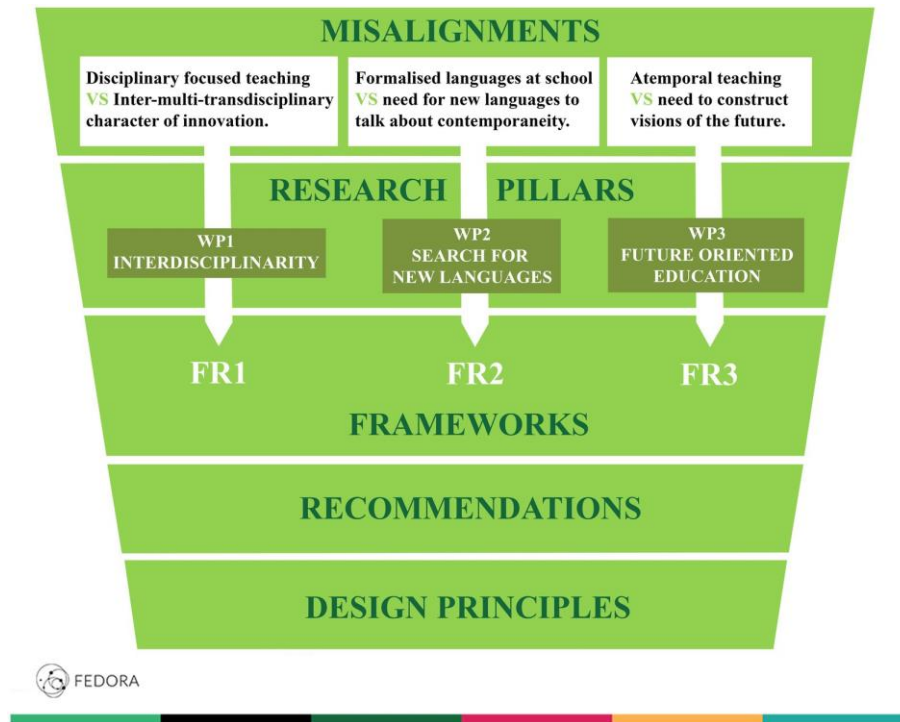


Figure 5: Design-process diagram. From top to bottom: three misalignments between education environments and society's labour market and R&I were identified; FEDORA's three research pillars were established, and three research frameworks were crafted; research shed light upon some crucial issues and some recommendations were designed to address them; finally a selection of relevant recommendations was made which brought to the creation of design principles for the development of educational activities (From "Enhancing relevance and authenticity in school science: design of two prototypical activities within the FEDORA project", De Zuani et al., 2024; p.4).

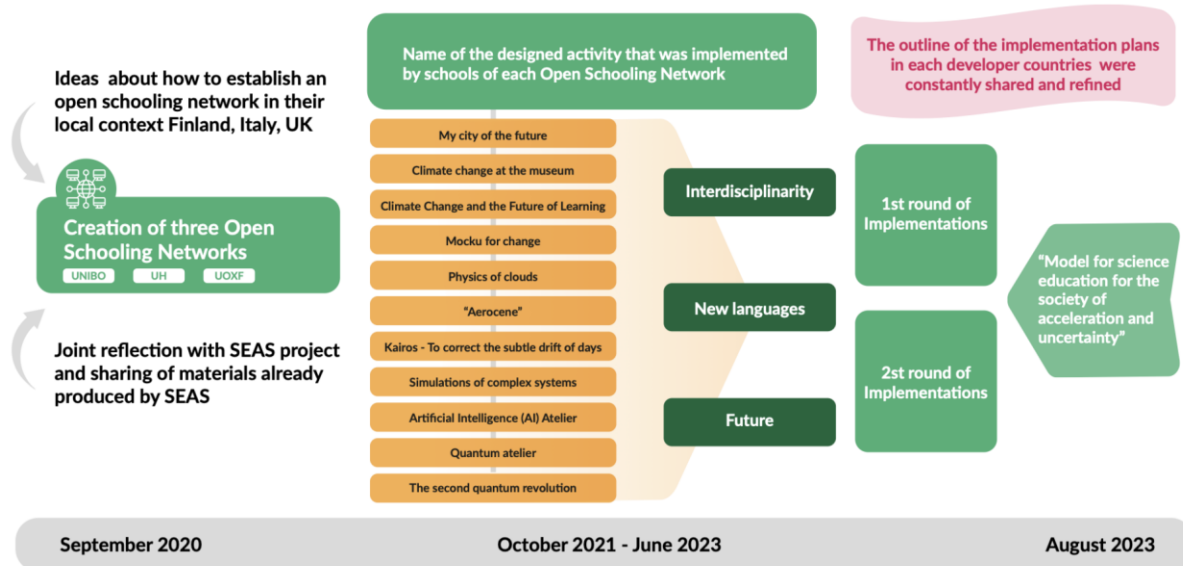


Figure 6: A zoom-in for the activities implemented over the last two years of the project. Eleven different activities, some of them repeated more than once for a total of 19 diverse implementations (From "Model for science education for the Society of Acceleration and Uncertainty", Tasquier, Chan et al., 2023; p. 15).

The Italian open-schooling network has been established in collaboration with a wide variety of Italian secondary schools in terms of geographical distribution, relationship with the social community of the region, political role and relationship with policy-making structures, cultural background and tradition, internal organization, curricula, typologies of teachers, disciplines involved and internal expertise. Furthermore, the network involved other stakeholders including researchers in science education, scientists, artists, science communicators and language experts (video-makers, bloggers, writers and data storytellers).

The implementations of the Italian network in particular addressed interdisciplinarity, new languages and futures by creating teaching modules around themes such as the simulation of complex systems, the space-time structures of physics of complex systems, quantum technologies and quantum revolutions, and climate change.

4. Conclusions

This chapter has outlined the foundational context and objectives of the FEDORA project, which notably⁹ developed a future-oriented approach aimed at fostering proactive and anticipatory policymaking to align science education with the societal and scientific landscapes. By framing these challenges within the broader scope of making science education personally relevant, I emphasized the importance of rethinking science education to better equip students with future-oriented skills. The FEDORA project aims to address these gaps through its focus on interdisciplinarity, the development of new educational languages, and fostering future-thinking in students. Also, I described the FEDORA pillars, and how they informed the three lines of desk research ending with the elaboration of FR1-3 theoretical frameworks and related recommendations. These recommendations were considered as premises for elaborating the design principles of the Open-Schooling network implementations.

Finally, in the next Chapter, I will report in detail one of the BOSN activities (Bologna Open Schooling Network) from the first round of implementations, referring both to the design process informed by the FEDORA recommendations and to the data analysis and findings which informed back the refinement of FEDORA frameworks and recommendations. The rationale behind the choice of focusing on this activity will also be elucidated. In the next Chapter, the data analysis will be carried out to answer the Research Questions introduced at the end of the first Chapter.

To conclude, one important step is still missing: to elucidate the position of the present PhD research within the FEDORA project.

Looking back at Figure 6, the two macro-studies discussed in Chapters 3 and 4 are the result of the data-analysis of two of the implementations displayed there (namely “Physics of clouds” and “Kairòs – To correct the subtle drift of days”). An analytical process for the implementations done was crucial in the FEDORA logic, as it is meant to test and validate teaching materials and tools and finally inform the formulation of recommendations and design principles. As described above, the two rounds of implementations (see Figure 4), were conceived as the grounding “laboratory” scaffolding the formulation and refinement of the three Theoretical Frameworks and related recommendations; but to do this we

⁹ https://cordis.europa.eu/article/id/449203-a-science-education-model-to-navigate-our-fast-changing-society?WT_mc_id=exp

needed a systematic analysis and arrangement of the data collected, which ended up in Deliverable 4.2 (Tasquier & Barelli, 2023) for the first round of implementations, and a final document including also the second round of implementations (Tasquier et al., 2023). In this sense I contributed to the final formulation of the Frameworks and Recommendations through the analysis of two implementations.

Moreover, I practically contributed to the analysis of the tensions perceived and/or experienced by actors of the educational system, interviewed for the WP1 objectives. This led to a presentation at the 16th European Sociology Association Conference in August 2024.

Finally, the activity discussed in Chapter 5 was not used to refine FEDORA frameworks as it was done some months after the end of the project but certainly contributed to keep alive the discussion and reflections around the recommendations presented in the final documents. The activity was indeed thought and designed taking the premises from the FEDORA outcomes and provided new data to test again the frameworks. One above all the creation of the game *FyouTURES* and the potential link of related results with respect to the Future Science Education Manifesto (Bol et al., 2023).

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Chapter 3

Introduction

In this chapter is presented the first case study of my dissertation, named “Physics of Clouds”. This was an interdisciplinary activity framed within the FEDORA project (Chapter 2), merging creative writing with the physics of complex systems, with students (upper secondary) producing a set of six essays as the final output.

The case study is aimed at addressing the Research Questions elaborated at the end of Chapter 1.

RQ I: *What methods and analytical lenses can be used to identify the connection between physics epistemology and identity development?*

RQ II: *What physics contents can inhibit or activate the link between epistemology and identity?*

RQ III: *What role do epistemic emotions play in the activation of this link?*

The Chapter is structured as follows.

In the first section is outlined the design of “Physics of Clouds”, by presenting the context and discussing the cultural framework (Section 1.1), the physics and literature epistemological frameworks (Section 1.2) and the participatory framework. As a conclusion of this part, it is highlighted how the design of the activity was informed by the recommendations of the FEDORA project (Section 1.4). In that Section there are also reflections of the challenges encountered during the activity, examining both the students’ and teachers’ points of view.

In the second section, there is a summary of the essays produced in the activity, which constituted the dataset I analyzed (Section 2.1), to allow the external readers to better enter into the analytical details. Then, a report of the two rounds of data analysis is presented, discussing the methodologies and related outcomes (Sections 2.2 and 2.3). In Section 2.4 there is a description of an analytical procedure to validate the reliability of my research interpretation.

In Section 3, the elements that emerged from each round of analysis are examined and conclusions are drawn. Finally, in Section 4, the Research Questions introduced in Chapter 1 and the theoretical construct at their basis are recalled and addressed in light of the data analysis’ outcomes. In particular, a first answer to RQ I-III is provided and three new Research Questions to address in the next Chapters are formulated. See the Figure below for a general overview of the Chapter.

Parts of Section 1 are contained in the paper “Enhancing relevance and authenticity in school science: design of two prototypical activities within the FEDORA project” (De Zuani Cassina et al., 2023). In addition, the two rounds of data analysis were the core of my first two oral presentations at international conferences, namely the GIREP Conference 2022 held in Ljubljana (<https://indico.cern.ch/event/1092708/>) and the 2023 NARST International Conference held in Chicago (<https://narst.org/conferences/2023-annual-conference>). Furthermore, the GIREP oral presentation led to a proceeding paper published in 2024: “Educational reconstruction of physics of complexity within a creative writing classroom activity” (De Zuani & Levri, 2024).

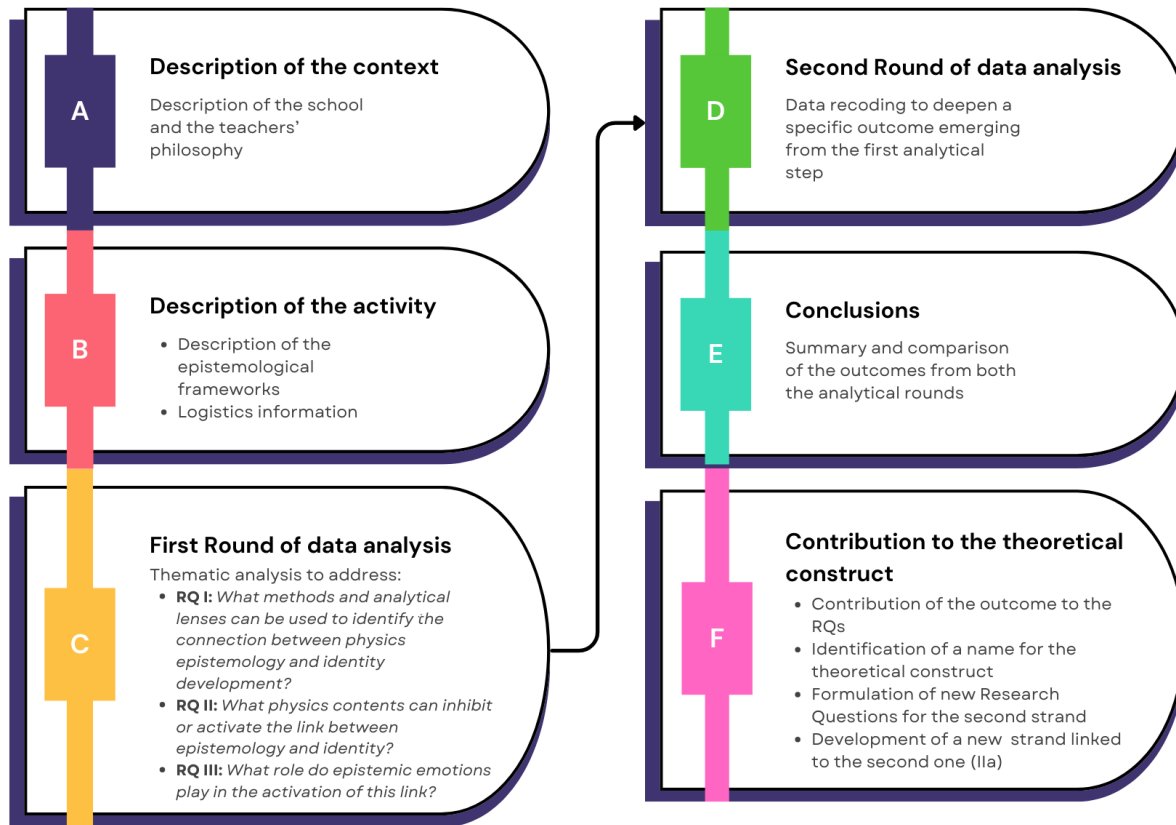


Figure 1: An overview of the parts of the Chapter.

1. Physics of clouds

In the previous Chapter, I outlined the activities that have been implemented within the FEDORA framework and organized by the local hubs connected through the open-schooling networks (Figure 5, Chapter 2). The BOSN (Bologna Open-Schooling Network) produced - over the three years - different activities around challenging and interdisciplinary topics such as AI, quantum technologies, climate change or complexity. The goal was to test the recommendations and support with an empirical layer the ongoing development of the “Model of Science Education” within WP4. Hence, all these activities contributed in specific ways to this objective, as D4.2 (first implementation) and D4.3 (second implementation) show (Tasquier & Barelli, 2023; Tasquier, Barelli, Levrini, Chan et al., 2023).

Among them, one activity (“Physics of Clouds”) demonstrated itself particularly relevant for the reflection I was carrying on within my PhD research, specifically for the connection between physics epistemology and students’ identity issues.

In the activity (which I explain more in detail later) the students were initially engaged in lectures about the main features of the physics of complex systems and subsequently they were guided by the literature teacher in a creative writing exercise in which the topic was somehow related with the physics concepts addressed in the first lectures. Notably, at first reading and after triangulation among three scholars, it was agreed that in the material produced by students (essays), there were implicit but also explicit references to identity issues connected with some epistemological elements of complex systems.

The (striking) presence of epistemological aspects somehow connected to the expression of personal demands was the rationale to include this dataset within my thesis and to develop analytical strategies to address the data. Thus, I examined both the context of the course (implemented in 2021) and analyzed the data through two separate phases outlined in Sections 2.2 and 2.3. In particular, since I was not present in class during the implementation and in the design process, to study the activity I used the following sources:

- One extended interview done in July 2023 at the end of the activity presented in Chapter 4, which again involved the same teachers and merged physics with creative writing. On that occasion both PF¹⁰ and SM were present and discussed their choices, some of them were mutated from the “Physics of clouds” experience.
- One presentation done within the teacher council by SM and PF in March 2024, regarding the two activities: Physics of Clouds and Kairòs.

For the data analysis, I instead used the essays in their final version (presented in Appendix A).

Before diving into the analytical part, I first provide a timeline of the project and related phases. Then, I describe the “special” context which probably contributed to an impressive “emergent result” (Sections 1.1, 1.2 and 1.3). Then in Section 1.4, I illustrate the design process of the activity concerning the FEDORA recommendations from FR1-2-3 and highlight how they have been transformed into contextual design principles and learning outcomes.

¹⁰ Prof. Paola Fantini and Prof. Sara Moresco - teachers of the activity - are sometimes referred to with their initials.

"Physics of clouds" timeline

"Physics of Clouds" took place at Liceo A. Einstein in Rimini as a curricular course over 8 months (October 2020–May 2021) for about 50 hours. It involved a class of 24 students in the first year of high school (9th grade) and three teachers: SM, PF and the history teacher.

Even though the real activity started in February, the whole process began in October 2020.

Indeed, from October 2020 to January 2021, students were introduced to various narratological techniques through the reading, analysis, and discussion of short stories, anthology excerpts, and novels. This was facilitated by the Italian language teacher during school hours, with ongoing assessments which included oral exams, evaluative essays, text analysis, and structured tests. Concurrently, from October to December, again SM in her curricular hours guided pupils through writing techniques, particularly subjective and objective description, rhythm, and stylistic choices.

From December to February, students were introduced to the life and works of Italo Calvino, with a specific focus on an analytical reading of his novel *"Palomar"* (Calvino, 1985). The reason for deepening this novel was to show how Calvino manages the intertwining of the two fields, scientific and literary, and how the narrative structure can be interpreted in terms of complexity. Also, they read and discussed other selected stories and excerpts including *"Cosmicomics"* (particularly "All at One Point"), *"The Cloud of Smog"*, *"The Argentine Ant"* and sections from *"T Zero"* (Calvino, 1968, 1969, 1981).

Additionally, PF conducted two informative lessons (2 hrs. each) titled *"Complicated and Complex"* in January and February and the lecture *"From the Physics of Clocks to the Physics of Clouds"* in February. In these lectures, the foundations of complex systems and their epistemology were introduced by examples from everyday life, like flocks of birds, anthills, clouds. The objective of the lectures was to allow students to increase epistemic skills such as aggregate and agent-based perspectives (systemic view on the system), and bottom-up or top-down perspectives (attention to the causal processes) (Jacobson & Wilensky, 2006): in general, the ability to have a systemic view.

In February, there was also a projection of the documentary film *"Anthropocene: The Human Epoch"* (Baichwal et al, 2018), which highlighted the extensive transformations human activity has brought to the landscape over the last century.

From March to May the second part of the activity occurred, managed only by SM. In the beginning, students were presented the 6 examples of complex systems to be used as the basis for the writing of creative essays. Then, students were divided into six groups, each comprising four members, and were assigned the task of observing selected complex systems outside school hours. During this period, students were also encouraged to read Calvino's *"Cosmicomics"* as an example of conveying complex messages through literature.

In addition, student groups started working on narratological constraints informing the diverse essays' structures. For instance, Group 1 focusing on "The Anthill¹¹" and Group 2 focusing on "Fluid Molecules," had to start with descriptive sequences and progress through narrative and reflective sequences, often without revealing the true nature of their characters until later in the story. On the other hand, Group 3 worked on "The Nest," starting from the end, exploring themes of certainty and sustainability, and including flashbacks to understand past errors. Group 4 tackled "The Sea," employing a narrative structure beginning from the end and involving introspection and dialogue to uncover the complexity and duality

¹¹ These were initial names which have been changed by the students in the final version of the essays.

of the sea. Groups 5 and 6, focusing on "A Flock of Birds" and "Clouds," respectively, used in medias res beginnings and explored themes of complexity and sustainability through subjective descriptions and reflections.

At the end of March, students began writing their essays, creating narratives with the possibility of including hand-drawn illustrations. From March to April, the Italian teacher conducted the first reading and editing of the stories, assessing their adherence to the assigned narratological constraints, narrative structure effectiveness, and correctness in spelling, syntax, and vocabulary.

In April, students revised their drafts based on feedback and engaged in cooperative learning by sharing their stories with peers who worked on similar complex systems, aiming to optimize their narratives.

Finally, in May, the project outcomes were communicated to all participants during school hours.

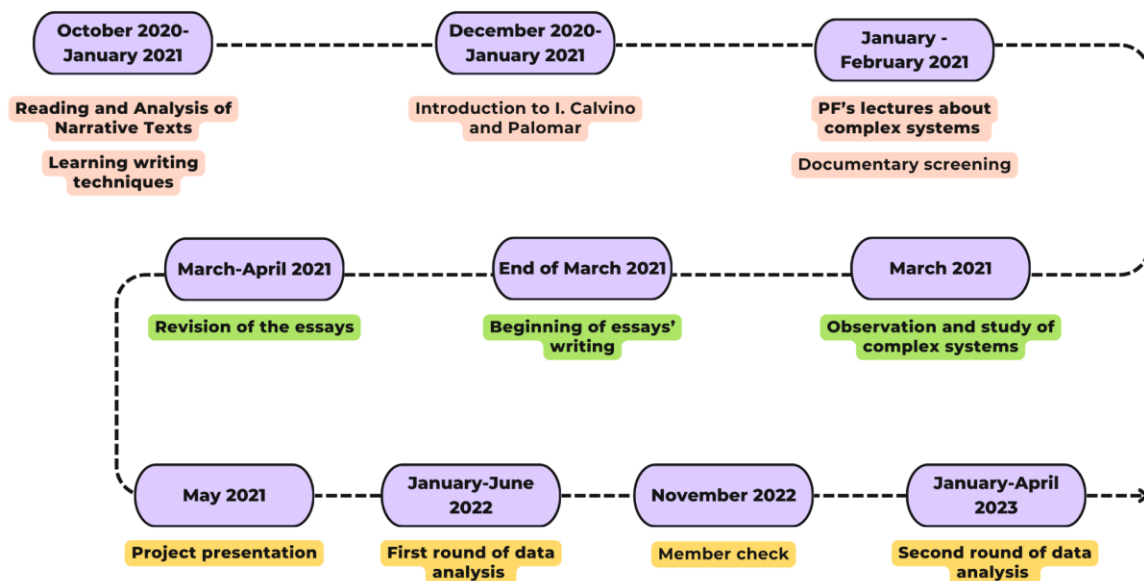


Figure 2: Timeline of the project and following analytical phases.

1.1 The school and its cultural frame

“Liceo Scientifico Einstein” (<https://www.einsteinrimini.edu.it/>) is one of the main stakeholders of the BOSN.

The school is one of the two public scientifically-oriented Licei (high schools) of Rimini, a medium-sized city in the northeast of Italy. The school is attended by students who live in the neighbourhood and, being public, is not selective from a social and economic point of view. Nevertheless, even if the range of family professions is rather large (from tourism employees to self-employed like physicians and engineers), the majority of the families have a relatively high level of education (secondary school or university degree).

Licei Scientifici (scientifically-oriented) are present throughout Italy and usually in medium/large cities, and they are becoming quite popular so that there is often more than one option for most of the towns. Being a science-oriented school, students throughout the five years deal intensively with scientific subjects such as Biology, Mathematics, and Physics, but also according to the path they choose they can deal with subjects such as Computer Science, Geology, Chemistry, etc. The other subjects studied are Italian literature, English language and literature, History, Philosophy, Art, and Physical Education, but sometimes, again according to the path, also an extra-language and Latin. Regarding physics, students study it through all the five years of upper secondary school (grades 9–13). During the first two years, teachers focus on phenomenological descriptions and laboratory activities about natural phenomena and physical concepts about motion, heat, light and vision, and waves. In the final three years (grades 11-13), the main goal of the curriculum is to reorganize and systematize what students have learned from their laboratory studies in terms of physical theories (mechanics, optics, thermodynamics, electromagnetism, relativity and quantum physics).

Nonetheless, even though there are many Licei Scientifici, Liceo Einstein happens to be one of a kind. It is indeed a sparkling school, with a lot of chances offered to students, such as free extra-curricular foreign language courses (Spanish, German, French, English) or music courses. The school has a huge library and hosts many seminars over the year, besides establishing close collaboration with external institutions (like the University of Bologna). Furthermore, students can select a double degree program attesting to a US high-school degree. However, one of the most distinguishing features of this school is a group of teachers who closely collaborate with the Physics Education research group of the University of Bologna. Since 2000, these teachers have regularly attended research seminars and meetings at the University of Bologna and they have worked together to co-design interventions to test in their classes, involving also other teachers from the same school over the last few years.

As a testament to teachers and the school’s commitment to the collaboration with the University of Bologna, from the initial implementation of teaching and learning modules (concerning thermodynamics, quantum physics, relativity, climate change, etc) which led also to research publications (Levrini, Fantini, Tasquier, et al., 2015; Tasquier, Levrini & Dillon, 2016), in 2016 the Liceo Einstein began to join European Projects in which the research group of the University of Bologna was involved.

It started with “I SEE”¹², an Erasmus + project coordinated by the University of Bologna and involving the University of Helsinki, other Finnish and Icelandic schools and a British association. The project aimed to design innovative teaching modules on STEM topics (climate change, carbon sequestration, artificial

¹² “Inclusive STEM Education to Enhance the capacity to aspire and imagine future careers” (<https://iseeproject.eu/>)

intelligence, quantum technologies) to foster students' capacities to imagine the future and develop desirable scenarios for them.

In 2019 Liceo Einstein joined again another European project, the H2020 SEAS project¹³, held by the University of Oslo and involving research centres and universities among which the University of Bologna. SEAS aimed to develop a model of *open schooling*, the one which inspired the three following networks within FEDORA. Liceo Einstein was part of the Bologna local network together with three schools and participated in figuring out the open-schooling model which contributed to identifying and matching local ideas and needs with the ones at the level of the whole SEAS consortium.

Hence in 2020, Liceo Einstein joined the FEDORA project, playing a pivotal role in model building and developing interdisciplinary courses co-designed by school teachers of different disciplines to test and refine the FEDORA frameworks.

After the FEDORA experience, in 2022 Liceo Einstein and the group of teachers became associated partners of CLIMADEMY¹⁴, an Erasmus+ Teacher Academy project coordinated by the University of Crete with the University of Bologna as a partner. CLIMADEMY aims “to offer a comprehensive program for teachers that will lead to a better understanding of climate change and to an efficient methodology of teaching the next generation of European citizens” (<https://climademy.eu/>). The project is developing and establishing a network and community of practice to create innovative strategies and programs for preparatory and continuous professional development for serving student teachers on climate change and its impacts. Liceo Einstein is actively participating in thinking about how to include climate change within school science curricula and to develop a pedagogical model for teachers' education.

The cultural framework

The projects mentioned above share common guiding ideas and are informed by the perspectives of these teachers in conceiving *knowledge* as well as the role of schools in addressing societal challenges.

In this context, knowledge appears as something that is *not-disciplinary*, but rather defined by an intrinsic complexity which cannot be reduced in single disciplines, with many nuances which can be related to many disciplines. Furthermore, the current *siloing* subject organization is extremely reducing the value and depth of knowledge itself by forcing it to fit into disciplinary boxes. One of the consequences of this structure is that students develop an image of knowledge that is compartmentalized into disciplines, with few connections but rather some inconsistencies between them (see the first blindspot of the FEDORA project).

Hence, these teachers were feeling the cultural tension between what is taught at school (disciplinary shaped) and the outside world (interdisciplinary by itself) and at the same time they were strongly guided by the principle that we should “address” somehow this tension. Therefore, by sharing their values and experiences they started to reason about new practices and ways of collaborating and designing activities in their classes. This led for instance to notable examples of projects merging different disciplines (Physics and Italian literature, Physics and Art, Physics and Mathematics, Computer Science and Art, etc.), intertwining topics and languages from both disciplines. Sometimes the co-design led also to co-teaching

¹³ “Science Education for Action and engagement towards Sustainability” (<https://www.seas.uio.no/>)

¹⁴ “Climate change teacher academy” <https://climademy.eu/>

experiments, as in “Physics of clouds” and “Kairòs” (which will be respectively discussed in this and the next chapter) or the “AI-Atelier” and the “Quantum Atelier”, two projects exploring the contribution that art’s languages and aesthetics can provide in reflecting on contemporary challenges introduced by generative artificial intelligence¹⁵ and quantum technologies¹⁶.

These activities were shared and accepted by the whole class council, to involve in future more and more teachers (hence also other disciplines) and make the interdisciplinary approach *structural* in the program, with the support of the school’s principal. Related to this, is worth mentioning that some of these interventions have been made within curricular hours properly because teachers wanted to create a dynamics involving all the students and push for such activities to become a kind of *signature* of the school (De Zuani et al., 2023).

On the other hand, the nature of these interventions discloses another strong cultural belief of the teachers. They have the ambition - for science education and education in general - to provide students with tools to make sense of the society around them and their possible roles within it. Indeed, the young generation has difficulty projecting themselves into the future since the speed at which the changes take place at different levels (social, economic, cultural, technological...) keeps increasing (Rosa, 2009). Again, the position is clear: formal education should allow students to develop an awareness of the revolutions occurring in today’s world and to explore them starting from disciplinary knowledge, exploiting a set of different languages coming from a bunch of disciplines (physics, art, literature, informatics, philosophy, etc.).

As prof. Maurizio Giuseppucci says in the introduction of Quantum Atelier,

“In such a scenario, the school feels, and not just now, the need to place itself within this transformation as an instrument and cultural filter of critical re-elaboration concerning what is happening, putting the old models of knowledge transmission into ‘crisis’ without dispersing the enormous heritage of knowledge that it has always made use of in the exercise of its function”.

It emerges from the excerpt the belief that when transformations occur, the aesthetic and the languages should change as well, challenged by the need to communicate something new. Hence the need for new interdisciplinary languages, with a possible option of merging the artistic language with the scientific one:

“It is possible to summarise the desired process (of Quantum Atelier project) in these terms: to bring students into contact with the ‘languages’ of science and art, stimulating them to elaborate their own words, i.e. a ‘sign’ that communicates the experience of the cognitive journey they have gone through and the modifications that this experience has imprinted on their way of perceiving reality”.

Hence, merging art and science practices to support new ways of perceiving and making sense of reality. Still, the intertwining must be deep, with the two disciplines and their epistemologies scaffolding each other:

“Often, especially in the field of popularisation, when art and creativity, typical of the humanities, is called upon to intervene in an exchange with scientific culture, it plays an ancillary role, not to mention the tendency typical of the ‘neo-baroque’ or ‘entertainment society’ age, to relegate the symbolic-poetic language to the role of a lever for spectacularising knowledge[...] However, the danger of falling into a

¹⁵ <https://old.einsteinrimini.edu.it/progetti-interdisciplinari/ai-atelier/>

¹⁶ <https://old.einsteinrimini.edu.it/progetti-interdisciplinari/quantum-atelier/>

banal form of spectacularisation of the scholastic 'explanation' is what we have been trying to avert from the outset”.

Thus rather, a real interdisciplinary practice is

“to be considered an opportunity to 'dry' contemporary language, so tempted by the fascination of the 'special effects' of entertainment, to resort instead to 'refining' the tools at our disposal, such as the new technologies to which we normally have access, art or the critical thinking developed around them [...] thus fostering a meaningful exchange between art, science and technological scientific knowledge, aimed at deepening all the fields of knowledge involved in this workshop (Quantum Atelier) and the contribution of the autonomous and original skills that students can bring into play in this challenge”.

1.2 “Physics of clouds” epistemological frame

Disciplinary epistemic elements (knowledge) can and should be merged, to illustrate how contents can be used as “thinking tools” to navigate society.

This position is certainly sustained by Prof. Sara Moresco (Italian literature teacher of Liceo Einstein) and Prof. Paola Fantini (former Liceo Einstein’s physics professor, now retired). In 2020, they started to reason about a possible collaboration, in particular merging physics and literature knowledge and practices, and they came up with the design of an activity where concepts from physics of complex systems (and the paradigm of complexity in general) were intertwined with a creative writing workshop. Specifically, they engaged students in writing creative essays (divided into 6 groups) based on the concepts of complex systems discussed in class (see Section 1.4.1 for details).

The general objective was to exploit the epistemological richness of science of complexity, which presents different features that can be “taken out” from the discipline and transformed into instruments to read the world around (see Section 3.1.3 in the next Chapter). The role of literature and creative writing is to support the conceptualization of physics contents through new languages, and their transformation into useful instruments beyond the original disciplinary boundaries.

In this regard, the teachers set a list of objectives both at an educational level and at a disciplinary one, which reflects a peculiar cultural position around the role of school and knowledge.

Educational Objectives
Reflect on one's own identity as an individual and as a member of a complex society, the result of circular relationships both between peers and between generations.
Reflect on one's role as an 'element' that is part of the complexity of the world.
Refine the ability to observe the social and natural context in which we live, in order to educate in caring for oneself, social relations and the natural space for a sustainable world.
Transmit and cultivate the value of listening and dialogue, observing others and an everyday life that risks remaining unnoticed, submerged in the frenzy of everyday life.
Enhance self-esteem through workshop activity and creative exercise (“ <i>Creativity is intelligence having fun</i> ” - A. Einstein).

Educating divergent thinking, thinking of different strategies to reach a conclusion and approach knowledge.

Table 1: Intended Educational Objectives from the “Physics of Clouds” project sheet.

Scientific-related Objectives
Investigate with examples - without going into mathematical concepts - the central concepts of complexity science by identifying what can be called the 'words of complexity': ○ Multiplicity ○ Irreducibility ○ Circular relationship and non-linear causality ○ Unpredictability ○ Self-organization

Table 2: Scientific-related intended objectives of the “Physics of Clouds” project.

Literature-related Objectives
To enhance narratological and linguistic knowledge and skills through workshop practice.
To educate to a multidisciplinary approach, creating a narrative space in which humanistic and scientific knowledge can be integrated into a single cultural dimension.
To rationalize the use of the language code and other languages in relation to specific communicative purposes.
Strengthen the expressive capacity of individuals.
Getting to know an author, Italo Calvino, who is fundamental to 20th-century literature.

Table 3: Literature-related intended objectives for the “Physics of Clouds” project.

Emerges the attitude of not being satisfied with students learning contents, whereas these must be pushed and structured in a way that they can inform identity development, relationship and communication skills development, and so on.

Hence, in the following subsections, I discuss respectively how the teachers reconstructed (Duit et al., 2013) and exploited the epistemology of complex systems (2.2.1) and that of writing and literature (2.2.2) to pursue such objectives.

1.2.1 Physics epistemological frame

As mentioned above, the choice for the physics part was to focus on complex systems. Before illustrating the educational potentialities of teaching complex systems (Barelli, 2022), I will introduce complex systems from a mathematical point of view and sum their features at odds with the Newtonian paradigm.

Complex systems

Complex systems are systems composed of many interconnected components, where the dynamical interactions between these components and the interaction with the external environment lead to collective behaviours that cannot be simply inferred from the properties of the individual components.

Their study is rooted in the works of different scholars from different disciplines (biology, thermodynamics, meteorology, and cybernetics among others), even though their features have become foundational concepts also in other fields such as economics, sociology, mobility, etc.

These systems have been defined as complex (Weaver, 1948) instead of complicated, not because of the difficulty of studying them but rather because of their intrinsic irreducibility which does not allow to apply reductionist approaches. Irreducibility means that a complex system's behaviour cannot be fully understood by analyzing its parts in isolation and the system exhibits properties that only emerge from the interactions between components, just like a nest which becomes unrecognisable if we look at the individual twigs that make it up (Figure 3).

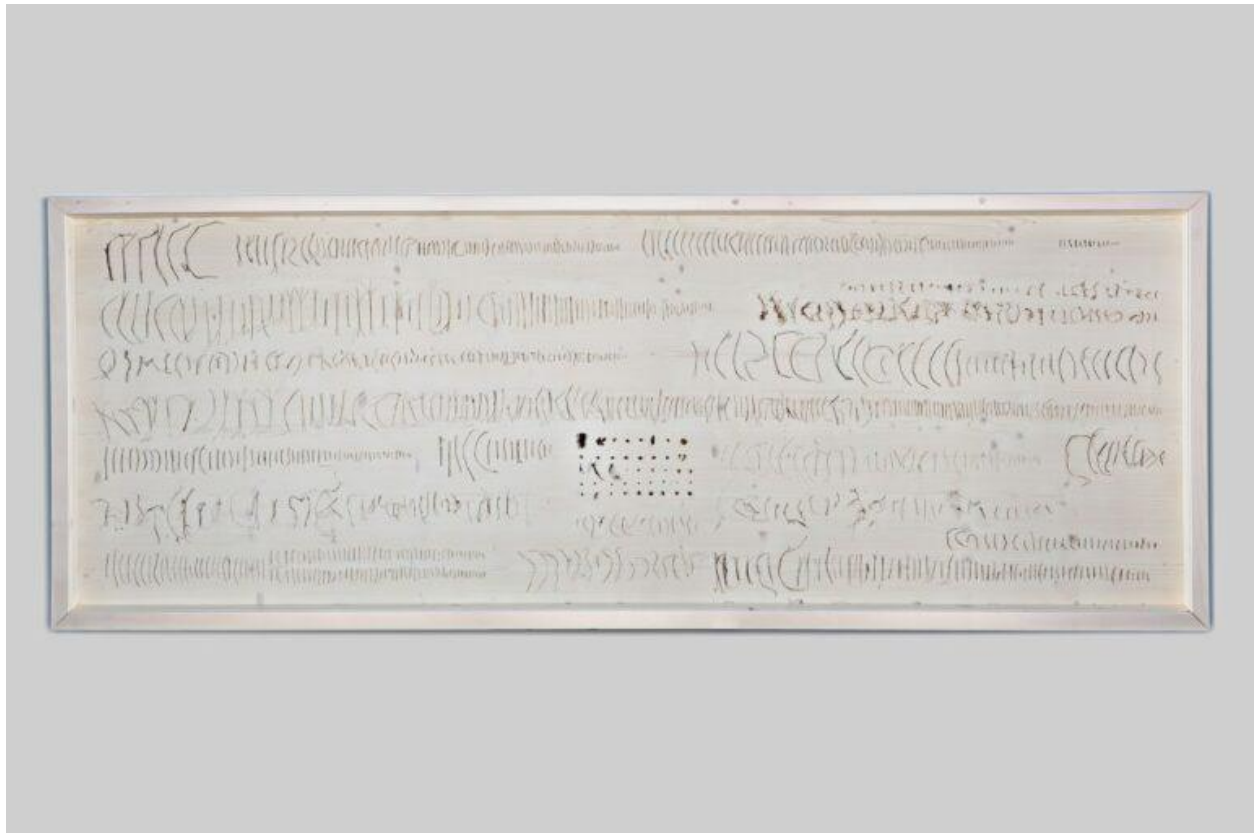


Figure 3: *Nido*, from Nico Vascellari (2009, courtesy Collezione Acacia). Nests are examples of irreducibility: if decomposed and studied focusing on their elements, they lose their meaning.

An example of irreducibility is represented by the famous Lotka-Volterra model, showing the dynamics between prey and predators within an environment (Volterra, 1926):

$$\frac{dx}{dt} = \alpha x - \beta xy$$

$$\frac{dy}{dt} = \delta xy - \gamma y$$

Here x and y are the prey and predator populations and α , β , γ and δ are constants representing interaction rates. These (coupled) equations show how the system cannot be studied referring to a single species and is complex.

Furthermore, the predator-prey model embeds also circular causality (feedback loops), another important feature of complex systems. Feedback loops are mechanisms of circular causality by which the increase of a variable activates a mechanism (involving also other variables) which ultimately determines its own increase (positive feedback) or decrease (negative feedback). If we consider the prey equation, the term αx means that for a larger population the increase rate is higher; thus, as the population increases, its rate of increase becomes higher and higher (positive feedback). However, considering the second term of the equation, βxy , the number of predators increases as the number of prey increases, as they find more “food”, thus decreasing the number of prey (negative feedback). The same holds for the second equation, with predators’ increase limited by competition for food ($-\gamma y$).

The combined effects of negative and positive feedback loops for both the prey and the predators determine a periodic solution of the system (see Figure 4).

Indeed, the system allows two equilibrium points (fixed points): one is the couple $(x = 0; y = 0)$ whereas the other is the solution $(x = \frac{\gamma}{\delta}; y = \frac{\alpha}{\beta})$. The first fixed point means the extinction of both species. The second fixed point is the equilibrium point around which oscillates the values of prey and predators at the centre of closed orbits of the trajectories in the phase space (Figure 5).

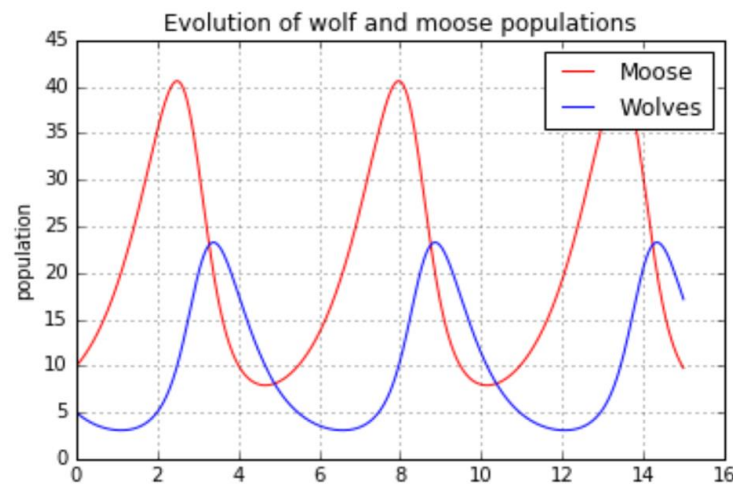


Figure 4: A normalized version of the set of Lotka-Volterra equations leads to the harmonic oscillator solutions (image from Barelli, 2022).

The periodic solutions of Lotka-Volterra - due to the feedback loops - display closed-orbits in the phase space (see Figure 5).

In complex systems, there are also other - but different - examples of closed orbits, named “limit cycles”: asymptotic and stable states reached by the dissipative system due to the interactions within their agents and with the environment. They are called limit cycles for two reasons:

- If we plot the oscillation into the phase space the trajectory is a closed line, as a cycle
- The trajectories of the system in the phase-space tend to converge towards this cycle, which is also called “attractor”.

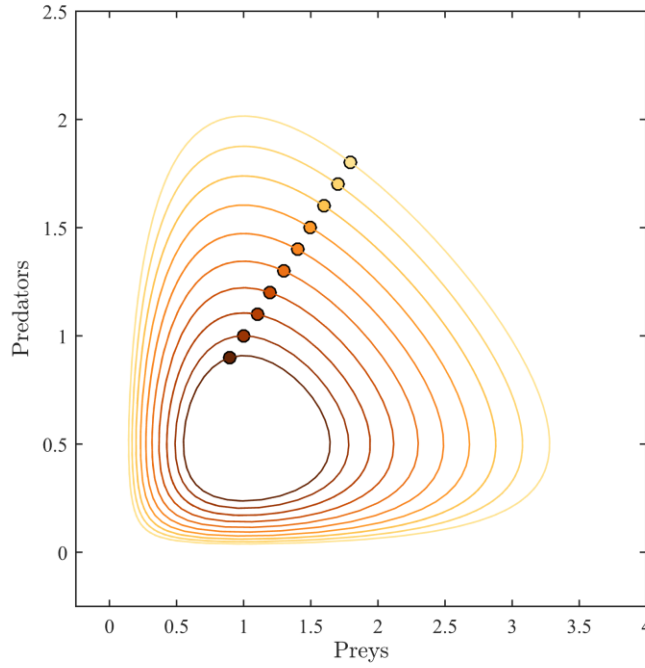


Figure 5: The closed-orbits of the Lotka-Volterra model for different initial conditions of x and y . The shape of the cycles is always the same and they are “centred” around the same equilibrium point (source: Wikipedia).

Many complex systems exhibit limit cycles, such as the Van der Pol oscillator (Van der Pol, 1926), the neuron spike model (Hodgkin & Huxley, 1952), the heartbeat model (Fitzhugh, 1961; Nagumo, 1962), etc.

For instance, the Van der Pol oscillator displays a limit cycle, again due to the combined effect of a positive and a negative feedback loop (see Figure 6).

The model,

$$\frac{d^2x}{dt^2} - \mu(1 - x^2) \frac{dx}{dt} + x = 0$$

represents the behaviour of a dynamical variable x (often associated for example with a current in a circuit).

The term $-\mu(1 - x^2) \frac{dx}{dt}$ acts as both a positive and negative feedback effect, depending on the value of $|x|$. If $|x|$ is larger than one, the whole term is positive and creates a positive feedback, whereas negative feedback holds for values of $|x|$ lower than 1.

In the the case of limit cycles, the systems reach this solution after passing through the so-called Hopf bifurcation. Hopf bifurcation occurs depending on the value of a controlling parameter (in the case of Van der Pol equations it is the term μ); when the value of the parameter exceeds a threshold, the equilibrium point becomes unstable, and the system passes from a non-oscillatory behaviour to a stable limit cycle. In this case, the change of behaviour occurs when μ becomes positive. For values of $\mu < 0$ the trajectory converges to 0, whereas when μ becomes positive the system transitions from a fixed point to a stable limit cycle, whose shape is determined by the value of μ (see Figure 7).

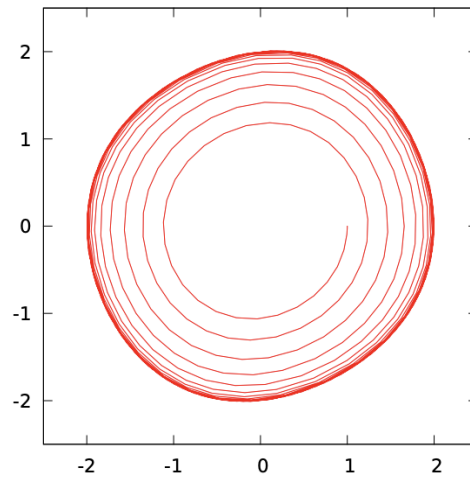


Figure 6: The shape of the limit cycle for the Van der Pol equations for μ close to 0 (from https://www.phys.uconn.edu/~rozman/Courses/P2200_13F/downloads/vanderpol/vanderpol-oscillator-draft.pdf).

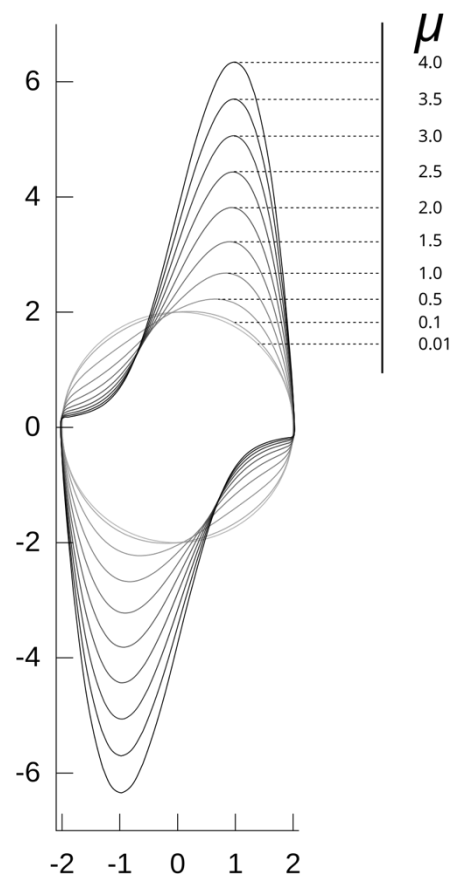


Figure 7: Shapes of the Van der Pol limit cycle in the phase space. The first shape occurring is circular, with a radius equal to 2 (see figure above). Then, as μ increases the shape squeezes (source: Wikipedia).

Bifurcations are characteristic phenomena for complex systems and are related to the idea of emergence. From an initial stable state, depending on the change of some critical value, it “emerges” a new stable state for the system. If we consider for example the “pitchfork” bifurcations, near a critical value and in the presence of oscillations due to an external noise, the system can transition from a unique stable state to one of the two new emerging stable states.

Pitchfork bifurcations occur in those systems described by the equation:

$$\frac{dx}{dt} = rx - x^3$$

with r representing the control parameter. The fixed points are $x = 0$ and $x = \pm\sqrt{r}$, with $r > 0$. With r around 0, the system starts to display two new stable states, whereas the previous state corresponding to $x = 0$ becomes unstable. The choice of $+\sqrt{r}$ or $-\sqrt{r}$ as the new state for the system cannot be predicted and depends only on the fluctuations near the critical point $r = 0$.

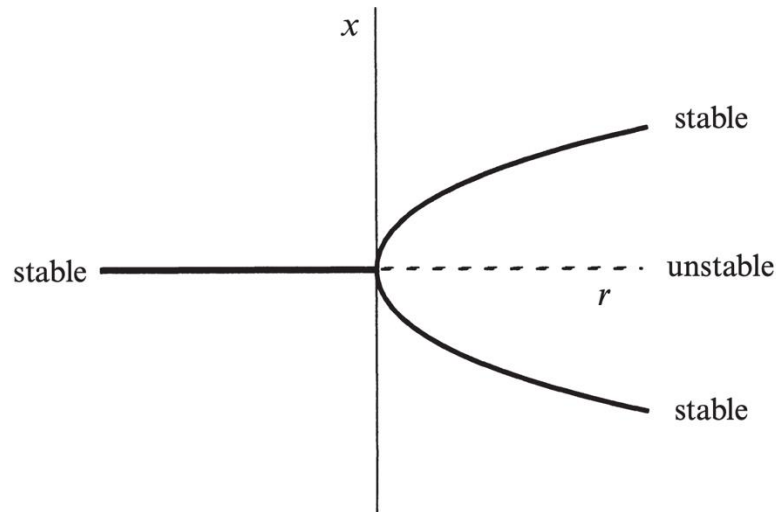


Figure 8: The supercritical pitchfork bifurcation (from “Non linear dynamics and chaos” by Strogatz, 2015).

Pitchfork bifurcations are at the basis of many interesting phenomena, such as the emergence of Bénard cells for a liquid exposed to differential heating (see next Chapter for details).

These bifurcations are particularly interesting as they embed many of the crucial features of complex systems which differentiate them from the systems of classical mechanics. They indeed enclose the idea of the emergence of new states but also the idea of unpredictability as there is no way we can predict which of the two emerging stable branches will be chosen by the system. Also, these bifurcations are associated with symmetry breaking and put into play irreversibility. Because of the random choice of the new branch, the moment of bifurcation becomes a critical time marker moment, as it creates a “before” and an “after”. Time gains directionality (see Chapter 4, Section 2).

Bifurcations can also be followed by a cascade of bifurcations, illustrating how a system can pass from order to chaos through a series of bifurcations. These can be better explained by using the logistic map example.

A logistic map is a one-dimensional, discrete-time dynamical system described by the equation:

$$x_{n+1} = rx_n(1 - x_n)$$

with x_n and x_{n+1} indicating the states of the system (for example the population increase rate or the fraction of two species)¹⁷ at timesteps n and $n+1$, and r as the control parameter. There are four possible cases according to the value of r :

- i) $0 < r < 1$: the system converges at $x = 0$
- ii) $1 < r \leq 3$: the system converges to a non-zero stable point
- iii) $3 < r \leq r_\infty \approx 3.56995$: the system undergoes a first bifurcation and as r increases it continues to face bifurcations, oscillating between 2 solutions (first bifurcation), 4 solutions (second bifurcation), 8 solutions (third bifurcation) and so on. So it makes orbits of two values (period 2 orbit), then 4 values (period 4 orbit), etc.
- iv) $r > r_\infty$: we cannot anymore determine an orbit and the system displays chaotic behaviour, with minimal differences in the population leading to extremely different solutions.

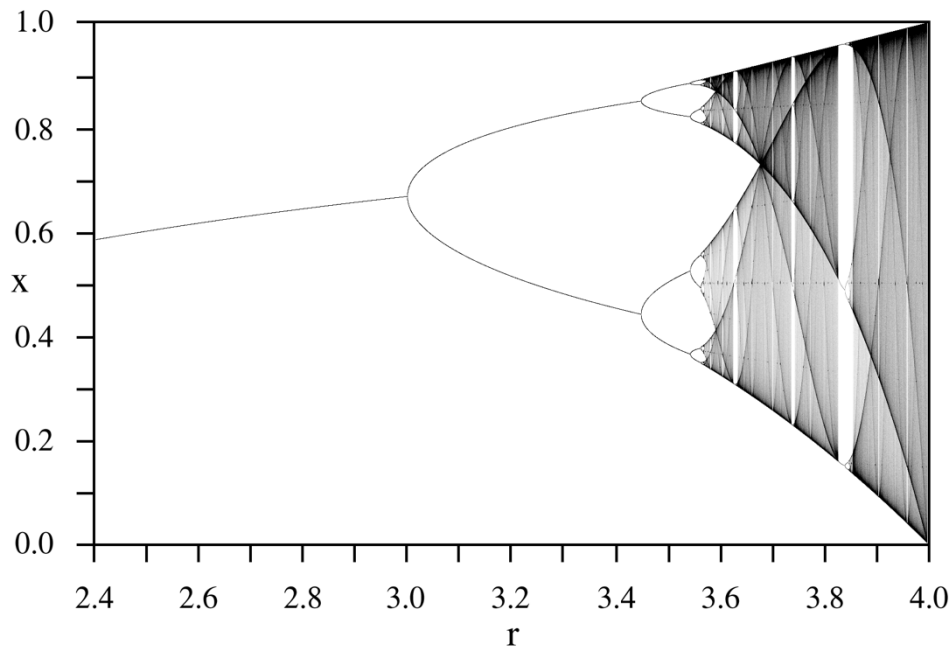


Figure 9: The diagram of the logistic map. As it can be seen around $r=3.56$ the system oscillates between almost infinite solutions, displaying a chaotic behaviour (source: Wikipedia).

As seen, from simple and clearly deterministic equations the system (under certain conditions of the control parameter) ended up being completely chaotic. This is a good example of what is known as “deterministic chaos”, a chaos which originates from deterministic laws.

Probably the most known example of deterministic chaos is the “Lorenz attractor” or the “butterfly effect” (due to the shape of the attractor). The Lorenz model treats the behaviour of another complex system, the climate.

¹⁷ x must be > 0 and < 1

Edward Lorenz was studying a simplified model of atmospheric convection and came up with a set of three non-linear differential equations:

$$\begin{aligned}\frac{dx}{dt} &= \sigma(y - x) \\ \frac{dy}{dt} &= x(\rho - z) - y \\ \frac{dz}{dt} &= xy - \beta z\end{aligned}$$

where x is a quantity related to the rate of convection, y stands for the horizontal temperature variation, and z stands for the vertical temperature variation; σ , ρ and β are instead positive constants related to viscosity and convection.

Looking at the trajectory of the system (for instance projecting in the x - z two-dimensional subspace), we notice that the system does not settle on a fixed point nor in a limit cycle solution, but rather it spirals around two lobes in a complex, non-repeating pattern, never intersecting itself, yet remaining confined to a bounded region of the phase space. This attractor has been defined “strange attractor” because of its fractal structure but also because of its high sensitivity to initial conditions. What Lorenz realized indeed was that by using initial conditions with minimal differences, the consequent trajectories ended up being exponentially divergent over time (a difference which is indicated by the Ljapunov exponent).

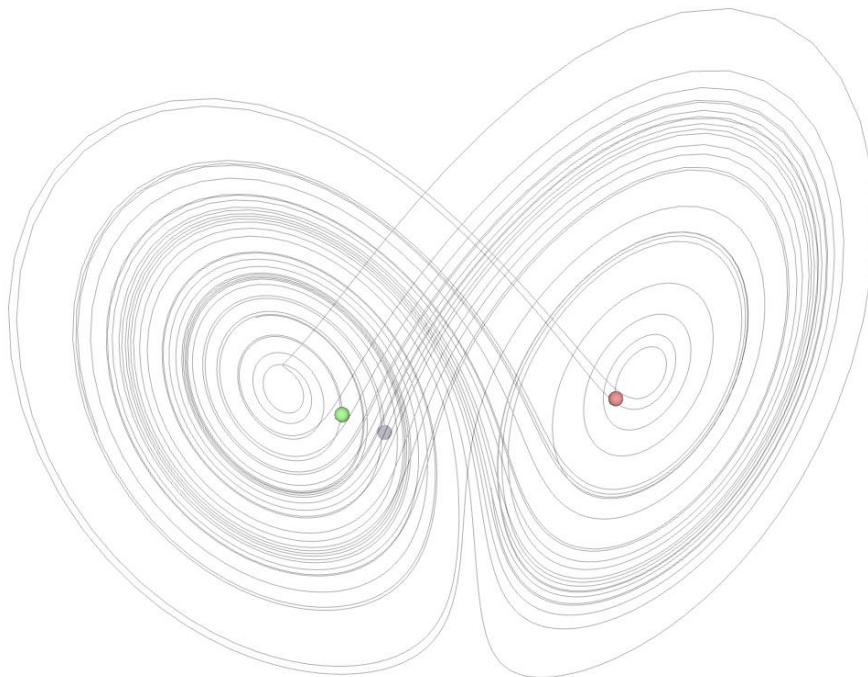


Figure 10: The typical two-lobe attractor for the Lorenz equations. The two coloured dots represent the position of the system after a certain amount of time Δt , starting with two initial conditions almost equal. It is evident the high sensitivity to the initial conditions (from <https://marksmath.org/visualization/LorenzExperiment/>).

The Lorenz model then shows how deterministic systems still can display chaotic behaviours, highlighting again the unpredictability often associated with complex systems. Also, it discloses how some complex systems can be extremely sensitive to initial conditions, leading to totally different outcomes from almost equal initial conditions (the so-called “butterfly effect”). This sensitivity emphasizes again unpredictability and the presence of attractors highlights also irreversibility.

Epistemological shift and its educational potentiality

I have so far outlined some of the most important characteristics of complex systems, which distinguish them from the classical mechanics' systems: unpredictability, irreversibility, deterministic chaotic behaviour, emergence of new states, high sensitivity to initial conditions, irreducibility and circular causality (feedback effects).

The study of these new systems has profoundly questioned classical physics from an epistemological point of view (Barelli, 2022; Jacobson & Wilensky, 2006). As Edgar Morin claims:

“For a long time, many believed - and many perhaps still believe today - that the shortcoming of the human and social sciences lay in their inability to get rid of the apparent complexity of human phenomena, to elevate themselves to the dignity of the natural sciences, sciences that established simple laws, simple principles, and let the order of determinism reign.

Today we see that the biological and physical sciences are characterised by a crisis of simple explanation. And as a result, what seemed to be the non-scientific remnants of the human sciences - uncertainty, disorder, contradiction, plurality, etc. - are now part of the basic problematic of scientific knowledge.” (Morin, 1986).

Linearity, determinism or predictability are foundational principles of modern society which seem not to work anymore to explain phenomena such as climate change, which instead dominates the *post*-modern society. In other words, the natural world but also the society itself (if they can be considered as separate entities) are showing behaviors that can only be embraced in their intrinsic complexity and non-linearity. In this sense, studying complex systems can be difficult as it requires to overcome rooted beliefs around causality, predictability etc. (Feltovich et al., 1989; Resnick & Wilensky, 1993). Nonetheless, the study of complex systems can provide the necessary skills to face complex challenges, to recognize the non-linearity, the irreducibility or the different causal structures embedded for instance in climate change issues (Barelli, 2022).

Barelli for instance showed how teaching “hard-scientific skills” of complex systems, “*like the ability to give up linear causality to embrace circular patterns of complex relationships between causes and effects, recognizing feedback loops*” can lead to the development of “citizenship skills”, as the “*skills needed to address typical citizenship issues, like the ability to make decisions, to recognize the various stakeholders involved in a civic problem and so on*” (Barelli, 2022; p. 24). For instance, Levrini, Tasquier and colleagues (2019) found out how the epistemological status and the main concepts of complex systems were particularly suitable to “*provide a new vocabulary for reasoning about the future in terms of a plurality of possible scenarios*” (p. 2669). The features of complex systems, within a module around climate change,

triggered in upper secondary students what the authors named “future scaffolding skills” (Levrini et al., 2019).

As PF introduces in the “Physics of Clouds” report, “*Complex systems science assumes that complexity is inherent in nature, cannot be eliminated, and must come to terms with concepts such as uncertainty, the unexpected, disorder, contradiction, plurality...*”. Hence, educating on “complex thinking”, through the study of complex systems, could provide useful instruments to navigate a society dominated by problems whose structure is complex.

The belief is that training students to make sense of the behaviour of such systems can scaffold the transition from linear to complex reasoning needed to face the complex societal challenges:

“the conceptual basis of complex systems ideas reflects a dramatic change in perspective that is increasingly important for students to develop as it opens up new intellectual horizons, new explanatory frameworks, and new methodologies that are becoming of central importance in scientific and professional environments” (Jacobson & Wilensky, 2006, p. 12).

Thus, in the context of the activity, PF introduced some examples of complex systems, such as a cloud, an ant-hill or a flock. Given the age of the students (14 years old), PF navigated the concepts of complexity without providing a (non-accessible) mathematical description but focusing on conveying the “message” embedded within them.

During the lectures, complex systems have been unpacked along three dimensions of description: *the kind of “spatiality”, the kind of “temporality” and the kind of “relationships”* displayed by complex systems.

As seen above, complex systems manifest “emergent properties”, collective behaviours which *emerge* unexpectedly due to interactions of single agents and external conditions (see Lotka-Volterra model).

In particular, spatial patterns may be visible *at the right distance* (e.g. adopting a macro-perspective in the Bènard convection phenomenon); or temporal patterns may be visible *at the right time*, where “right” means characteristic of the system (for instance the critical time in a bifurcation process; see B-Z reaction in the next chapter for details). These patterns emerge from the interaction of the single components of the system (under some conditions), so it is crucial to consider the *dimension of relationships*.

The sentence “at the right distance” reflects another feature of complex systems that the teachers highlighted several times: there are two focuses within the *spatial dimension*, the macroscopic one where the patterns are visible and the microscopic one where the interactions are visible. Thus, the observer “can go” **inside** the system and be surrounded by the interactions (microscopic perspective) or it “can stay” **outside** the system and see the global behaviour (macroscopic perspective).

So, the perspective taken determines the accessible information.

Considering instead the temporality displayed by complex systems, it comes out for example the idea of a characteristic time after which patterns emerge due to the local interactions. This feature has been stressed in class with the discussion of a few examples:

- The Bènard cells, an experiment in which a fluid is heated by a ΔT , and above a threshold ΔT_c . After a time that depends on the heating power, the kind of fluid, and the environment’s temperature, two circular flows emerge within the fluid, which becomes macroscopically ordered.
- Self-organization of agents and circular causality, for example in the behaviour of ants: waiting some time allows to see how macroscopic patterns, due to local interactions, condition the following local interaction between agents. Prof. Fantini in this case stressed the idea of a “circular relation between the parts and the whole”, so a circular relation between agents and the system which they form.

Thus, complex systems were introduced enhancing their core features: complex because is not always possible to foresee the outcomes of the interactions, complex because the output will become the input and *vice versa*, complex as from the order it emerges chaos, complex because is not possible to reduce the system to the single constituents. Complex systems are returned as systems organized on spatiotemporal scales different from those of their constituents, as systems connected to the environment and exchanging matter and energy, and as systems which display disorder (differentiation, heterogeneity) but also order (connection, homogeneity) through emergent phenomena.

In addition, the epistemological reconstruction of complex systems made by PF, aligns with a vision of time and space as entities which change shape creating temporal or spatial patterns, entities with multiple internal dimensions; hence they can be used as lenses by which look at the system.

To conclude, the epistemological structure of the science of complex systems is reconstructed to guide the students to: a) recognise emergent properties in dynamical systems; b) get to know the different levels of description (the “micro” level of the agent, the “macro” level of the whole system and the “meso” level needed to explain the emergent properties) (Barth-Cohen, 2018) and the mechanisms of interaction among the levels; c) reflect on the impact of individual agents on the system and vice versa; d) recognise the new kind of causality introduced, with respect to the one of classical mechanics (circular causality vs linear causality); e) observe the contraposition between a deterministic system (classical) and chaotically deterministic (so unpredictable) system.

This, with the aim that:

“the concepts of complex systems science can and perhaps must go beyond the realm of science and become a key to looking at the world consciously [...] (and contribute for) an education, therefore, to a way of thinking that does not close off concepts, that re-establishes the links between what seems separate, striving to understand the many dimensions involved, thinking locally but without losing sight of the totality” (PF in the introduction to the project sheet).

1.2.2 Literature epistemological frame

In this section is discussed the literature framework used by the Italian literature teacher, trying to answer the following questions: *Why engaging students in reading examples of good writing? Why engaging students in writing themselves creative essays? What are the crucial elements of creative writing? What are the educational potentialities of writing sessions?*

Writing was central in this project, but preliminary to writing there were reading sessions. Reading novels is indeed a foundational activity for those interested in writing, as it provides a rich source of complex themes and narratives that help develop a deeper understanding of human experiences and social dynamics. The objective of this activity was to expose students to diverse perspectives and styles of writing, which in turn may enhance their writing skills. In this case, the novel *Palomar* (Calvino, 1985) was chosen as an example of narrative around complex themes, and the students both autonomously both in scheduled moments in class read all the novel. Students were also guided to do a critical analysis of the novel through questionnaires assigned by the teachers.

Therefore, the project shifted to the hands-on session of creative writing. Creative-writing (which includes poetry, novels, pièce, etc.) has some general differences with non-creative writing (journals, academic

essays, reports, news articles, etc.). Writing's primary objective is indeed to inform, explain, document, or communicate clearly and precisely, with a formal, direct, and structured language. It adheres to strict grammatical, syntactical, and formatting rules to ensure clarity and consistency. Creative writing, on the other hand, focuses on artistic, narrative, and stylistic expression. The objective is to evoke emotions, tell stories, explore themes and ideas, and entertain the reader. The style is more free, expressive, and experimental, frequently employing figurative language, vivid descriptions, complex characters, and realistic dialogue.

In this case, given the thematic constraint of complexity and the not-so-developed writing expertise of her students¹⁸, SM introduced some narratological constraints. These constraints indicated what kind of sequences (dialogue, self-reflection, description, external narration) should be alternated and sometimes indicated the broad themes of the sequences (see Table 4).

Sequence Number	Indications
1	Descriptive sequence; subjective description ordered spatially; setting, contextualization.
Narrative Start	Encounter and dialogue.
2	Dialogued sequence; direct and indirect psychological and social presentation of characters (two or more ants, two or more molecules) through dialogue. One character is convinced of their knowledge and 'bets' on their ability to understand and predict; another character behaves randomly, responds randomly. The reader should not realize they are ants and molecules. The two characters are the protagonist and the antagonist. The object of desire (understanding complexity) narratively translates into...
3	Reflective and narrative sequence (the character constructs through reasoning and thought); first-person narration.
4	Dialogued sequence. The object of desire must emerge.
5	Descriptive-narrative sequence (there is another structure, another reality, but who made it that way? Who could have thought and realized it that way?). Spannung: it becomes clear that the characters are either ants or molecules. First-person narration.
6	Dialogued sequence. The sender assigns the object of desire.
7	Narrative-reflective sequence. Resolution and return to a state of equilibrium. Third-person narration (omniscient narrator).

Table 4: An example of narratological constraints assigned for two essays.

¹⁸ Nonetheless, she usually engages her classes (from the 9 to the 13 grade) to write, even though this is not demanded by the Italian literature curriculum.

It is interesting to notice that, although the indications in the Table were assigned for the creation of two essays, at the end of the day they came up quite different (see Section 2.3.2 for more details). This is to show how the indications still left much space for creation.

In general, creative writing has been chosen as a central activity because it helps students articulate their thoughts, develop critical thinking, and engage deeply with the subject matter. Writing is seen as a tool to encourage students to process and internalize information, making it a valuable educational exercise.

Moreover, the main goal of writing was to create an environment in which students could use different lenses to look at the complex systems studied and verbalize them with a new language. Thus, the goal was to get them to maximise their engagement to the *process* rather than optimize the *outcome*. In a school more and more performance-oriented this activity set itself as something new. In fact, writing is intrinsically a time-consuming work which cannot and should not be optimized, for the sake of quality. In this sense students were also stimulated to meta-reflect about the process they were doing with log-books, reporting the different phases, the obstacles, the inspiring moments as well as those of emptiness.

SM described this with a metaphor of sandcastles, from the Italian archistar Renzo Piano. Indeed sandcastles are not made to last, still the process of building them trains expertise and attention without focusing on the possible outcomes. As she commented,

“It's not in that construction there that it's all about but in what we leave behind in the guys. [...] And so here I have included the idea of a different construction project at school, and so perhaps we need to change our perspective with respect to the usefulness of the construction of a didactic knowledge in a very fast-paced present, [...] with the serenity that comes from the value of the construction process beyond the end product” (SM in the final interview).

Writing - to SM - hence supports a shift from a focus on the output to a focus on the underlying process, which also activates an ethical dimension:

“Many times we say to ourselves with PF why (that) these things work because we don't ask children to invent anything, we ask them to imagine, to internalise knowledge and then, with the mind's eye tell it in a different way. This imagination is very powerful and I think that this, as Leopardi says, becomes dear, because when you do this in an attempt to read the world in this way, it is an attempt to read the world well, and when there is an attempt to read the world well there is an ethical dimension”.

The participatory framework

As we said, the objective of the module was to create a “space” to make students reflect on themselves and their roles as members of a complex society. This was sustained by continuously stressing the idea that society itself can be considered a complex system, so it can be looked at through the “lenses” scientists use to address complex systems.

Nonetheless, this meta-reflection about the role of contents as thinking tools needs to be supported by particular conditions, in which students are let free to develop and share their ideas with each other. For

this reason, SM decided to host the activity entirely during her curricular hours, as she wanted to involve all the students and trigger a common class experience.

Another interesting feature regarding the setting is that the teachers designed the activity to make students participate as much as possible in the co-construction of the physics knowledge and the writing process. During the Physics lectures they were continuously involved by the teacher in helping her to report what a complex system actually is. In particular prof. Fantini stressed many times the similarity of their class as a complex system, and them as agents interacting within it; so, by asking them to map into their class some features of complex systems - as *emergence*, *feedback effects*, *local interactions* - students were stimulated to participate in the discussion about complexity.

Anyway, the level of participation increased more and more during the writing. Initially students were guided through the reading of some excerpts from the works of Italo Calvino (in particular from the novels: *Palomar*, *La formica argentina*, *Ti con Zero*, *Le cosmicomiche*, *La nuvola di smog*), which served both as an introduction to creative writing and as writing examples about complexity. Next to these lectures, the writing process started, and became as a periodic appointment for the class, from March until the end of school in the first week of June.

Nonetheless, the nature of the product (a free essay) and the organization (groups of 4 people), provided students with the chance to confront with the classmates about their ideas on complex systems and writing process.

1.3 From FEDORA recommendations to “Physics of clouds” design principles

In the previous Chapter, I outlined FEDORA project’s objectives and structure, mentioning how the recommendations produced within the theoretical frameworks have been considered as guidelines to elaborate the design principles of classroom implementations (see Figure 4 of Chapter 2).

For what concerns the “Physics of clouds” projects, only some recommendations have been mutated and turned into design principles:

- **Cross and integrate different disciplines:** FEDORA indicates that interdisciplinary teaching creates value also for the disciplines and their teaching at different scholastic levels (from primary school to university contexts); indeed, valuing interdisciplinarity means reworking the concepts, aims, values and methods which define disciplinary identities. Disciplines and their epistemic cores are still considered crucial for guiding students to make and consolidate “structured” educational experiences. Such experiences represent a solid ground from which a student can take up the process of crossing boundaries and developing interdisciplinary skills.
- **Elicit epistemic emotions:** FEDORA research indicates that learning and thinking are entrenched with epistemic emotions. The objective is to leave room for the affect to become a tool, promoting a shift from emotive polarisation (Levrini et al., 2021) towards epistemic emotions coming from a critical approach to the discipline, epistemic emotions to support pro-action in imagining and pursuing the personal future.
Hence, FEDORA recommends exploiting alternative forms of expression (e.g., artistic forms), in teaching and practising a discipline, which could foster students to express and question their epistemic emotions.

- **Exercise scenario building and thinking about the future in pluralistic ways:** youngsters often have the idea of the future as prescriptive, unidirectional, imposed from above, and beyond their control (Cook, 2015). Thus, to enlarge the vision of the future means cultivating an ability to think in terms of multiple and possible scenarios; at the same time fostering a sense of agency in the future (Emirbayer et al., 1998) means taking into account values, dreams and choices to construct plausible, possible and preferable scenarios.
Hence, FEDORA recommends developing activities where the future is represented as something still not defined, as a cone made of multiple possible scenarios (Voros, 2003), and engaging students in scenario-building workshops.
- **Dismantle dichotomous thinking and telling:** youngsters have a dichotomous image of the future, particularly a tension between the collective and the individual one. This dichotomy leads to a polarization of thinking. Linked to this dichotomy there is another one related to climate change and the tendency to address future scenarios by studying raw projections of scientific data (non-fiction/reality) or, on the contrary, by picturing narrative but totally imaginative future scenarios (fiction/imagination) that do not consider scientific knowledge coming from climate models. Hence, trying to overcome dichotomous thinking and telling means sharing a kind of knowledge that can go beyond the polarisations and overcome a binary vision of the world; it also means embedding in the language the intrinsic richness of shades world.
Regarding this, FEDORA recommends designing activities aimed at sustaining strange-making skills (Bol & de Wolf, 2023), addressing scientific concepts by making use of artistic/creative format and languages, to create contexts of dialogue where the scientific discourse is created by leveraging on students' input and creativity and imagination are fostered.
- **Embrace and embed complexity and uncertainty:** physics epistemology has a high degree of complexity that can be exploited as a tool (Duit, 2013). The knowledge, practices, aims and values (Erduran & Dagher, 2014) which define the epistemic core of physics, should be highlighted in their conceptual depth rather than being simplified and trivialised in their meaning. An example is the educational potential of the concept of uncertainty, which is a crucial epistemological pillar of physics (Rosenberg et al., 2022). This epistemic richness (in terms of reasoning structures, rigour's criteria, explication of principles...) can be used as an instrument to train students' "sense-making" skills.
Hence, FEDORA incorporated the recommendation to choose topics, models and concepts which are intrinsically complex and have uncertainty as a characteristic feature, and put them under debate so that they can trigger epistemic emotions related to complexity (Levrini et al., 2019b).

In light of the above, I present here how these FEDORA recommendations were "projected" into design principles at the basis of the activity:

- **Cross and integrate different disciplines:** design and activate a process of translation from one disciplinary language (physics) to another (literature and creative writing). In the translation, make the disciplinary and narratological constraints visible to foster the conceptualisation in one domain (scientific) and the re-conceptualisation in another domain (narrative). Creative writing allows to conceptualize again the physics content, since writing has an intrinsic space of freedom (see Section 1.2.2), beyond the narratological constraints. This space can be populated by students' thoughts about the contents (complex systems) and can enrich the meaning attached to the content itself.

- **Elicit epistemic emotions:** create a shared space in which students can experience and work on epistemic emotions. Indeed, complex systems are epistemologically revolutionary, since the very basic foundations of classical physics are questioned; the complex system heuristics then implies a cognitive (Abrahamson & Wilensky, 2005) but also emotional challenge to deal with (Jacobson & Wilensky, 2006). Hence, take care of guiding the emotions of discomfort and problematize any polarization attitude. Instead, take care of fostering any attempt to feel, recognise and name emotional nuances in dealing with the challenge of the activity.
- **Exercise scenario building and thinking about the future in pluralistic ways:** exploit the science of complexity as a source for developing future-scaffolding skills (Levrini et al., 2019b). This implies to stress the importance of events, chance, and the probabilistic nature of the emergence of new organised structures. It also implies educating on the concept of scenarios and being ready for the possibility that many different scenarios may open up.
- **Dismantle dichotomous thinking and telling:** exploit the concepts of complexity which can help promote the ability to problematize the dichotomy between the individual and the collective dimensions. More specifically, use the science of complex systems to activate a reflection on the relationship between emerging collective structures and individual agency, highlighting aggregate and agent-based perspectives. This implies emphasizing concepts such as the circular relationship between the whole and the parts, the rules which individuals (agents) obey in modelling a complex system, and the emergent properties of the system.

The adherence to the recommendation “Embrace and embed complexity and uncertainty” is in the choice of the content itself. The theme of the activity (complexity and complex systems) has been developed in both literary and scientific languages. For this reason, we consider this principle as “structural” in the activity.

1.3.1 Further reflections on the design and implementation

Balancing constraints

The activity was designed to “Cross and integrate different disciplines”. The intrinsic features of the disciplines involved (physics and creative writing), in terms of their languages, concepts and epistemological structures, were valued and combined in such a way that the features of one discipline could act as the scaffolding for the other.

In addition, the boundaries introduced by SM in “Physics of clouds” were properly meant to trigger students reasoning about the complexity using languages other than physics. Hence, despite initial difficulties to see the “overarching sense of the project”, students in the end started to see the general ambition of the activity. Students indeed recognized and appreciated the ideas behind the project, and their connection with real-life topics, and were satisfied that finally something at school was being done “for them”, in ways “close to them”. I am confident in claiming so, as they expressed these thoughts with the teachers and with me, and even the families shared their positive impressions (I will discuss this later in Section 2.4). One interesting comment comes from one of the logbooks of the groups:

“One thing I have noticed through this work is that when I am walking or riding in a car/bus I observe my surroundings and try to understand more about that place/object/man even if I only see it for a second.

Complexity does not exist only when you realize it, when you really find out what it means. Complexity is everydayness and it just exists”.

Structural challenges

Another challenge faced was due to the number of hours devoted to the project. As we have seen the project spanned over 8 months occupying many hours not allocated for that. However, this choice had two main consequences:

- The constant search for a balance between staying somehow connected with the ordinary Italian literature curriculum of grade 9 (for example by inserting literature contents, key readings, etc.) and not lagging behind other classes, and on the other hand to carefully cultivate the novelty of the creative writing process. Thus, SM had to redefine the curriculum according to the activity but respecting the institutional curricular constraints. Furthermore, it is worth reminding that this new equilibrium had to be shared and accepted by the whole class council.
- The problem of finding ways to introduce assessment, since it was a curricular activity. In this case, SM was forced to give students marks at the end of May, evaluating the process of writing and the essays made (and it was not easy since they were divided into groups), but also assessing the level of participation. The essays passed through multiple editing steps, and at each step partial evaluation had to be made and considered in the final assessment. In spite of the non-standard evaluation procedure, the school and the families were very supportive, also because of the contextualization of the activity within a European project, the acknowledged quality of the work and the strong engagement of the students. However, this aspect can be an issue for the reproducibility of the activity in other contexts.

2. Data analysis

This Section is structured as follows.

Section 2.1 is devoted to a brief summary of the essays, useful to understand the following analysis. Sections 2.2 and 2.3 describe respectively the two rounds of (qualitative) data analysis. Section 2.4 reports instead about the “member check” step, a common procedure to validate the outcomes of qualitative analyses (Anfara et al., 2002).

2.1 Summary of the essays

The Eyes of the Moon (Gli occhi della luna)

In "Gli occhi della luna," the story unfolds around Joy, a young bird living in his nest with his mother. They begin to reinforce their nest with small twigs that Lily has gathered, working together to ensure it remains strong and secure against predators. As they weave the twigs, Joy's mind wanders to the moon and stars above, which he often admires from the safety of their nest. He becomes consumed with curiosity about what their nest and the world around them look like from such a high point of view. The desire to see things from the moon's perspective leads him to dream of soaring high into the night sky. Joy imagines looking down on his nest, seeing it as a small but intricate part of a vast, beautiful world. Then at the end Joy is waken up by the mother and they discuss about the dream, showing Joy's ingenuity and his mother wisdom.

Thoughts in Flight (Pensieri in volo)

"Pensieri in volo" opens with a young observer, likely a child, eagerly searching for a pair of binoculars to watch a swallow that flits across the sky. The observer's uncle helps locate the binoculars, allowing the child to study the swallow's elegant flight in detail. The child marvels at the bird's white underbelly, orange-brown throat, and bifurcated tail, noting the sharp contrast between its movements and the backdrop of the sky. This close observation sparks an imaginative dialogue between the swallow, named Hirundo, and a magpie, representing materialism and solitude. Hirundo describes the hardships and joys of migration, emphasizing the beauty and necessity of communal life. In contrast, the magpie boasts about its independence and love for shiny objects, extolling the virtues of a solitary existence.

Vivere cogitare est

"Vivere cogitare est" begins in a Trieste kitchen where an elderly woman named Marianna prepares chicken broth for her grandchildren, who visit every Sunday. The scene then shifts to the interior of the pot, where two personified molecules, Ricky and Charles, engage in a philosophical discussion. Ricky, characterized by his reflective and analytical nature, questions the formation of bubbles on the broth's surface, while Charles, more straightforward and less contemplative, is intrigued by the broth's appearance and aroma. Ricky's deep curiosity leads him to lean too far over the pot, causing him to fall into the boiling broth. Inside, he experiences the chaotic currents and swirling liquid, realizing that the surface phenomena are influenced by complex interactions beneath.

Heartbeat (Battito)

In "Battito," a solitary bird narrates its journey through the skies, having lost its flock at a young age. The bird finds solace in the freedom of flight, exploring the world alone. One day, it encounters a majestic white cloud, a sight avoided by others due to the risk of getting lost within it. Intrigued by the cloud's beauty, the bird ventures inside, discovering a dark, pulsating mass at its center, which it identifies as the cloud's heart. The bird and the cloud engage in a profound conversation about existence, loneliness, and the passage of time. The cloud, unique and eternal, reveals its sadness and longing for companionship, contrasting with the bird's transient life and constant search for its flock. As a storm approaches, the cloud's heart begins to break apart, symbolizing its impending dissolution. Despite the cloud's imminent demise, it helps the bird find its way back to its flock, imparting wisdom and comfort. The bird, grateful for the cloud's guidance, witnesses its final moments, understanding the beauty and tragedy of life and death.

Ignorant Knowledge (Conoscenza ignorante)

"Conoscenza ignorante" follows the adventurous journey of Scott, a personified ant with an insatiable thirst for knowledge. Unlike his peers who mock his curiosity, Scott leaves his colony to explore the vast world, driven by stories from his grandfather about a grand palace. Scott travels through various landscapes, facing numerous dangers and meeting diverse creatures, all while being fueled by his desire to understand the world. He experiences breathtaking scenery, including deserts, oceans, and stormy skies, each contributing to his growing knowledge. Upon reaching the grand palace, Scott is astonished by its enormity and intricate design, reminiscent of the detailed descriptions from his grandfather. Inside, he encounters an old, dismissive ant who questions the value of Scott's quest for knowledge. The old ant represents the closed-mindedness of those who see no worth in intellectual pursuits. Scott, however, passionately defends his journey, explaining the importance of understanding the complexity and beauty of the palace's construction. He reflects on the metaphor of life as a series of interconnected parts, each contributing to a greater whole. After the meeting Scott comes back to his place proud of his matured awareness of the world.

The Other Half of the World (L'altra metà del mondo)

"L'altra metà del mondo" centers on Jero, who finds himself on a ship, staring at the vast expanse of the ocean as the sun sets and darkness takes over the sky. The narrative captures Jero's contemplations as he observes a bird briefly touching the water's surface before soaring back into the sky, and a fish breaking through the water momentarily. Jero ponders the contrasting perspectives of these creatures – the bird's view from above and the fish's from below. He reflects on philosophical questions about existence, self-awareness, and the nature of being, inspired by the teachings of Parmenides, who argued that being is and cannot not be. Jero's thoughts drift to the idea that one's understanding of the world is shaped by their perspective and experiences. He longs to transcend his limitations and see the world from a higher vantage point, akin to the bird's flight. As he contemplates the interconnectedness of all life, he experiences a moment of profound realization and self-awareness. This epiphany leads him to appreciate the complexities of existence and the beauty of seeing life from different perspectives. As the essay concludes, Jero realizes that understanding the other half of the world requires seeing beyond one's immediate surroundings, acknowledging the vastness and complexity of life that lies beneath the surface.

2.2 First round of analysis

In this section is discussed the methodology of the first round of analysis done for the 6 essays of the dataset. This led to preliminary outcomes which were then enriched and checked against a second round of analysis and the final member check (see next sections).

2.2.1 Data-collection and methodology of analysis

The objective of the first round of data-analysis was to contribute to the on-going reflection on the link between identity and physics disciplinary epistemology introduced in the first chapter, guided by an initial intuition that this dataset could have been possibly interesting under that lens.

Therefore, the aim of the data analysis is first to gather traces of such links between physics epistemology and identity-related issues emerging from students' voices/words, to contribute to the Research Questions:

RQ I: What methods and analytical lenses can be used to identify the connection between physics epistemology and identity development?

RQ II: What physics contents can inhibit or activate the link between epistemology and identity?

RQ III: What role do epistemic emotions play in the activation of this link?

Given the sensitivity needed to gather the kind of data useful for the research objective and due also to the size of the dataset, the most appropriate analysis seemed to be a qualitative one. In particular a thematic analysis (Braun & Clarke, 2006) has been done, with the intention to grasp every little contextual nuance possibly related to the connection between identity and epistemology. Therefore, the essays have been uploaded in NVivo 12 and then coded accordingly to the following procedure, choosing sentences as units of analysis.

The first step was an *open coding* procedure (Braun & Clarke, 2006) aimed at tracing every aspect related to identity issues of the characters, for instance their relationship with the others, their emotions, their feelings, their doubts, and so on. Here, it is necessary to evidence a sort of assumption I made: the characters, beyond the literary constraints provided by SM, have been freely imagined and developed by students. Students have decided the actions they do and more importantly the words they say, hence they could in good respect be considered somehow related to students themselves. In other words, the choice to populate a "free space" as the essay with specific issues can represent the "implicit" need to give voice to personal issues.

Then, I coded every reference to physics concepts introduced in the lectures such as irreducibility, emergent properties, local interactions, circularity or unpredictability.

The initial procedure produced 38 codes emerged from the contents identified in the essays. This number reflects the intention to be "as close as possible" to the data in this initial step (see Figure 11 for the codes). At this stage, following the procedure suggested by Braun and Clarke (2006), I looked for similarities between the 38 codes and clustered them into themes (see Figure 11), with 13 themes emerging at the end (see table below).

Theme name	Number of files	Number of references
Characteristic of complex systems	3	4
Consequences of the process of perspective change	4	10
Understanding as reconciliation of two perspectives by approximate view	2	4
Emotions with respect to complexity	3	4
Inability to have total information	2	2
Vertical perspective	2	6
Local-global view	4	6
Individual as distinct from the group and with its own specificities	4	17
Individual seeking himself outside the group and in the dual relationship	3	8
Fear and risks of being alone	3	5
Perspective toward the future	3	5
Relationship of the individual with the group	4	17
Rationality rather than emotionality	3	3

Table 5: The 13 emerging themes after the initial codification (yellow for identity-related themes and green for physics-related themes). Each theme is a compound of some of the previous codes: hence, once I grouped all the codes referring to a similar theme, I aggregated the data they were containing (the references). Hence the last columns mean the number of sentences coded to a code which was then grouped within the related overarching theme in the first column. The number of files instead means how many of the 6 essays present that theme, hence which contains sentences coded to one of the codes aggregated into the theme.

Looking at the themes, it can be seen the analytical intention to take trace of both physics epistemological aspects and identity related ones.

I will first start a brief overview of the creation of themes related to physics epistemology (again recall Figure 11 for an overview). For instance, the theme “*Characteristics of complex systems*” contains the subcodes “*A complex system is not decomposable*”, “*Reality within and reality outside the system*” and “*The whole and its constituent parts*”, which signal excerpts in the essays with references to typical features of complex systems as irreducibility, the different possible perspectives and the dualism between interactions and emergent behaviour.

Therefore, the themes “*Vertical perspective*”, “*Understanding as reconciliation of two perspectives by approximate view*”, “*Local-global view*”, “*Consequences of the process of perspective change*” and “*Inability to have total information*” respectively contain different codes all related to the idea that complex systems require many points of view from which to be looked at. Indeed, the interactions between agents which follow determined rules call for a perspective at the *micro-scale* whereas the collective behaviour and properties emerging unexpectedly from the interactions demand a *macro-scale* perspective. Nonetheless, if we adopt a *vertical perspective* – hence from the top (macro) to the bottom (micro) - we can’t access anymore a local information, whereas if we just focus on the interactions we will lose the global emerging phenomena. Therefore, there could be *consequences* (hence the name of the theme) of surprise when the perspective is changed since new information can be gained but still the more complete understanding is conveyed by an *approximate view* (see the theme) result of a *conciliation* of the two possible perspectives (again see the related theme).

As an example, in the essay “**The other half of the world**” the main character says:

“He thought that the birds had opposite views to the inhabitants of the sea who, on the contrary, were forced to look at the world from below. Two opposite perspectives looking at the same world, both aware of each other's existence, but unable to understand each other”.

This has been coded initially with the code “*Difficulty in reconciling two different perspectives*” which converged into the theme “*Understanding as reconciliation of two perspectives by approximate view*”. Or again in the essay “**The eyes of the Moon**” the main character – a bird which dreams of going to the Moon – reports:

“He couldn't wait to be able to observe his nest from above, he felt extremely useless and limited, he wanted to be able to glimpse every detail of what he was creating, he wanted to see how his companion who emerged each night into that sea of stars saw the product of his hard work, he wanted to see it through his eyes”.

This excerpt instead has been coded initially with the code “*Desire to look from the top*” which then converged into the theme “*Vertical perspective*”.

Or again respectively in the essays “**Ignorant knowledge**” and “**Vivere cogitare est**” the characters report the following sentences:

“This whole palace is what you have to understand, each piece that supports it has been placed according to a specific logic and order, each person has worked on it with care and skill, fitting, welding and screwing millions of small pieces together to make up a single larger one”. (Ignorant knowledge)

“On the other hand, it is something that cannot be broken down, or it would lose its very meaning”. (Vivere cogitare est).

In the first excerpt, initially coded with the code “*The whole and its constituents*”, the protagonist explains why is fascinated by the castle which is visiting, revealing both a fascination of the global structure but also of the scheme which arranges each block. In the second excerpt two cells protagonists of the essay are speaking about the fluid within which they jumped, and while describing the currents of cold and hot water determining the cells movements, they acknowledge the complexity of the thermodynamic system. Even though these two excerpts have been initially coded to different codes, namely “*The whole and its*

constituent parts" and *"A complex system is not decomposable"* they finally converged into the same theme - *"Characteristic of complex systems"* - since they are related to features of complex systems.

One further theme linked to the physics epistemology contains all the references reflecting emotions with respect to elements of complexity. Even though I mentioned before that doubts, feelings and issues of relationship with others are closer to a discourse around identity, still I grouped the emotions related to the elements of complexity in separate codes, namely *"Accepting complexity requires courage"* and *"Complexity fascinates"*, which then converged into the more general theme *"Emotions with respect to complexity"*.

For instance, in **"The other half of the world"** the protagonist uses these words: *"The lack of fixed rules, uncertainty and greatness (they) frighten, and only those who are able to peek beyond and keep their fear in check are able, though never absolutely, to come to terms with it"*, coded to *"Accepting complexity requires courage"*; or again in another part he reports *"The complicated interests, but the complex fascinates"* coded to *"Complexity fascinates"*. The sense of fascination is shown also in the essay **"Vivere cogitare est"**: *"Finally, he decided to dive back into the liquid and experience the complexity again, the ideal that fascinated him most"* (again coded with *"Complexity fascinates"*).

As mentioned above, coding the excerpts related to physics epistemology was just half of the work, since I wanted to look for the connection between epistemology and the identity development of the students. Thus 18 codes out of the initial 38 were highlighting traces of identity issues displayed by the characters in the essays. As for before, they then converged into 6 out of the 13 broader themes: *"Fear and risks of being alone"*, *"Individual as distinct from group and with its specificities"*, *"Individual seeking himself outside the group and in the dual relationship"*, *"Perspective toward the future"*, *"Rationality rather than emotionality"*, *"Relationship of the individual with the group"*.

In this case, there is one theme - *"Rationality rather than emotionality"* - which is not a compound of subcodes whereas all the others are constituted of at least 2 codes each. For instance the theme *"Fear and risks of being alone"* is composed by the codes *"Being alone is risky"* and *"Fear of not making it alone"*, to which excerpts manifesting anxiety and fear about loneliness have been coded, such as when in **"Thoughts in flight"** the narrator reflects in this way: *"How could the swallow, used to living in 'society', abandon everything and go away alone? Swallows have always found themselves in flocks, in a group, perhaps this is their destiny, what nature has reserved for them"*.

Then three major themes seem really close: *"Individual as distinct from group and with its specificities"*, *"Individual seeking himself outside the group and in the dual relationship"* and *"Relationship of the individual with the group"*. Nonetheless, they capture slightly different nuances of the issue concerning how individuals relate with the group, triggered by the constraint to talk about a complex system hence to talk about agents and groups of agents.

The theme *"Relationship of the individual with the group"* contains all the codes which describe the possible dynamics occurring between an individual and its own group (peer, family, etc.), as the *Contrast* (one code), the *Attachment* (another code), the *Rejection* (another code) and so on. For example, in the essay **"Thoughts in flight"** the main character while describing its peer group, says: *"I grew up with them, I experienced my first emotions there with my friends"* (coded to *"Attachment to the group"*). Or again in **"Ignorant knowledge"** the ant is described with these words: *"He was highly persuasive and brilliantly reasoned, but in spite of this he was considered by society to be nothing more than a work machine!"* (coded to *"Group distances"*), whereas in the essay **"Thoughts in flight"** again the protagonist says: *"It's because I think of myself, I take extravagant and shiny objects just for me, I don't think of others, they have to make do and make their own, just like I do!"* (coded to *"Rejection of the group"*).

The theme *“Individual seeking himself outside the group and in the dual relationship”* instead is more related to the individual move-out of the group dynamics as a chance for self-awareness. This theme is a compound of three sub-codes: *“Coming out of the group-home to understand oneself”*, *“With the other I understand who I am”* and *“Willingness to know oneself”*. These three codes have been grouped together since they capture the expressions of individuals who want to leave the group and find their identity by themselves or within just a dualistic dimension. For example, in the essay **“Ignorant knowledge”** the protagonist shares: *“To live without feeling curiosity, that is useless, to merely stay in the comfort of one's home without ever challenging oneself, without discovering what one's potential might be, that is useless!”* (coded to *“Willing to know oneself”*).

As for the last theme related to the group issue - *“Individual as distinct from group and with its specificities”* - this is different again from the other two since it focuses more on expressions which point out the differences between individuals and the group, as the following three excerpts exemplify:

“What differentiated it from the rest was precisely why it was so essential” (from **The other half of the world**, coded to *“Distinct and distinguishable individual”*)

“I immediately noticed that there was something different about you though.

- Yes, I am different... I always have been and always will be” (from **Heartbeat**, coded to *“Distinct and distinguishable individual”*)

“For me it is taken for granted that some animals live alone, that loneliness is imprinted in their nature; like when we see a fox and a wolf: the fox does not have a group with which it can be associated, we recognise it by itself, by its cunning, its tawny fur. Instead, one of the first thoughts we associate with the wolf is its pack, like a swallow its flock” (from **Thoughts in flight**, coded to *“Individual on its own, independent”*).

In the first excerpt the protagonist – Deet – acknowledges that the differences between him and the rest of the world are the ones which define him. In the second excerpt, there is a meeting between a cloud and a bird, with the latter recognizing the cloud as unique and remarkably different from the other clouds around her. Finally, the third excerpt is part of a reflection done by the protagonist (a young guy observing a swallow and a magpie “talking”) while he compares the lifestyle of animals and humans.

To conclude the last theme - *“Perspective toward the future”* - groups four codes which all share sentences with instances, desires, and fears expressed by the characters about their future, as:

“Will I ever really feel part of something one day? - he thought, as one hand rested on his chest” (from **The other half of the world**, coded to *“Desire to belong to something”*) or *“What frightens me is that there may be another reality that we can neither see nor understand”* (from **Ignorant knowledge**, coded to *“Fear of missing out”*) or *“I don't even know my destiny”* (from **Thoughts in flight**, coded to *“Lack of vision about the future”*).



Figure 11: The diagram shows the qualitative data analysis process. Codes are displayed on the two sides; in the squared blocks there are the corresponding themes in which they were grouped; at the centre the two categories in which the themes were finally clustered.

These were all the 13 themes created from the initial selection of 38 codes which then have been made converging according to the issues they were expressing. Therefore, as it is clear also from the structure I used for introducing the themes, I divided the themes related to identity issues from those closer to physics epistemology, under two macro-categories named correspondingly **“The individual with himself and with the group”** and **“Practices and values of the study of complex systems”**.

These two categories mark the two poles of interest (epistemology and identity) of the Research Questions.

It is crucial here to understand an analytical operation at the bottom of the data analysis. Even though I knew from the beginning that these were two macro-categories I wanted to develop, passing through the data and the codification provided me with the specificity needed. In other words, the “group connotation” of the identity category comes from data and was not conceived at the beginning. Indeed, it is properly thanks to this specificity in the name of the categories and in the kind of themes which form them that I will claim later conclusions which are *data-driven*.

Once the dataset was coded then I focused on the interrelations between themes, with specific care to the parts of the text where codes of the two categories were spatially close, subsequent or overlapped, given our interest in the kind of links which could emerge between physics disciplinary epistemology and identity issues.

2.2.2 Outcomes and discussion

As it emerged from the previous section, the students referred to many specificities of the complexity paradigm but looking at the themes it is evident that in particular two epistemological issues came out: the need for multiple perspectives when dealing with complex systems and the highlight on the difference between single interacting agents and an emerging macro-structure.

Considering all the themes but two from those on the right side of the figure above, namely “*Vertical perspective*”, “*Understanding as a reconciliation of two perspectives by approximation*”, “*Local-global view*”, “*Inability to have total information*”, “*Consequences of the process of perspective change*”, they all point out the same idea: complex systems are systems which request the adoption of diverse perspectives according to the intention of the observer. One could argue that is always the case, but the specificity of these systems is that we cannot preserve the same explanation when changing scale, hence the name *complex*. Indeed, as discussed in Section 1.2.1, these systems “change shape” according to same critical conditions, hence we cannot predict what is going to happen at the whole system based on the rules governing the local interactions and at the same time we cannot model the interaction based on the macroscopy phenomenology. Nonetheless sometimes a third perspective can be useful, the *mesoscopic*; from this point of view we focus on a medium range of interactions and by studying the critical conditions it is possible to understand the transition between the microscopic deterministic behaviour and the macroscopic unpredictable one (see for example the case of Bénard cells in the next Chapter).

This is probably the most important among the features of complex systems addressed in class. What is interesting to notice is that the kind of issues brought by the themes identified in the essays show that students caught the centrality of this by stressing it in every essay and in multiple ways according to their taste.

For instance, students report the inability to have total information, since it is impossible to locally look at all the agents at the same time, as well as impossible to grasp the whole system since “you will always miss” a little part:

"To better understand this phenomenon, I could try to observe a single cell, but from this perspective I can only see that the bubble will soon be engulfed by another or burst, so we can never predict what will happen. Observing the whole would be a very good perspective, as we can see what external agents are changing the whole. But in doing so, we would lose sight of the elementary unit of the phenomenon, that is, the single bubble, so understanding is impossible; I cannot understand how this reality can exist" (from **Vivere cogitare est**).

Thus, dealing with complexity requires courage to accept this inability and question the meaning itself of "knowing": *"This complexity cannot be fully understood, but one can try to reach a truth very close to it [...] (since a complex system) is something that cannot be broken down, or it would lose its very meaning"* (from **Vivere cogitare est**).

For what concerns the identity-related elements emerging, there is one main topic recurring in 4 out of the 6 themes identified: the reference to the relationship between the self and a group, such as the family, the peers, and the class. Students indeed report the tension between the need for independence and the safety provided by the community; being alone is risky but allows one to know oneself, whereas the group is commonly a safe place but sometimes it can inhibit exploring personal individuality and the personal future:

"Wow, it would be wonderful to disconnect from everything, to be able to feel free from the group I belong to. [...] I would like to have time to pamper myself, to travel, to stop somewhere in the knowledge that I am not in a hurry or have to look after the group. MY group, MY home. [...] Would I be capable?" (from **Thoughts in flight**).

For instance, the essay "Ignorant knowledge" starts as:

"He was laughed at and mocked by everyone. Not because he was in conflict with the society he lived in, but because he was born with an irrepressible, insatiable desire for knowledge.

A problem?

- Come back soon my son! Come back soon!... - repeats the mother.

- Don't worry mother, I will come back and tell you my adventure in the most beautiful words you have ever heard.

And so it was that in the twelfth year after the founding of the colony, little (or big depending on your point of view) Scott left, leaving behind not only his family, but also the mockery of his companions".

Here it comes out the idea of a difficult relationship with the group (in this case the peers) which inhibits the seeking for the sense of oneself, forcing one to change place. This is presented often in contraposition with an image of the group as a support, as a scaffolding for the self-realization, leading to an interesting tension exemplified by the following excerpt:

"In every person there is a swallow (tied to the group) and a magpie (alone, independent) and we probably just need to have the audacity to want to know both, to learn to accept life in society, but also be aware of our individuality. Perhaps this is precisely what the swallow did. It has become aware of its uniqueness, aware that it is no longer just a bird in the flock" (from **Thoughts in flight**).

I argue that there is almost a self-evident similarity between the trending issues of the identity-linked themes and the physics epistemology ones. On the one hand - in the epistemological dimension - the focus on the agents as individuals ruled by precise mechanisms but also the recursive attention to an alternative dimension (the macroscopic one) where all the agents are considered as a unique compound,

and the difficulty in balancing these two perspectives. On the other hand - in the identity dimension - the constant tension between individuals who strongly desire to develop themselves in a unique way and the attachment to the group which is a comfort zone that can also sometimes support self-development.

Hence, given such strong analogy one could argue that maybe the epistemological elements discussed in class over many lectures somehow “inspired” or “informed” the expression of a particular personal instance. To this regard it is important to make a clarification. The expression of personal issues that we see emerging from the essays cannot be due to the concepts taught but originates more likely because of the context created by the teachers and the kind of “free space” provided by a creative writing activity. Still, given this space for expression, what I am arguing now is that the **specificity** of the personal issues systematically expressed by students (relationship between individuals and groups) may be due to the kind of contents discussed. Indeed, it was not mandatory to focus on the discourse around the different perspectives as the only constraint was to insert elements of the complexity epistemology presented in class. Hence, the final consideration is that maybe students wanted (consciously or unconsciously) to express that specific personal problem (group-individual dynamics) and chose from the disciplinary elements available those which they considered as helpful instruments to convey such issue.

Thus, it seems that the connection between epistemology and identity development functioned as a scaffolding. The kind of activity provided with the space to express personal issues but the epistemological structure of specific contents of complexity was used as an instrument to revoice and reconceptualize idiosyncratic identity-related aspects.

In the following paragraph this conjecture is tested presenting one significative example and the kind of work done with the codes. Further elements supporting this claim are discussed in Section 2.4.

Overlapping analysis

As anticipated in the previous section, I am particularly interested in the sections of the essays in which themes of the two macro-categories are close, subsequent or even overlapping. Indeed, if students chose to share issues that could be usefully conveyed through specific epistemological elements, that is to say that those specific elements were considered appropriate instruments for expression. This can be seen at a macro-level by looking at the strong similarity between the two sets of themes composing the macro categories of identity and physics epistemology. Nonetheless it could be reasonable to think that this *activation* process can be found also at a micro-level. Thus, I could look for parts in which themes from the disciplinary category are followed or even intertwined with themes from the identity category, and then investigate if this is a random proximity or rather the themes are close because they are supporting each other.

This procedure is pretty easy using NVivo: once the codes are done it is possible to display the “Coding stripes” which appear at the right side of the text and allow to quickly see if and where are the selected codes (see Figure 15 for an example). Hence, I first looked for parts in which proximity or overlapping of the two macro-categories was evident and then I displayed the specific themes coded for both categories in that part.

I present here one representative excerpt in which I will show a non-random proximity of themes belonging to the two macro-categories.

The excerpt is:

“He thought that the birds had opposite views than the sea dwellers who, on the contrary, were forced to look at the world from below. Two opposite perspectives looking at the same world, both aware of

each other's existence but unable to understand each other. He would have loved to have known how to fly, to have the ability to observe the whole thing from above. He often wondered how many things could be captured from that perspective, details that were overlooked by anyone and yet, observed from up there, might seem like something extraordinary. He fish, never able to float, destined for an existence on the bottom, at that moment only wished he could have been able to twist his nature and know the other half of the world. He remembered when, sitting on the bed in his room, he told about Parmenides, how he argued that "The Being" is and cannot not be. "The Being" knows that he/she/it exists, but is he/she/it able to know him/her/itself? Or "The Being" is, without knowing him/her/itself? Its existence at that moment was amalgamated with the other thousand unanswered questions, mingled with the nothingness claiming to be so. The complicated interests, but the complex fascinates. The lack of fixed rules, uncertainty and greatness frighten, and only those who are able to peek beyond and control the fear, succeed in coming to terms with the fear, even if never in an absolute way" (from "The other side of the world").

The excerpt presents a dense overlapping of themes of the two categories as shown in the table below.

Text	Theme
He thought that the birds had opposite views than the sea dwellers who, on the contrary, were forced to look at the world from below. Two opposite perspectives looking at the same world, both aware of each other's existence but unable to understand each other.	Understanding as reconciliation of two perspectives by approximate view
He would have loved to have known how to fly, to have the ability to observe the whole thing from above.	Vertical perspective
He often wondered how many things could be captured from that perspective, details that were overlooked by anyone and yet, observed from up there, might seem like something extraordinary.	- Local- global view - Consequences of the process of perspective change
He fish, never able to float, destined for an existence on the bottom, at that moment only wished he could have been able to twist his nature and know the other half of the world.	Consequences of the process of perspective change
He remembered when, sitting on the bed in his room, he told about Parmenides, how he argued that "The Being" is and cannot not be. "The Being" knows that it exists, but is it able to know itself? Or "The Being" is, without knowing itself? Its existence at that moment was amalgamated with the other thousand unanswered questions, mingled with the nothingness claiming to be so.	Individual seeking himself outside the group and in the dual relationship
The complicated interests, but the complex fascinates. The lack of fixed rules, uncertainty and greatness frighten, and only those who are able to peek beyond and control the fear, succeed in coming to terms with the fear, even if never in an absolute way.	Emotions with respect to complexity

Table 6. Sentences and related themes created by codes. The highlighted parts are the parts coded to the theme on the right. The blank parts have not been coded.

The students, in their story, are dealing with the personal demand related to the possibility of knowing themselves: *“the ‘being’ knows that it exists, but is it able to know itself?”*. In front of this demand the “fish”, which is looking at the world from its own perspective, *“only wished he could have been able to twist his nature and know the other half of the world”*. Borrowing multi-perspectiveness from the epistemological methodologies of physics of complex systems, the narrative is built to show that other views are possible; the bird, for example, can see the world from above and, thanks to this alternative, the dichotomy between “the known world” and the “other unknown half” is reframed and problematized.

We see in particular four subsequent excerpts coded to themes which all display the idea of perspective changing and the possible consequences to that, followed by two excerpts linked to identity but in particular related to the process of knowing oneself. Finally at the end there is also a brief digression around the emotions that complexity can stimulate (*“The complicated interests, but the complex fascinates...”*). This can be interpreted as a sort of “local” mechanism: the discourse around the perspectives is used as a basis for scaffolding the verbalization of inner questions about identity, properly because of a structural resonance. The similarity indeed between a dualistic point of view and the dichotomy between what is the current state of identity and the other half of the self, the features of identity still to be developed. This is explicitly reported few lines after in the same essay: *“he had to come back to the surface, he had to show himself to the other half of himself”*.

This is not the only case of expression of epistemic emotions (Arango-Muñoz & Michaelian, 2014; Davidson et al., 2020; Jaber & Hammer, 2016) found in the essays. Indeed, the reference to complexity knowledge epistemology is conscious and is often accompanied by an expression of judgment. For example, a sense of fascination for the forms of complexity and properties such as emergent phenomena have been found in more than one essay. On the other side it appears often a feeling of discomfort and fear towards complexity. Furthermore, also a sense of frustration and impotence is popular in characters’ voices, given the impossibility to keep the view on all the parts composing the complex system during their dynamics: *“After a while, however, he huffed: he still could not see everything, could not register in his mind every little facet of what he was observing; each time he noticed that he had missed something, an extra leaf, a small hidden branch”* (from **The eyes of the moon**).

I argue that the thematization (as the connection with features of complexity) of these emotions contributed to connecting the matter of the emotions (elements of the physics knowledge) with personal demands; thus, feeling an affect enhances the personal relevance of the contents themselves.

2.3 Second round of analysis

In the previous section I presented in detail the first round of analysis, which allowed to:

- Determine a specific and contextual connotation of the kind of disciplinary elements chosen by students and personal issues presented by them, respectively the discourse around the multiple perspectives and the individual-group dynamics problem;
- See how both at a macro-level (themes found) and a micro-level (overlapping analysis) disciplinary elements seem to trigger the expression of personal issues.

Starting with these premises, in this section the second round of analysis is presented, which has been guided by the three following ideas:

1. The need to shift the analysis to a more general level, to be informative also with those who do not know the dataset (indeed the first round was intended to be as close to the data as possible).
2. The intention to keep the nuances emerging from the first round of analysis.
3. The ambition to better grasp and describe the “local” mechanism seen in the overlapping analysis. I showed in the specific example how the epistemological elements set the premises for the expression of identity-related elements. Such mechanism can be interpreted as a “scaffolding”.

2.3.1 Methodology of analysis

The second round of analysis is a follow-up of the first one, in the sense that I kept the 38 codes initially identified but this time I grouped them according to the new objective (describe a “local” mechanism of scaffolding).

I initially recognised 3 macro-trends emerging from the previous codification.

- 1) In particular, as discussed in Section 2.2.2, students systematically referred in the essays to the epistemological practice of physics of complex systems to span over different perspectives: looking at the single agent/at the whole system, looking from above the system/from below, looking staying inside the system (focus on the interactions)/outside the system (focus on the emergent collective behaviour). Thus, I created a new macro category named “*Systemic thinking*”¹⁹. Indeed, “systemic thinking” (Checkland, 1981; Verhoeff et al., 2018) refers to the attitude of approaching the study of systems by considering them entirely, including the components and their interrelationships, rather than focusing on just individual parts in isolation.
- 2) There were many references to complexity epistemology elements which were linked to an expression of demands and feelings. In particular:
 - a. In 5/6 essays it is expressed the need for new perspectives to be used as lenses by which examine something (the home, the group, themselves, their actions). This was expressed through codes such as “*Desire to look from the top*” or “*Desiring another’s perspective*”. I named this a need of perspective-widening shared by the characters.
 - b. In 3/6 essays it is reported the need but also the tension to keep together and align multiple perspectives, through codes such as “*Difficulty in reconciling two different perspectives*” or “*Understanding by approximation*”. Thus, it comes out the need of perspective-aligning for the characters.
 - c. In 6/6 essays it is expressed the wonder and fascination that these new perspectives provide, through codes such as “*New vision causes wonders*” or “*Complexity fascinates*”.

This led me to create three other macro-categories, respectively: “*Epistemic demand of widening the perspective*”, “*Epistemic demand of aligning the perspectives*” and “*Epistemic feelings*”.

- 3) To conclude I wanted to keep trace of the central issue emerging from the first codification around the tension between the group and individuals. This, together with the references to personal emotions (different from the epistemic emotions of bullet point 2), brought me to create the last two macro categories, namely: “*Positioning toward the others*” and “*Fears and desires*”.

Secondly, I grouped the 38 codes into the new 6 macro-categories, as it is shown in Figure 12.

¹⁹ I use here the term category instead of theme as it is more general than the themes displayed in Table 5.

Characteristics of complex systems		Understanding as reconciliation of two perspectives by approximate view		Consequences of the process of perspective change		Emotions with respect to complexity	
Inability to have total information		Vertical perspective		Local-global view		Individual as distinct from the group and with its own specificities	
Individual seeking himself outside and in the dual relationship		Fear and risks of being alone		Perspective toward the future		Relationship of the individual with the group	

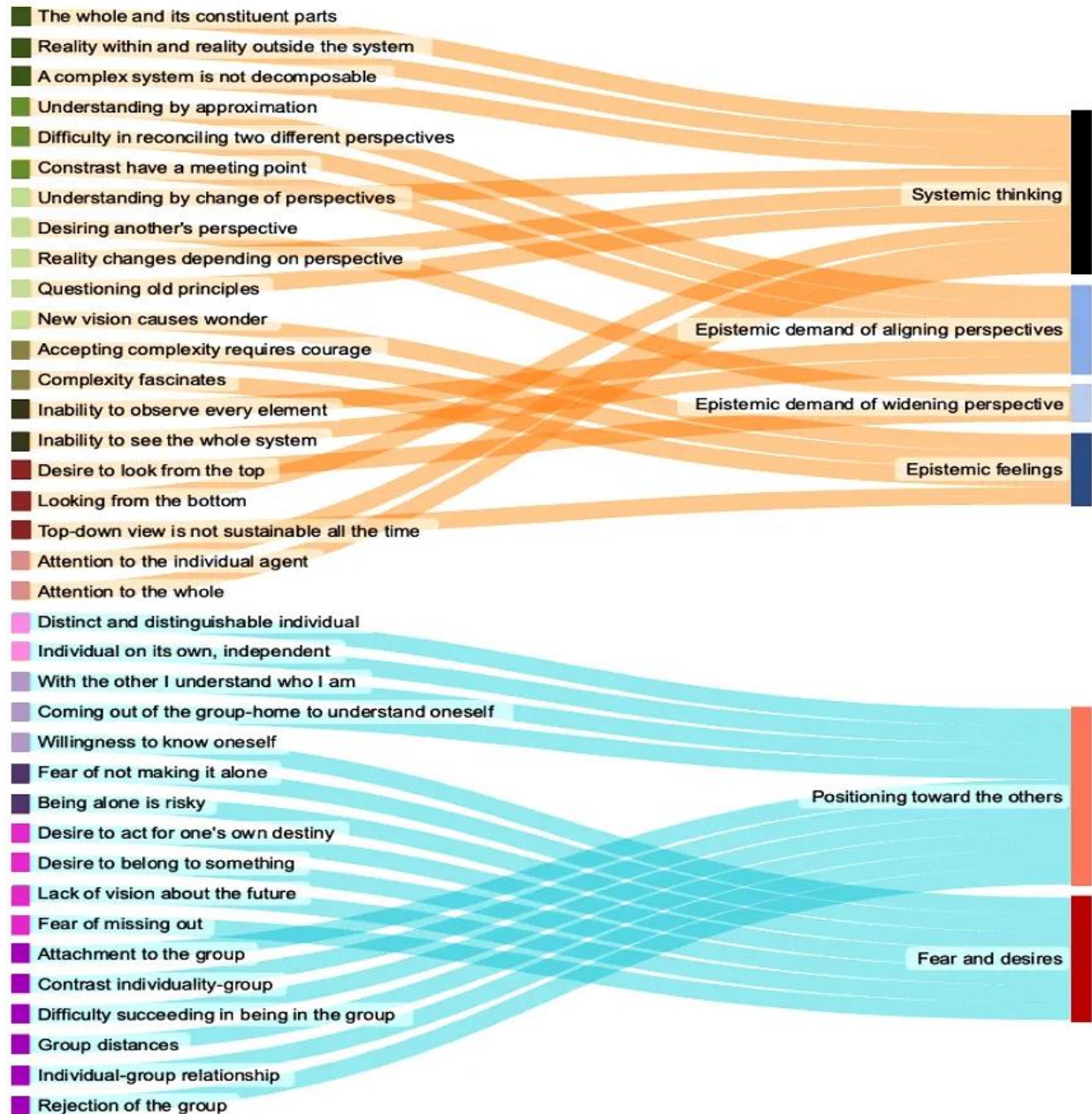


Figure 12: At the top of the figure there are the 12 original themes with related codes and on the left the 38 codes/labels grouped accordingly to the corresponding theme of the first round of analysis. The same codes/labels have been re-coded to the new macro-categories on the right side. The codes/labels linked with an orange arrow are those which belonged to the physics macro-category of the first round, whereas those linked with a blue arrow are those which belonged to the identity macro-category of the first round.

As a final step for this second round of analysis I represented the new codification of each essay as a spectrum (see Figure 13), to provide an easy and fast look of the thematic structure. In particular, I associated every line of each essay to a column of a specific height and width, setting the line as a unit of analysis. Then for every line coded to one of the 6 new categories I painted the related column with the associated color (see Figure above) whereas all the lines not coded were left blank.

In the following section I will describe how I used the spectra and discuss the results emerging from the second round of analysis.

2.3.2 Outcomes and discussion

In this section I present the spectra obtained in the second round of analysis (Figure 13 below).

The value of these spectra is that they show immediately crucial results gained also from the previous round of analysis.

Indeed 5 out of 6 essays show *redish* codes, hence lines coded either to *Fears and desires* or to *Positioning towards the others*. This is relevant since it was not indicated as an objective of the activity to embed issues on the identity dimension such as feelings or the group-individual dynamics, as the essay “*Vivere cogitare est*” demonstrates. In fact, this essay has only lines coded to either *Systemic thinking* or blue section: *Epistemic feelings*, *Epistemic demand of aligning perspectives* and *Epistemic demand of widening perspectives*.

If we look for example at the spectrum of the essay “*Thoughts in flight*” very few references to complexity epistemology are present, hence we could say that this essay did not respect the assignment.

Thus, the spectra help us to pursue the objective of the second round of analysis, which is trying to describe a *scaffolding* process in which elements of the knowledge of complexity (black and blueish codes) create “room” for the expression of personal issues (redish codes). Having this in mind, is pretty easy to identify the essays which better show this merging between identity and complexity, namely “*The other half of the world*”, “*Ignorant knowledge*” and “*Heartbeat*”. Thus, I chose to focus on these three rather than the other three because of their unbalance, as they are either coded to just the blue and black categories or to red ones.

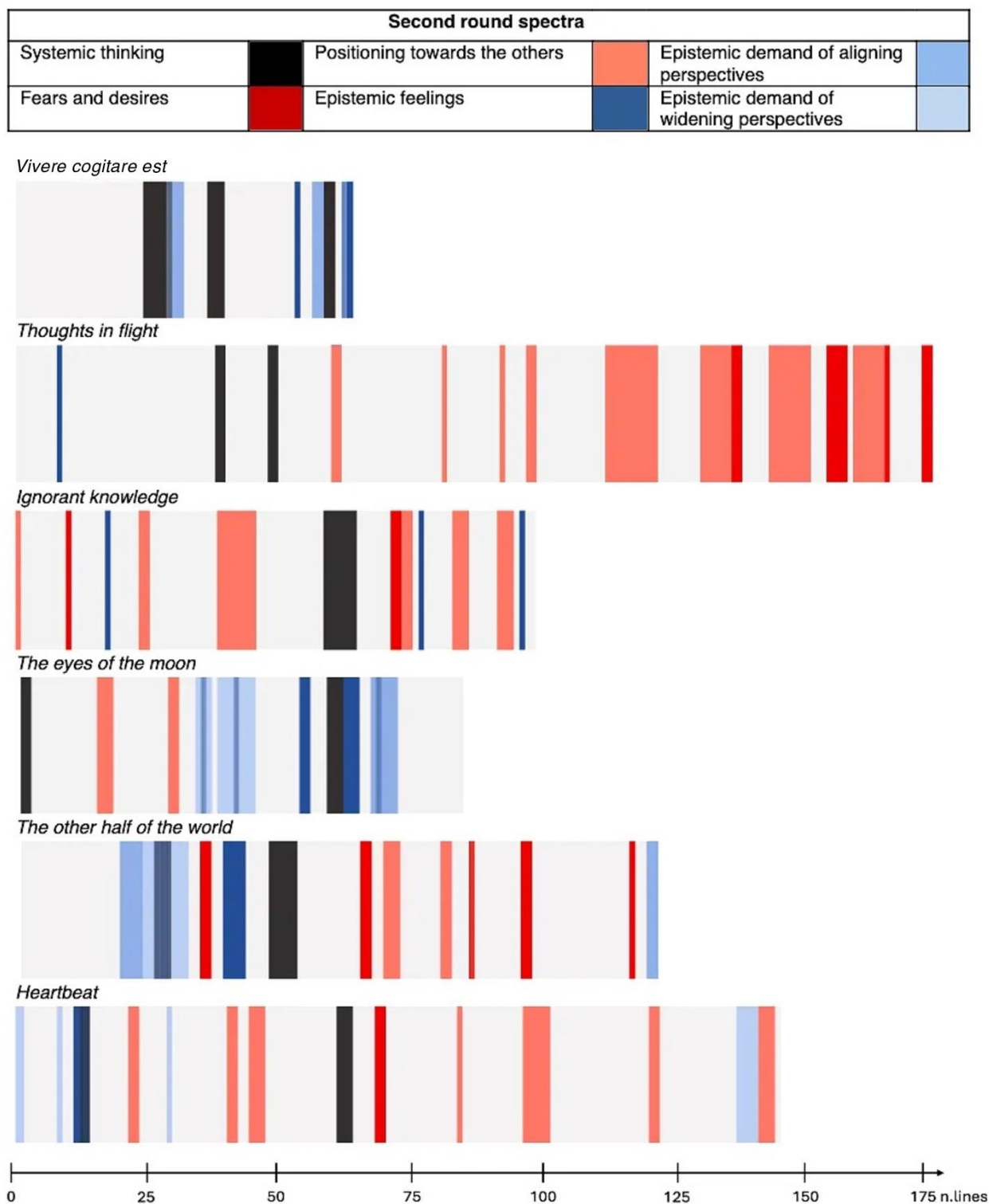


Figure 13: The spectra for each essay produced with the new codification (see the legend at the top). The different lengths of the spectra represent the different lengths of the essays (note that I did not normalize the lengths so that two bars of the same thickness represent the same numbers of lines for each essay).

If we focus on the three “balanced” essays, we notice that the category “*Systemic thinking*” (black) - where epistemic features of complexity emerge - is always clustered in one or two blocks and is always followed by the “*Fears and desires*” category (dark red).

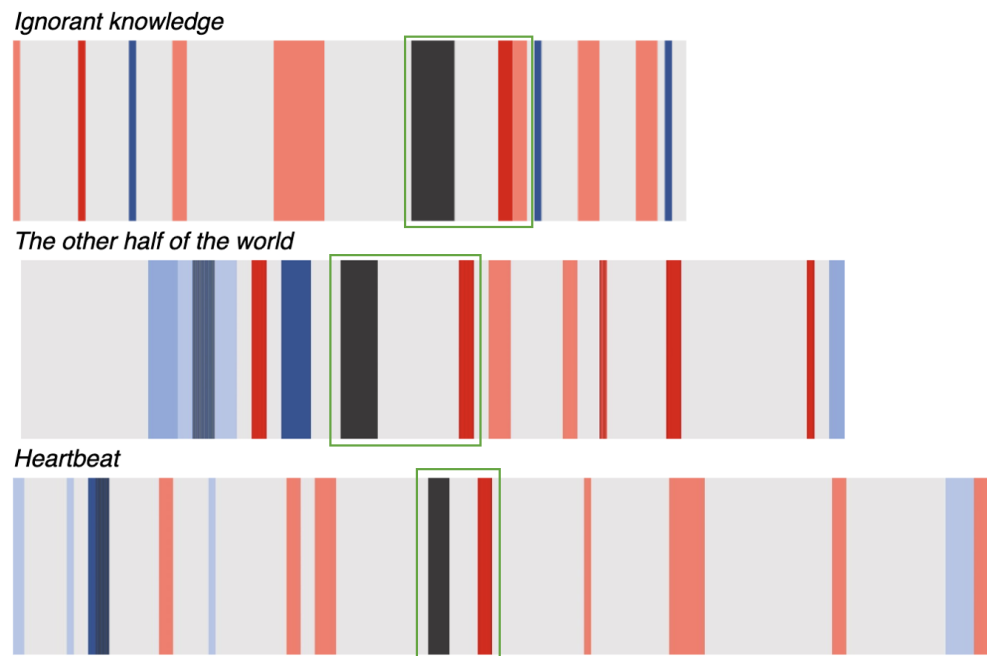


Figure 14: Spectra for three essays and within the green boxes the position of the typical cluster for the macro-category of *Systemic Thinking* followed by references of the category *Fears and Desires*.

The proximity could be by chance, but having found that in all the three cases (identified as best candidates for showing the scaffolding of complexity elements) could be rather an indication of a tendency. I now inquire into the nature of this proximity by discussing one of the three examples (**Ignorant Knowledge**), reported in the Figure below.

In the first coded part, the protagonist is looking at all the pieces constituting the whole palace and is admiring the general scheme which regulates their positions and functions. This has been coded to “Systemic thinking” as he is looking at the single element and the relation with other elements and catch the global picture (the building). It is an example of micro-perspective which then shifts to macro-perspective, from the local interactions to the global emergent property. In this sense the character is *taking a new perspective* which allows to see a new reality.

The second part coded sees Scott (the character) expressing a fear of not understanding this new reality, and maybe other realities (coded to “Fears and desires”). This triggers a reflection that shifts from the reality (the building and the bricks) to the individual level, as the ant recalls his own difficult experience within the group dimension (coded to “Positioning toward the others”) with the following expression of fear of not understanding himself and the group (anthill). The anthill, which is a complex system, again as the palace did before provokes admiration, which is an *epistemic* emotion as the reference is the complex system (coded to “Epistemic feelings”).

To conclude again there is a shift to the personal dimension concerning the challenge to know oneself and oneself’s potential going out of the comfort zone (coded to “Positioning toward the others” since there is here the one which affirm himself against the others).

- It is not easy to explain it with the hurry you seem to be in, but still I try. This whole palace is what you need to understand, each piece that supports it has been placed according to a specific logic and order, each person has worked on it with care and skill, fitting, welding and screwing millions of small pieces together to make up a single larger one. It seems like a wise metaphor for life, brick by brick, placed evenly to form a wall, but what you need to pay attention to is not the goal to be achieved, but the method you need to follow.

- Are you always so philosophical? I, and with me the whole colony I am sure, see nothing extraordinarily interesting in this building; it is just a pile of iron and cement with no reason to be here. You, on the other hand, try to see another picture, to follow another reality. I ask you why you are here and you answer me "to know"; you compare life to working in the colony; and what do you mean then by "I want to understand the complexity?" Of course you are so strange! But where do you live?

- How easy you make it! I am not so different, except perhaps for fears: what frightens me is that there may be another reality that we can neither see nor understand. After all, can you tell me who built all this? Who dreamed it up and managed to make it real, perhaps having to overcome insults, mockery, and ignoring the envious ones who induced him to abandon everything because he would fail anyway? The ants are too small, not only physically, and I will probably never be able to understand the meaning of all this, of me, of the anthill, but I will just look at it, admiring in my own small way the immense beauty around and that of asking questions that most of the time are not really answered.

- You are such a strange ant, you know? You risk your life unnecessarily to see an anthill -- Bah, so silly!

- It's not silly or even useless! - replied Scott - To live without feeling curiosity, that is useless, to merely stay in the comfort of one's home without ever challenging oneself, without discovering what one's potential might be, that is useless! In life perhaps there is nothing to truly fear, only to understand. And now I think it is time to return.

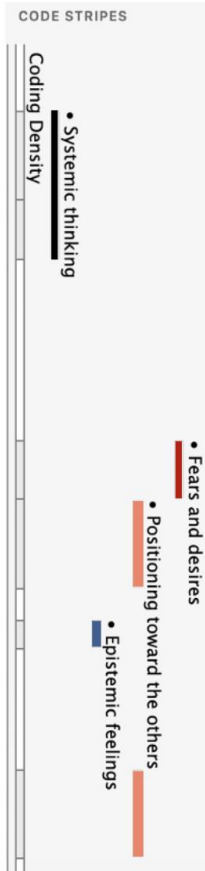


Figure 15: The excerpt with the related "Coding stripes" as they appear in NVivo12. The highlighted part represents the piece of text coded to the macro-category displayed in the right part, with corresponding colours. The colour-codification is the same of Figures 12-14.

In this brief yet exemplary fragment, "visiting" the complexity (going within a complex system as the palace) requires to adopt new perspectives, and this operation triggers reflections about possible ways to get to know themselves and the own potential. In this sense, it seems that embedding references to complexity (emergence, local interactions, diverse perspectives) activated into the students the need to express something about the identity of the character which is again inspired by the reference to complexity itself (speaking about agents and global structure in complex systems -> speaking about oneself and the group).

So far, the claim of complexity scaffolding specific personal issues (agents and whole system -> individual and group dimension), was just an analytical interpretation, yet triangulated between between me, PF and my supervisor). However, as I will argue in the next section, we did our best to also provide reliability and trustworthiness to the analytical results, through one of the methods suggested by the qualitative analysis literature (Anfara et al., 2002).

2.4 Member check

In November 2022 we conducted a "member check" session, to confirm or disconfirm the outcomes produced by the two rounds of analysis.

Member checking, also known as *participant* or *respondent validation*, is a technique used in qualitative research to enhance the credibility and validity of the study. This process involves sharing the findings, interpretations, or data with participants to ensure that their perspectives have been accurately represented. It allows participants to confirm the accuracy of the recorded data, offer additional insights, and correct any errors or misunderstandings (Lincoln & Guba, 1985). By involving participants in the verification process, researchers can mitigate bias and improve the trustworthiness of their analysis (Birt et al., 2016). An example of member checking in the science education literature can be found in the study by Carlone and Johnson (2007). In their research on the identities of successful women of color in science, they conducted interviews and later returned to the participants with their findings, to validate them.

Thus, in a meeting held in the second half of November 2022 with the secondary students who produced the essays, we resumed the teaching module with PF and SM and I presented the analysis made, with an emphasis on the outcomes found and my interpretation (at that time only the first round of analysis was concluded, yet there was already the idea of a scaffolding process).

In the discussion after the presentation, students confirmed that in the essays they were talking about themselves consciously or even unconsciously, hence validating the hypothesis made in section 2.2.1 about interpreting characters' issues as real students' issues.

For example:

"so in the end we told precisely ourselves inside that cloud. But it's something we normally do when we talk to each other as well [...] so writing about complexity through a cloud that is already a complex structure anyway turned into something simple because we were talking about us" (student from the group of **Heartbeat**)

or again

"So this text also served very much as a dialogue between us, to figure out just how we wanted it to represent us" (student from the group of **The eyes of the moon**).

They recognized and shared with us also the reason for the "group connotation" of the identity category:

"(we wrote them) in a period (pandemic) when we had to relate so much to our own personal reality and much less in our relationship with others [...] personally I thought a lot during those months about the relationship with others and the relationship with myself and I think you can also perceive from the themes the fact that personal identity was a highlight because by not having a relationship with the other the conception of ourselves is amplified and is constantly being questioned" (student from the group of **The eyes of the moon**).

This quote is particularly interesting since it provides an explanation for the "individual-group" connotation of the identity references, which was found as a contextual result of the first round of analysis. Students in this case were forced to stay most of the time alone because of pandemic, detached from the others, at an age which is usually dominated by the group dimension (at least in the school environment). Thus, the reflection around the meaning of the group popped out as a consequence of the forced condition.

They reported also the spontaneity of talking about themselves, implied by the choice of using creative essay workshops: *"In my opinion, it was quite spontaneous"* (student 3) or *"When you write it you don't think about it very much. When you write you throw down what is in your head."* (student from the group of **Heartbeat**).

Such discussion with students led me to claim that the essays were conceived as a “place” with a lot of freedom and students talked about personal questions because of the “safety” embedded in creative writing. As SM comments: *“And here is that freedom to be able to talk about us freely because if I have to give a heart to the cloud, the first thing that comes to me is to give my heart, and then put myself as the subject”*.

Therefore, the member check confirmed the research claim developed through the two rounds of data analysis. Even though the second round of analysis was done after the member checking, it did not add completely new results, nor added completely new codes. Specifically, the operation of recoding grouped already existing codes into new categories to better focus the analysis, and this led to identify specific cases of “balanced” essays, which confirmed (in a more contextual and precise way) insights from the first round of analysis.

Yet, member checking highlighted also something about how the design of the activity was perceived by students. Indeed, the task of writing about complexity by merging two disciplines was completely new to them and kind of unusual for a school context. Yet, being in groups rather than alone, made them find a solution and also supported a personal interaction and connection. When we asked them some adjectives representative of their group experience they answered this way:

“Our group, we were the ant-hill group, that is to say, it was very important for us to work as a group, because we were individuals who did not have many ideas together... that is to say, when the outline was proposed we did not know how to work, but by putting it together we managed to find the way....to write the theme. As a symbol to represent our theme, we chose something a bit special, Thomson's panettone model, which represents our path in this theme, because the panettone represents the written theme, finished but inside there are scattered electrons and protons, from the confusion that existed at the beginning, which in the end created a beautiful thing, a beautiful theme” (student from the group of **Ignorant knowledge**).

“So as adjectives we chose contemplative, different, provocative, awkward, secular and as a symbol the tying of a rope. Because, in our opinion, this project was something as complex as tying a rope, but also a way of tying together different aspects such as physics and literature” (student from the group of **Thoughts in flight**).

3. Conclusions

In the previous sections, I presented the design of the activity, discussed the cultural framework of the school and the teachers involved and illustrated the epistemological framework of both the physics of complexity and creative writing. Then, I outlined the methodologies of the two rounds of data analysis and discussed the results that emerged.

Specifically, the first round allowed to see that students understood the aim of the activity and respected the assignment by including specific references to complex systems in their essays. In addition, they populated their writings with many references to identity-related issues. In this regard the themes identified through the analysis showed the specificity of both epistemological and identity issues displayed, disclosing a striking analogy. On the one hand the dualism between agent-to-agent local interactions and collective emergent behaviour (for physics) and a general discourse between an individual and its group (for identity). Such analogy was interpreted as a thematic scaffolding operated by the contents of complexity represented in the essays, that for their meaning have been selected to re-conceptualize a specific and shared inner problem (the relation with the group).

The second round of analysis, showed that the scaffolding mechanism was not systematic for all the groups. In this sense, having found that only three groups show a balanced intertwining between identity and epistemological aspects helps to argue that the result is real and not driven by the assignment. Also, the second round illustrated through a meaningful example how the digression around complexity issues *activated* – also via a thematization of personal emotions - reflections about inner demands.

Finally, I showed how the member check activity confirmed the research claim. Students admitted that they were really speaking about themselves in the essays and added some insights about the group connotation of the identity-related issue found in the analysis. That confirmed how they expressed a strong feeling they were experiencing (because of the lockdown during the Covid 19 pandemic) by using the contents of complexity discussed in the lectures.

Hence, the outcomes show a special form of students' engagement with science topics and practices: students used science epistemology as a "space" where to represent, re-conceptualise, and re-address issues related to their core identity (Gee, 2000). In particular, the dualism between "agents" and the "system" in complex systems behaviour, was used as a scaffolding for the expression of the tension between the "individuals" and the "group", a very common and distinctive phenomenon for teenagers, further increased during the pandemic.

For this reason, the teachers decided to repeat the activity. This led to the follow-up activity of "Physics of clouds", which is named "Kairos", with a grade-10 class in the same school. This time teachers were able to involve (besides the retired physics teacher and Italian literature teacher) the in-service physics teacher, the in-service chemistry teacher and two laboratory technicians. This will be the core of Chapter 4.

4. Contributions and refinement of Research Questions and theoretical construct

The outcomes presented in this Chapter illustrate how students were inspired by the epistemological structures of complex systems (in particular the concepts of different points of view and the dualism between local interactions and the emergent collective properties) to express personal identity demands.

Regarding the theoretical construct introduced in Chapter 1 with the term “link between physics epistemology and identity development”, based on what emerged from the analysis I can start differentiating it from other theoretical constructs which recall identity and physics epistemology. I can for instance argue that what emerges cannot be interpreted as the development of *epistemic identity*. Even though the name may evoke something close to the theoretical construct introduced in this thesis, epistemic identity refers to the set of approaches that may be preferred by learners while entering the epistemological structure of a discipline. If we take physics as an example, its different practices which constitute part of its epistemology (Erduran & Dagher, 2014) allow for different “roles” available for students. Students can develop more of an “experimental attitude” or a “theoretical one”, hence increasing a kind of disciplinary identity closer to the epistemic practice involved in lab experiments or that concerning theoretical reflections (even if they are strongly intertwined). There are studies which inquired about the reasons for these preferences (see Kaleva et al., 2019, or Palmer et al., 2017 for example) which may include other positions according to diverse disciplines (hence diverse epistemologies) (Chen et al., 2023). Most of the time the motivations guiding students are grounded on self-efficacy (Bandura, 1977) or utility values discourses (Eccles, 2002). Nonetheless, epistemic identity does not help us to frame what emerged from the outcomes.

As Osbeck and Nersessian (2017) describe, epistemic identities are “*the various ways one’s “sense of oneself” as a scientist*” (p.2). In this sense, cultivating an epistemic identity means positioning yourself with respect to a set of predetermined and normative roles (the “experimental”, the “theoretical”, the one who loves the computations, or the simulations, etc.). As discussed above, the results of this Chapter suggest rather how the contents allowed students to position themselves not only with respect to some disciplinary aspects (as they seem to have preferred some concepts over others) but more importantly with respect to personal questions which are outside the disciplinary domain. Thus, the epistemology here helped them to affirm themselves outside rather than inside the physics realm.

Another candidate theoretical construct embedding physics epistemology and identity is *appropriation* developed by Levrini and colleagues (Levrini et al., 2015a; Levrini et al., 2019a), discussed in detail in the first Chapter. Since appropriation is a non-incidental selection of epistemological elements felt as personally meaningful and relevant, which also brings to a social positioning, it may lead to the conclusion that we are facing a case of appropriation. However, I claim that the scaffolding process described cannot be properly framed with appropriation. Appropriation indeed, indicates an idiosyncratic self-positioning of the students with respect to knowledge. Even though it is a personal decision which involves tastes and preferences and activates cognitive but also emotional dimensions, it guarantees a positioning still within the discipline. It is way less normative than epistemic identity as it does not encapsulate the possible positionings within a close set (hence normative) of possible roles, but it leaves to the individual to find its specific position (see the case studies presented in the paper). Nonetheless, the outcome is students finding comfortable room for staying in the disciplinary discourse and developing their learning. What emerged instead from the analysis is again how concepts scaffolded

(Vygotsky, 1987) students' expression of identity-related issues **outside** the disciplinary boundaries. Indeed, I noticed that students exploited a specific selection of physics contents because of their structural similarity to personal inner troubles they were reflecting on at that time.

Therefore, the empirical data drove me to realize that an idea that may characterize the theoretical construct is that of “resonance”. It was indeed the acknowledgement of a resonance that led students to select the epistemological elements of emergence and local interactions. If we think more generally, this was a positive case: a similarity was recognized hence a link between epistemology and identity issues was actually activated. However, it is equally important to pay attention to those cases in which epistemological elements are somehow seen as disturbing by students (Festinger, 1962). So, instead of resonance, I can borrow from music the dualism *consonance/dissonance*²⁰ to indicate those cases in which epistemic elements resonate in a positive or negative way with the individual. Nonetheless, it is fundamental to acknowledge that both cases (consonance and dissonance) are traces of the establishment of a link between the individual and epistemic elements, even if with diverse possible consequences. A consonance, as the one discussed in this Chapter, can activate a scaffolding link between physics epistemology and identity issues, hence supporting identity development as defined in Chapter 1. The dissonance is more delicate and could lead to forms of disengagement and detachment from the knowledge or being the premises for a critical metacognitive reflection (see Chapter 5 for more details).

Based on the data collected and addressed in this Chapter I can only argue about the role of consonances, leaving the discussion of dissonances for the next Chapters. Hence, I suggest here a first name for the theoretical construct: ***personal-epistemological consonance/dissonance***.

Furthermore, the outcomes found through the data analysis let me address the Research Questions introduced in Chapter 1.

As for RQ I (*What methods and analytical lenses can be used to identify the connection between physics epistemology and identity development?*), I was able to identify episodes of link activation by focusing on the two poles of interest, hence labelling all the traces of instances identity-related as well as references to elements of complexity epistemology. Then I passed through each case to see if and how the expressions of identity issues were anyhow related to the elements of complexity displayed in the essays. In other words, I looked for *activators* of identity-related sentences. Still, this is just an option and I will leave the question open to further contributions from the following Chapters.

Recalling instead RQ II (*What physics contents can inhibit or activate the link between epistemology and identity?*), I showed that the epistemology of complexity represents a good candidate for activating a link with identity issues. In particular, it emerged how a discourse around the “spatial structures” of complexity was profitable in activating *consonance* with students.

Regarding RQ III (*What role do epistemic emotions play in the activation of this link?*), I am not completely able to provide an answer, but from this implementation it seems at least that epistemic emotions were commonly present in all the essays, confirming that the physics contents triggered an emotional reaction in students.

To conclude, I would like to add some points to the way I addressed RQ II, as it witnesses the value of complexity (especially in its spatial structures and features) in activating a personal reaction. One then could argue if it was a chance or instead complexity particularly resonates with students because it

²⁰ Even though jazz musicians will certainly be upset in considering dissonance as something disturbing (in the canonical connotation of the term).

introduces a new paradigm questioning the classical mechanical one. Related to this, another interesting point could be to test if the reflection around the “temporal structures” of physics, introduced by the complexity paradigm (especially in the interpretation of I. Prigogine) resonate (consonance/dissonance) with students’ identity questions, as they also present a new image of time compared to the classical one.

Hence a new set of Research Questions, related to the strand II:

RQ II.1: To what extent can the epistemology of complex systems scaffold the expression of identity issues?

RQ II.2: What personal-epistemological consonances/dissonances can activate the temporal structures of complex systems?

I highlighted above the importance of the cultural and epistemological frameworks of the activity. The value assigned to the knowledge by the teachers and the exploitation of an interdisciplinary approach created indeed the premises for self-expression. Hence, I plan to evaluate the effectiveness of these choices in the next implementations, guided by the following Research Question:

RQ IIa: To what extent does a particular way of teaching physics concepts activate personal-epistemological consonances/dissonances?

This represents a new strand, still related to the content (as strand II) but focused on the way contents can be dealt to support personal relevance for the subject matter. I named this new strand IIa (see Figure below). From this Chapter the strands then become four: strand I (methods), strand II (what kind of contents), strand IIa (how to deal with contents) and strand III (epistemic emotions).

All these new questions will be faced in the next Chapters.

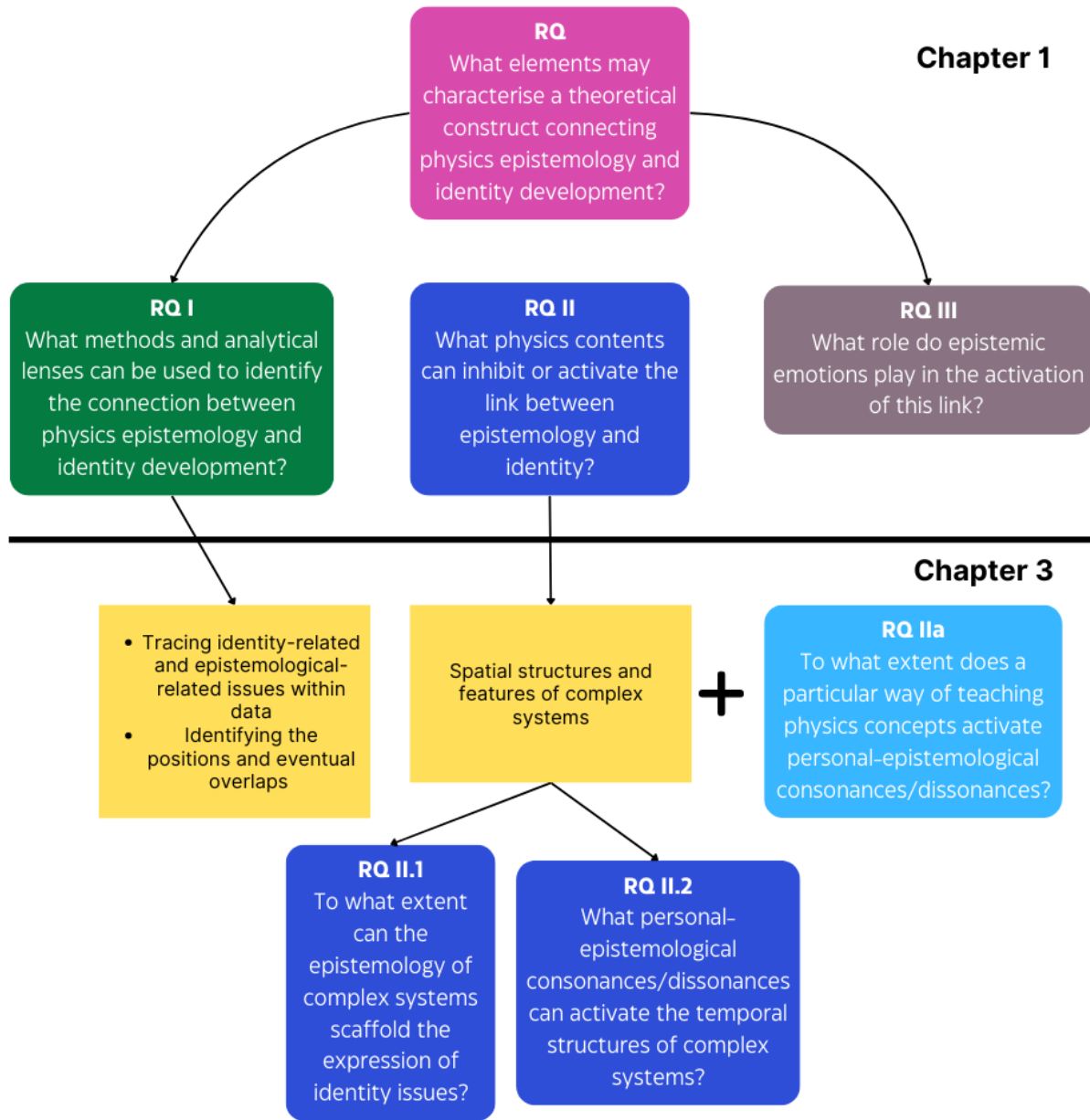


Figure 16: The evolution of the scheme presented in Chapter 1. Strands 1 and 2 have been addressed and the first results emerged (yellow stickers). The result of strand II made the strand itself evolve, leading to the formulation of two further RQs (RQ II.1 and RQ II.2). In addition, what came out from the case study brought out a new strand (light blue) still connected to the contents (so again strand II) but more focused on the way of dealing with them. As a consequence, RQ IIa was formulated.

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Appendix A

Vivere cogitare est

It all started in a pot.

In a house located in Trieste, as in all houses, there was a kitchen made up of the usual utensils. In this lodging lived Marianna, an elderly lady who was cooking chicken broth for her grandchildren who came to eat with her every Sunday. At the edge of this pot there was a heavy atmosphere due to the hot steam escaping. Below you could see the broth bubbling continuously and the reflection created by the metal which was such as to dazzle the eyes; all of which created a surreal environment.

Two elements met, Ricky and Charles and began to talk about the strange reflection of the broth. Ricky is reflective by nature and everything he does must be the subject of his own personal analysis. Furthermore, he is a lively person, but above all nervous, because when he fixes something in his head, he absolutely has to do it otherwise he becomes even more agitated than usual.

Charles, on the other hand, has a much calmer and more relaxing personality but, unlike the first, has zero reflective capacity compared to him and an objective vision of things, because he never stopped to understand the mechanisms of nature and of all the objects present in it, as it never has its own personal opinion.

Suddenly they both noticed on the surface of the broth the formation of some yellowish bubbles that had clear boundaries between them and began to talk.

- I want to understand why there are these strange little cells on the surface as, being a liquid, it should be smooth - said Ricky.

- Have you seen the glow of the broth? That says so much about it! Maybe you could taste it, who knows how good it is! replied Charles.

- To better understand this phenomenon, I could try to observe a single cell, but from this perspective I can only see that the bubble will soon be engulfed by another or burst, so we can never predict what will happen. Observing the whole would be a very good perspective, as we can see what external agents are changing the whole. But in doing so, we would lose sight of the elementary unit of the phenomenon, that is, the single bubble, so understanding is impossible; I cannot understand how this reality can exist.

- Stop thinking about all these aspects! You think about considering only the irrational part of the phenomena.

- The problem is that you don't understand that the true essence of reality is deep inside! Try for once to stop considering everything at first glance.

This last sentence gave Ricky a flash of genius because he understood that he too was wrong to consider the bubbles only from a superficial point of view: he had to do it below the water level. In the meantime, however, he had gotten too close to the edge of the pot and, making a false step, fell into the liquid.

Everything was dark, clouded; the noises were muffled in the distance, he didn't even have time to understand what was happening when he found himself upside down and began to move in a whirlwind, dragged by some currents from the pot. His head was spinning and he didn't know how to get out of that chaos. The explosion of a nearby bubble hit him so hard that he flew for a long time in the air.

Finding himself in that situation, Ricky absolutely had to manoeuvre his arms to get back to the surface before ending up back in the broth. He decided to exploit a very important element: the steam that was rising upwards, created by the boiling of the liquid. In fact, he could slow down his fall thanks to the tiny particles of the gaseous substance that hit him and, fortunately, he managed to return to the starting point.

He was shocked by what had just happened, but this made him understand that the cells formed on the surface were certainly stimulated by hot water currents inside the liquid. Each was formed by its own current, similar but not identical to each of the others. This complexity cannot be fully understood, but one can try to reach a truth very close to it.

On the other hand, it is something that cannot be broken down, or it would lose its very meaning. At that moment the molecule had managed to reach this truth, feeling very very satisfied.

Finally, he decided to dive back into the liquid and experience the complexity again, the ideal that fascinated him the most.

Thoughts in flight

- Uncle where did you put the binoculars?

I have to find it! Otherwise, that swallow will fly away and I won't be able to observe it, while it flutters in the sky. Actually, I don't think she's all that keen to leave: she's been wandering around for at least fifteen minutes. It could at least get a little closer so I don't have to scramble up a shelf to get this thing.

Finally, I reposition myself on the balcony, in a slyly studied way; I adjust the focus of the binoculars and point at the bird and it seems to hover right in front of me. I admit that the continuous movement of the head to which I am forced to submit, in order not to lose sight of the swallow for a moment, makes me feel sick, but compared to the elegance of the show I am witnessing it is highly irrelevant.

Hirundo rusticates its scientific name, definitely appropriate.

Looking at her from below, her chin, chest and belly are visible; they're supposed to be white, but she reckons they're a little muddy. From the latter, the orange-brown of the chin stands out, which in the midst of all the rest almost looks like a stain of dirt, like when you grease your shirt with gravy.

Also from this angle, I can see the forked tail, they look like two swordsmen.

My uncle taught me that in swallows, if the tail is longer, they are male and if it is shorter, they are female. I confess that I can not understand what it is, so I choose ... and for me, he is a boy.

Finally, after having analyzed the lower part of the body, I can concentrate on the wings: the line that separates the white of the chest from the hypnotic metallic reflections of the grey plumage is very clear. Their continuous movement in contrast with the wind brings to light the small grooves and all the bristles of the beard, that part of the feather that one is always afraid to touch because it is said there are hidden diseases inside; the breeze passes through them, brings them closer and further away, shakes them until it creates cracks between them where the sky can be glimpsed... Black.

Black? Since when has the sky been dark?

But right now the binoculars must have broken, I can't believe it!

Oh, too hasty, far too impulsive. Did they block out the sun and I expect they won't obscure the small lens of a binocular? Very insightful Palomino, congratulations! It was also the first days of spring, it was obvious that one of these days the flock would migrate here again, especially if I had seen one of them, the swallow from before, to be clear, arriving alone to probe the ground.

The bird family has always fascinated me. I can't call myself an ornithologist, but I'm modestly prepared. This is why I know that flocks do not have any kind of leader, but simply behavioural attitudes to follow in order to always remain united during the flight. I strongly doubt it, it is impossible that the swallow, which I have observed up until a few minutes ago, was not the leader waiting for all the others, while she checked that the established place was going well. By the way... Where did my chosen one go? I knew I shouldn't have distracted myself.

It's the guide. So everyone follows it. Therefore it must necessarily be the leader.

Hurriedly I take the binoculars back and... phew!, they're still there where I left them.

Their chirping has begun to fill the silences of the city; I imagine the children who after the long journey complain and desperately ask to be able to find a comfortable branch to sleep on. I dream and wonder about the hellos and goodbyes they might exchange after spending so many days together and perhaps condolences to the little families who have lost someone.

Gradually they thin out, leaving room for the sunlight and the blue sky.

And finally, they dissolve as if they never arrived. They find their place, all but one. The beloved I had chosen to analyze is still up in the sky, alone.

But this time he doesn't seem like he's waiting or reconnaissance; on the contrary, his gaze seems cautious, suspicious, doubtful and always points there.

With the binoculars, I trace the trajectory of the view and end up at that exact point, thanks to which I can fully understand the swallow's doubts. There is a magpie who knows why she is intent on protecting her treasure sparkling under the shade of a tree. I never liked magpies; not because they are lonely, the eagle is too, but I like her. No, it's their materialism. She could travel the world, and explore places... but she prefers to hoard things and pamper herself under the shade of trees. The swallow does not know this and perhaps her curiosity is stronger than her tiredness. After all, she is only observing, perhaps even enchanted, the elegant plumage, the black broken beak and legs of the patches of a regal white, and decidedly cleaner than that of hers. She is seeing, perhaps for the first time, its own kind alone, independent. And I bet she wants to know, yet she might be scared, and so I guess she starts to wonder...

Am I going or am I not going?

What does it do alone? Maybe he wants company.

What do I do? Do I pose or not?

Come on yes, if he doesn't want me then I'll leave, what's the problem...

And in fact here I see the swallow approaching, reckless.

They are both curious about the knowledge of a different species from their own, and for this reason, they are surely saying something to each other, they can't just stand there, scrutinizing each other; they have to communicate something. I can't be sure, but I like to think it is so, so I decided that I just have to let my mind be carried away by their looks and chirps that, infrequently, interrupt the silence of the afternoon.

The magpie was perplexed at the sight of the swallow that had darted towards her, so she remained silent.

On the contrary, the swallow wants to talk, to tell its story; I knew right away since she was positioned in front of the magpie with her chest out and she started emitting powerful squaws from her little beak.

- Where I come from, well, there are many plants, tall, every autumn we build new nests that are destroyed every spring; we prepare for a long journey. I don't want to say that I hate it, there's all my family, my origins. But it's a continuous agony, we never stop, for weeks, not even to drink: we descend close to the water, we touch it with our beaks, we drink as much as we can and then up again, towards the sky.

Furthermore, when we cross that blue expanse, which never seems to end, the gusts of wind hit us, undeterred, making the flight terribly annoying.

I can already imagine the magpie, so brazenly proud, bursting out with her usual perfectly studied presentation: "Mh, my treasure attracted you, didn't it? It's normal, so glittering that I'm forced to put it in the shade to prevent it from blinding a flock of bad birds like you..." I don't know if out of bravado or stupidity, the swallow emits a faint peep, but strong enough to make so that the magpie stops its speech.

It's possible he tried to defend his family. It doesn't matter to the solitary bird that reopens its black beak and continues to recite its script: "I didn't ask your opinion, swallow, for me, you are and will remain a bunch of bad birds. However, I am a magpie.

Humans consider me one of the most intelligent species, after all, I know how to make myself adored. I'm elegant unlike you, and much more independent too. I manage totally by myself".

At this point I see the swallow open its beak and close it immediately afterwards, as if it wanted to counter, as if the magpie's last statement had thrown it off balance.

And here I am also taken aback, when at the focal point of the conversation my neighbour, the lady who lives in the apartment above, decides to hang out the sheets that have just come out of the washing machine and block my view of the two birds.

I don't know what to do and, seized by anxiety, all my senses are dulled; I have to stay focused if I want to understand what the swallow and the magpie communicate to each other, so I take deep breaths, as my uncle taught me, and try to find a solution.

Among the thousand thoughts that I have in my head, one idea stands out: I cannot use my sight, but I can always listen, so I close my eyes and let myself be carried away by the sounds of nature: the rustling of the leaves, the droplets of water falling from the sheets and land on the fresh grass, the breath of wind in the lavender bushes in the garden and, finally, the chirping of two birds in conversation. I calm down definitively, I have heard the swallow and the magpie, I hear precisely the squawking of the first,

and I hear that the verses alternate in tones from the most acute and irritating to the most serious and calm. Evidently, the conversation is proceeding, but I was left with the swallow's reaction, after learning that it was possible to be alone. For me it is taken for granted that some animals live alone, that loneliness is imprinted in their nature; like when we see a fox and a wolf: the fox does not have a group with which it can be associated, we recognise it by itself, by its cunning, its tawny fur. Instead, one of the first thoughts we associate with the wolf is its pack, like a swallow its flock. Yet it is not so obvious.

A bird like a swallow that throughout its life has been used to living in a group, to respecting rules, to having to share everything, that finds itself discovering that it can live alone, that if there is the possibility of being able to survive and even much more for another bird similar to him, maybe even for itself.

I was so caught up in my thoughts that I didn't realize that by now the sheets were gone. Now the situation has changed, the two birds don't bicker, and there is silence. The magpie has returned to her hoard, and the swallow, well, keep on gazing at her; more detached, passive than everything else, or so it seems to me. I like to think that she stayed there for a reason, that two conflicting thoughts are fighting inside her that do not allow her either to get closer, for fear of learning even more about the magpie's exciting lifestyle, or to leave, for fear of not having the possibility to know again. She must be heartbreaking.

- Wow, it would be wonderful to disconnect from everything, to be able to feel free from the group I belong to. It's my family, it's my friends but, I would like to have time to pamper myself, to travel, to stop somewhere in the knowledge that I am not in a hurry or have to look after the group. MY group, MY home.. I grew up with them, I experienced my first emotions there with my friends, I'd like to give it a break, but then what? Would I be capable? Would I have the courage to face a predator, or the shrewdness to find shelter quickly?"

Now he's approaching the magpie again, hesitant as if he's trying to ask her something but afraid to know the answer. Finally, I guess she gathered some courage because I heard her peep:-Hey, sorry to bother you again, but I need to know. How did you learn to be alone?

The answer comes quickly, a caw that interrupts the silence as if the magpie knew that sooner or later that question would come, and had already prepared the answer: - So you would like to be alone, eh? Replies - I've been alone since I learned to fly, freedom and light-heartedness are my daily life, relaxing under the shade of the trees, enjoying the days as they are - continues the magpie in a very pedantic tone.

- *I'm not like you, I'm lonely and I'm fine, I live for myself and I don't care about others. This is the basic principle of being alone. In my opinion, you're not the type to be alone, you don't have what it takes; do you see how majestic I am? It's because I think about myself, I take extravagant and shiny objects just for me, I don't think of others, they have to make do and make their own, just like I do!* -continues the magpie always with a certain tone of superiority.

Perhaps the response received was even worse than he believed. While the magpie answered, the swallow took steps backwards as if those croaked words were blows that forced her to return her mind to reality, making her understand that hers was only an ephemeral dream. How could the swallow, used to living in "society", abandon everything and go away alone?

Swallows have always found themselves in flocks, in a group, perhaps this is their destiny, what nature has reserved for them.

What if it were the same for men? On the other hand, man is a social individual; an oxymoron highlighted by the wills in continuous opposition to each other. In every person there is a swallow (tied to the group) and a magpie (alone, independent) and we probably just need to have the audacity to want to know both, to learn to accept life in society, but also be aware of our individuality. Perhaps this is precisely what the swallow did. It has become aware of its uniqueness, aware that it is no longer just a bird in the flock.

And now that I know, will I succeed to survive? -asks the swallow, maybe not, or maybe yes.

I will never know. Maybe one day he will decide to do it and fly away. But for now, I think she's decided to go back to his flock of him. I hear her chirping one last time as if to greet the magpie who had already returned to her beloved treasure.

I see her turn her head, spread her wings, hover again up in the sky, and fly away almost not seeing her anymore, to the point that for a moment I even hope she doesn't land on that tree. In the end, I too turn

my head, go back into the house, close the window and let her choose for herself which destiny to take. Besides, I couldn't help her, I don't even know my destiny.

The other half of the world

The silence was deafening, the air thick with unspoken words.
Darkness was quickly engulfing the thousand shades of red that populated the sky at dusk,
free from clouds and accompanied by warm summer air.

Until a few minutes before, the sun seemed to not want to stop dominating the scene, but now there it was, an expert diver, capable of splitting the surface of the water without even a splash, ready to give way to the moon and the stars, in a fast run towards a goal without a finish line.

The lights of the port overwhelmed all the cumbersome boundaries dictated by darkness and the approach of that shore did not bring with it the familiar sense of tranquillity and melancholy that had always characterized the end of their voyages.

Jero rhythmically tapped the sole of his shoe against the metal plate at his feet, his dark hair loosely tied up with string, his sweaty hands running over the fabric of his shorts.

He looked at the water.

Miles and miles of dark, flat, still water.

He saw a bird, but he couldn't tell which it was; he touched the surface of the water for a few fractions of a second, before rising again towards the sky.

Then he saw a fish, cut the same surface and dive right after.

He thought that the birds had opposite views than the sea dwellers who, on the contrary, were forced to look at the world from below. Two opposite perspectives looking at the same world, both aware of each other's existence but unable to understand each other. He would have loved to have known how to fly, to have the ability to observe the whole thing from above. He often wondered how many things could be captured from that perspective, details that were overlooked by anyone and yet, observed from up there, might seem like something extraordinary. He fish, never able to float, destined for an existence on the bottom, at that moment only wished he could have been able to twist his nature and know the other half of the world. He remembered when, sitting on the bed in his room, he told about Parmenides, how he argued that "The Being" is and cannot not be. "The Being" knows that he/she/it exists, but is he/she/it able to know him/her/itself? Or "The Being" is, without knowing him/her/itself? Its existence at that moment was amalgamated with the other thousand unanswered questions, mingled with the nothingness claiming to be so. The complicated interests, but the complex fascinates. The lack of fixed rules, uncertainty and greatness frighten, and only those who are able to peek beyond and control the fear, succeed in coming to terms with the fear, even if never in an absolute way.

The formula of life, although it may seem something mechanical on a structural level, has so many variables that it would be difficult to include it even in the indefinite set of complexity.

And now, looking at the way the moon was mirrored on what he had for years considered his stage, he came to the conclusion that all the principles, which he considered fundamental for resolving situations that went beyond his sphere of comprehension, had done nothing but push him away from the target.

Things don't have a unique nature, but change according to the eyes, the light under which they are looked at is clear.

He looked at the moon and wondered if he felt everything he was feeling, if there was someone on the other side watching him and, while his mind formulated a thousand other questions, all his thoughts stopped in a fraction of a second, his head he lightened up.

He had managed to stop himself before it all became too much, to save himself.

At that moment he re-emerged from the water, brushed his hair from his forehead and turned his gaze away.

He watched his skin, how it shone under that new light and for the first time in his life he wished he had a mirror to know if his eyes shone the same way.

He couldn't help but raise a corner of his mouth in a half smile as he let himself be rocked by the surface of the sea, feeling safe.

Will I ever really feel part of something one day? - he thought, as one hand rested on his chest.

- You are already part of something Jero, you just have to be able to see it. Her voice came far and thin, a whisper, so familiar...she didn't open her eyes yet.

- How do I figure it out? Where should I start? How do I do if I'm alone?

The thrust on his chest became rhythmic, almost desperate. - You are not alone, I am here! We are here!... Look at me Jero, look at me...

His eyes snapped open.

He let himself be enveloped again by the reflected light and, now that he was observing the moon from below, he understood why Narcissus could not help but fall in love with himself, how the natural mirror of water accentuated the living nature of things and how much, immersed in that little glimmer of light, felt right.

He raised his head and saw the way the white of the moon contrasted with the darkness of what was around it, but at the same time, it was clear that this was exactly where he belonged, as if what differentiated him from the rest was precisely why it was so essential and the water seemed so human to him that for a moment he wondered if, in the middle of that landscape, he wasn't the dead element.

The thought couldn't even form itself completely, the next moment he was drowning; the circle of the moon was above him, but no longer a part of it.

He had known the moon, he had known himself.

He thought it was worth it, touching the sky for a moment, feeling completely alive for a fraction of a second, to the point that nothing could match what he had managed to feel.

Emotions are the basis of everything and without their control, the claim to be able to completely rationalize the rest is nothing but utopia.

But it couldn't end like this. If fate had already written its ending, he must be able to recite another; he couldn't have realized his mistakes and done nothing to fix them.

He regained control of his body, he had to come back to the surface, he had to show himself to the other half of himself.

Tears streamed down Deet's cheeks, the other's helpless, soaked and cold body lay before his eyes, his pulse so slow as to seem null.

Jero trudged towards the moon; in the background, a cry, getting closer, getting louder.

He saw all the birthdays pass before his eyes, his parents' funeral, Deet's family which had also become his own, the plate of pasta his mother prepared for him every Sunday, the breakfasts at the bar, his homework made the night, his belongings scattered around the house of the other, the final exam, the first time he had touched his shoulder in second year "Can you tell me where the chemistry classroom is?"

The crying continued, its increasingly tiring run, a warm grip around her wrist - Please come back to me!

Jero had never felt more on the surface before.

The pulse under her fingers quickened, and she saw him cough, she saw how his body seemed to come back to life, the way his eyes snapped open and he was the first thing they looked for; he sat up, his hand gripped her shirt and rested her head on his shoulder.

He observed her closed eyes, the heavy breathing and then how she opened her mouth to speak - I found Deet, I met...- it came weak and slow, muffled, as if they were both under water; a secret that not even the sea and the stars could afford to know.

An oxymoron, sun and moon, light and dark, surface and depth, two curved lines destined to always have a meeting point, the natural correlation of two parallel universes.

Heartbeat

By flying I can go wherever I want, all I need is a flap of my wings, a current of air and I'm already there.

A white mass in front of me; everyone has always tried to avoid it because you get lost in there; and it's true, you get lost...

You get lost among the shades of a white that I didn't even believe existed, a blue even lighter and more delicate than that of the sky that I ride at the first light of day, and then a few touches of yellow.

A sun-kissed cloud, that's where I am.

I don't want to back away from such splendour, so I dive into the cloud, but as soon as I see what it hides I freeze. At its center a darker, darker and more frightening mass is pulsating: the heart. I get closer and closer and every second I am more enchanted by it. It is as if I were drawn to its heart as if I could feel it.

- It's beautiful! I didn't think that something so big could be hidden inside such a simple reality!

- Big, but empty...

- ... Who is speaking?

- Well, I'd say there aren't that many of us up here, look around and tell me what you see.

- A cloud? A talking cloud?

- Exactly! And what are you doing here?

- I lost my flock when I was little and since then I have travelled alone and you know, the rules of nature prevent you from joining unfamiliar people. I was flying and I came across you. I immediately noticed that there was something different about you though.

- Yes, I am different... I always have been and always will be. Every day my peers are born, travel, hang out and die all in the same way, like a cycle that repeats itself endlessly. And I am not.

- Don't you like to travel?

- I've seen too many lands now, but that's all I have left. I love to travel, of course!

- I like it a lot too! From above we can see everything and even the air seems different. And then you are a cloud... It must be beautiful! I have always seen your figure as something so serene that it could reach the seventh heaven.

- Are there really seven heavens?

- I certainly don't know, but you cloud, so immense, must have already reached it who knows how many times!

- I'm sorry to disappoint your expectations, but I believe that there is only this blue sky and I think that sometimes it's more than enough. And it's the sun that lives joyfully and peacefully, not us. In fact, even our presence alone sometimes destroys this harmonious balance. We are seen negatively even in our most delicate moment: death.

- You clouds... Are you dying?

- Of course!... Or at least the others, I can't. I'm different and I've never understood why; I simply gave up and I don't care to understand why anymore. I've been sad for too long now; the only thing I need now is a little serenity.

- Sorry, I didn't mean to...

- Don't worry, in fact, it's been a long time since I spoke to anyone. So you're lonely like me?

- Yes, I've been looking for my flock for a long time and I think I've figured out where it is. When I was little I remember that during this period we always flew over fields full of flowers and I seem to remember the road.

- If you want I can help you find them. In all these years I have seen many flocks migrate.

A bird and a cloud, together; a couple never seen before, but I needed her help and I too could offer her a wing to lean on and let herself be carried.

Suddenly its companions began to move in the sky, too quickly to understand what was about to happen. Then the sun's rays vanished and I realized that it was about to rain. I waved goodbye to the cloud and went to hide to avoid getting wet.

Would I have found it again?

The rain continued to fall, never stopping. I could not allow this storm to kill my cloud too. If she died, how could I return to my flock? I came out of the shelter I had found, took courage and started again towards the sky. I saw her hidden among the others, but as soon as I called her she did not answer.

Every time I managed to separate the smallest cloud from the mass, it seemed to me that if I looked away even for a second, its boundaries would extend further and further, so that I would never be able to find it again.

One of its kind was slowly crumbling until it dissolved.

In her place another appeared, young, pure, beautiful, who allowed a ray of sunshine to pass through. It reached my little black eyes and I couldn't see anything anymore, but I didn't want to stop; what if my cloud had really disappeared? Maybe now it would be happy, but I would be alone. I kept going forward, but I didn't know where to go. I tried to call her, but in vain, she couldn't hear me. I decided to enter that mass. I tried to go beyond the walls that separated the clear sky from the stormy one. The ray of sunshine had softened by now, but I still struggled to see. Despite this, I passed the cloud and found myself as if on a white carpet. Here there were no more turbulent noises, only peace.

But I did manage to perceive a sound. At first, I didn't understand what it was and I tried to get closer to distinguish it better, the more I flew, the more the sound grew.

I collided with something: soft, almost transparent, like a soap bubble. It was cool and now my vision was clear, the pain was disappearing. I finally recognized that I was inside a cloud. I didn't know which one, but something distinguished it once again: that sound.

I looked around with difficulty and saw something. I froze.

- It's you?

I hear that noise again, that sound that is only ours and that distinguishes us from each other. They say that we will all return to a point since we started from there.

The heart.

A more intense part; muffled noises as if there was a war going on above the sky, and everything moves and everything is destroyed. Who knows if like a real heart, it feels something and if it can really die; can such beauty end?

I was inside the cloud and suddenly, like a drum that resonates, invading the whole room, a noise tore the sky. A small part of the heart of the cloud had opened, letting a ray of light pass through, maybe a flash. For the first time, the centre of the cloud was expanding and the grey seemed darker, the noises were no longer very muffled, and the whole cloud seemed heavier and darker. It was as if its innermost part was taking its place as if it was destroying it from the inside.

A cloud's life lasts only a day, but she was special; all her life she spent her time watching her peers being born, only to dissolve as they appeared. During a storm she was the only cloud that was still white; she couldn't die. Day after day she accumulated inside herself everything that prevented her from going away with the other clouds; her heart was actually what was killing her. There was no cure or at least no one had ever thought of it, time simply passed and the cloud was unhappy.

Another sound broke the quiet and then silence.

- We have to hurry if you want to get back to the flock.

- What's happening to you?

A situation like this could only be explained with two words, beautiful for some, and devastating for others.

- I am dying!

...

Another thunder preceded by a flash that pierced another piece of the heart.

- You can't die now, no! It's too soon!

- I think after all these years it's time, don't you think? But don't worry, I'll help you find your family before this is all over and I can't hear your voice anymore.

I began to fly with all the strength I had in my fragile wings and the cloud watched all around with the little strength it had left.

I can never be grateful enough to her; what have I done for her? Nothing! I promised myself to help her, but I am just a simple swallow who can't even stay with her flock.

- I will never be able to repay you... - my thoughts came to me spontaneously.

With a sweetness comparable to that of a mother, she turned, looked at me and smiled.

- What are you saying? You have made me the happiest cloud in the whole sky! You have been close to me, you have been a friend to me and for this, I thank you sincerely. Now you have to go back to where you came from and be with who you belong. Your family is there, flying, beyond those fields and that little hill! Hurry up!

- Thank you!

I could say so many things, but sometimes a single thank you can sum them all up. I smile at her too and fly away, as fast as I can before my mind, too full to be the head of a simple bird, makes me change my mind.

I fly, I fly, I fly, I cross the fields and now the hill is behind me, as is it.

I hear a storm in the distance. It breaks out turbulent, strong, like a desperate cry, but in reality, it is a cry of joy. My cloud is dead and has finally managed to give space to its heart and its happiness.

A faraway place, different and that will surely see me differently.

By flying I can go wherever I want, all it takes is a flap of my wings, a current of air and I find myself here again.

The days were shorter, the evenings cooler and it was time for a change of scenery. A warmer country was waiting for me, was waiting for us; finally, I had a flock, a family, someone to count on. Before that, someone was the cloud, my cloud. We helped each other to be and understand, even if not everything, at least a part of the meaning.

A bird and a cloud, together; a couple never seen before, but a fantastic couple.

Ignorant knowledge

He was laughed at and mocked by everyone. Not because he was in conflict with the society he lived in, but because he was born with an irrepressible, insatiable desire for knowledge.

A problem?

- Come back soon my son! Come back soon!... - repeats the mother.

- Don't worry mother, I will come back and tell you my adventure in the most beautiful words you have ever heard.

And so it was that in the twelfth year after the founding of the colony, little (or big depending on your point of view) Scott left, leaving behind not only his family, but also the mockery of his companions.

He travelled many, many kilometres alone, risking his life several times and meeting the most varied and friendly creatures, but for this he had distanced himself from his very large family, not listening to the advice of his peers. Despite this, fueled by the desire to know and understand, Scott crossed roads and cities, passing through seas and deserts, seeing landscapes that seemed to be shaped by the expert brush strokes of the most talented of artists, skies as still as if they were plastic and storms provoked by the angriest of gods.

After a long time, he finally arrived at his destination: a palace that to call enormous would have been reductive, fascinating, and wonderful. He heard about it from his grandfather who had been there before him and, before dying, he described it to him in great detail, briefly, concisely, but absolutely precisely: - It is large, very large, of a single, sad and dull colour, but with unparalleled complexity and structure!...

Scott, overcome by euphoria, ran in as soon as he saw it, thinking how wonderful it would be to tell all of this to his peers who were laughing at him, seeing expressions on their faces that were trying, but failing, to hide envy; and he faced his fate head-on. Once inside, Scott found no one. - Hey... Is anyone there? - he kept repeating loudly, but nothing, dead silence, almost disturbing; until a shadow in the distance began to walk towards him, slowly he could see the silhouette of a man, visibly old.

- What are you doing here? - he asked in a reprehensible tone. The man immediately struck Scott as an ignorant person, without a brain or almost; a cold person, capable only of following the orders of those who seemed to be greater than him. In the colony, he certainly held an unimportant position, exploited and ridiculed by people who believed themselves more intelligent and had higher positions than him.

- Um... good morning! Sir?...

- I'm Scott! I've been on the road for a long time and this is my destination.

Scott was shrewd: his experience in the colony had taught him who to trust and who to be wary of, who to talk to and who to avoid. He was highly persuasive and brilliantly reasoned, but in spite of this he was considered by society to be nothing more than a work machine! His superiors said harsh words that marked him every time indelibly as if they were coffee stains on his silky soul. Although he loved knowledge, and

the search for beauty even in the most common things, he was not understood by any member of the colony. He was like everyone else, but so different.

- Why are you here? Business purposes? - asked the old man.

- No!... It's something much more important.

- What is more important than trade and money?

- Something is important only to those who truly believe it is, and for me, trade is not.

- Then why are you here? To waste time? - the old man asked gruffly.

He was certainly a simple being, almost too simple; he did not in any way arouse any desire to know him, he seemed sad, gloomy.

- No! I am here to learn and I thank you very much Mr. without a name, because thanks to you I was able to understand.

- What?

- It is not easy to explain it with the hurry you seem to be in, but still I try. This whole palace is what you have to understand, each piece that supports it has been placed according to a specific logic and order, each person has worked on it with care and skill, fitting, welding and screwing millions of small pieces together to make up a single larger one. It seems like a wise metaphor for life, brick by brick, placed evenly to form a wall, but what you need to pay attention to is not the goal to be achieved, but the method you need to follow.

- Are you always so philosophical? I, and with me the whole colony I am sure, see nothing extraordinarily interesting in this building; it is just a pile of iron and cement with no reason to be here. You, on the other hand, try to see another picture, to follow another reality. I ask you why you are here and you answer to me "to know"; you compare life to working in the colony; and what do you mean then by "I want to understand the complexity?" Of course, you are so strange! But where do you live?

- How easy you make it! I am not so different, except perhaps for fears: what frightens me is that there may be another reality that we can neither see nor understand. After all, can you tell me who built all this? Who dreamed it and managed to make it real, perhaps having to overcome insults, mockery, and ignoring the envious ones who induced him to abandon everything because he would fail anyway? The ants are too small, not only physically, and I will probably never be able to understand the meaning of all this, of me, of the anthill, but I will just look at it, admiring in my own small way the immense beauty around and that of asking questions that most of the time are not really answered.

- You are such a strange ant, you know? You risk your life unnecessarily to see an anthill... Bah, so silly!

- It's not silly or even useless! - replied Scott. - To live without feeling curiosity, that is useless, to merely stay in the comfort of one's home without ever challenging oneself, without discovering what one's potential might be, that is useless! In life, perhaps, there is nothing to truly fear, only to understand. And now I think it is time to return.

- You're right, I'm sick of hearing you babble things like that!... Goodbye, it's time for you to go.

Leaving that gloomy man behind him, Scott walked out of the palace and went home, thinking how wonderful it would be to be able to tell all his new discoveries to his mother and to all those who always belittled him before he thought, acted, left. He was proud to be able to return with his head held high, without the fear of being laughed at, because he had understood that he was not inferior to anyone and he had also understood that complexity must remain unknown, unknown, because life is ultimately so simple when you are grown up, but complex when you are small and looking for meaning. Perhaps without complexity, we would all be grown up, bored and depressed, just like the old man in the wonderful palace, big, very big, of a single, sad and dull colour.

The eyes of the Moon

The little one, comfortably perched in the centre of his nest, on the highest branch of a majestic oak tree, was observing the clearing below, in a relaxing silence that was abruptly interrupted by the shrill call of his mother. - Joy, I'm home!

The son turned and exclaimed, "I said you wouldn't come back. It's almost evening!"

The sky was becoming coloured with increasingly dark and deep shades, through the thick foliage of the oak tree one could see the soft shades of red that coloured that immense expanse of a clear blue; thin rays of light crossed the thick foliage, hitting some points of that complex intertwining on which the two birds were located.

- I'm sorry darling, I hope no one bothered you while I was away - said Lily worried that some bird of prey in the area had disturbed her little one.

- No, Mom! Everything is fine, no one has come near - the mother sighed with relief, happy to see that the shelter she had built had proven to be effective and safe.

- I'm happy to hear that. Now come here! - Lily urged him, who in the meantime had placed some small twigs in front of her. Joy looked at her perplexed, not understanding her intentions; she, seeing his confused look, approached him saying - I recovered these twigs, we will need them to make our nest safer and more resistant; we need to protect ourselves from birds of prey and bad weather, my little one.

Joy watched her mother with admiration, happy to be able to help in the difficult construction of their home; she began to weave the small branches with her beak, under Lily's careful supervision.

She looked dreamily at her son and his enthusiasm in carrying out that simple operation, remembering the period during which she too had felt that feeling of curiosity: she remembered how her mother had taught her that art passed down from generation to generation, how euphoric and impatient she was, eager to know as many things as possible about that immense world. She also remembered with a sweet smile how she tended to make numerous mistakes that forced her to repeat the work over and over again. Her goal, therefore, was to teach her son not to be carried away by emotions, but to act rationally, paying close attention to every detail of that procedure, so as to be able to create a shelter and a stable refuge for his family.

Joy was so focused that he didn't notice the passage of time; when he raised his eyes from the dense tangle he had created, he noticed that the sun had disappeared, giving way to a dense expanse of stars, among which stood out an enormous ivory-coloured sphere. Every night he saw it, up there, imperturbable, he admired it, enchanted by its beauty and by the sense of inferiority and impotence he felt in front of that vision. How high could it be? How far does it go? What could be seen from up there?

He stood there contemplating her for several seconds, enraptured by her presence; then, suddenly, an idea crossed his mind, a question that had been tormenting him: what would the work he was working on look like when seen from up there? The little bird tried not to think about it, but that question continued to haunt him, his curiosity had to be satisfied; he couldn't wait to be able to observe his nest from above, he felt extremely useless and limited, he wanted to be able to glimpse every detail of what he was creating, he wanted to see how his companion who emerged each night into that sea of stars saw the product of his hard work, he wanted to see it through his eyes.

Joy then began to fly, she flew high, and through the wings of her mind, she observed how everything she was used to seeing a few meters away had become smaller and smaller, tiny until it was just a simple point of colour, similar to those bright and small signs that coloured the darkness of the night skies.

After a long journey, Joy reached his destination. Stunned by the vision that presented itself before his eyes, he could not believe he was so high. He let his gaze wander over all those small and different subjects that were below him, not knowing where to focus his attention. Then he recognized the thick foliage of the oak, his oak, and further down he saw it, he saw his home and in front of that vision, he was amazed, almost speechless; to anyone it could have seemed like a simple tangle of branches, but for him that was the result of his own commitment, of his own effort. He even managed to see his mother resting, the small fruits hanging from those fragile leaves of the branch that supported her nest, the branches of different sizes that joined almost as if they were a single large body; he was amazed to notice the complex plot that had been created and he realized that, from inside that intricate labyrinth, he had never seen everything that he now had the opportunity to observe.

Suddenly a deep sense of melancholy enveloped him, as he realized that he would never have the chance to see that vision again once he returned to earth and once again he felt helpless.

Joy, however, decided not to let herself be carried away by her bad mood; instead, she chose to make the most of that moment, to glimpse everything that she would no longer be able to see once she returned home. She concentrated on every detail, little thing, finishing touch, trying to capture as many particulars

as possible. After a while, however, he huffed: he still could not see everything, could not register in his mind every little facet of what he was observing; each time he noticed that he had missed something, an extra leaf, a small hidden branch... So she decided that the time had come for him to return and slowly retraced his steps, arriving at his beloved nest.

- My little one, is there something bothering you? - Lily's voice woke him from his thoughts.
- Mom, have you ever been to the moon?

Lily turned around with a surprised and confused look. "What are you asking me?" she exclaimed, giggling. "It's not possible to reach up there, not even with our strong wings! Why do you ask me such a thing?"

Joy thought for a moment - I was thinking, I wonder what it must look like from up there? I wonder how small it must be?

The mother smiled at her son's naivety and did not answer those absurd questions; then she turned her face and returned to paying attention to a pair of small twigs that she was busy intertwining.

Chapter 4

Introduction

In the previous Chapter, I started to address the theoretical construct formulated in the first Chapter, concerning the link between physics epistemology and identity development. Grounding the reflection on the empirical data collected within the project “Physics of clouds”, I provided a contribution to the initial Research Questions and I found a name to the theoretical construct: *personal-epistemological consonance/dissonance*.

The data analysis illustrated that the epistemology of complexity represents a good candidate for activating a link with identity issues, as the scaffolding role of “spatial structures” of complexity showed. At the basis of the choice to focus on complex systems, there was indeed the belief in the richness of their epistemology, specifically with respect to space and time. As discussed in Section 1.2.1 of the previous Chapter, the features of these systems strongly question the idea of time and space as we are accustomed to conceiving classical physics. When studying such systems in fact, new spatial and temporal structures emerge, due to bifurcations, emerging properties, etc.

Within “Physics of Clouds”, the teachers mostly emphasized discourses related to spatial structures, such as the role of local interactions or global emergent properties, as well as the diverse possible perspectives related. At the conclusion of the last Chapter then, I wondered whether also the **temporal structures** embedded in complexity could act as scaffolding for episodes of consonance.

Thus, the objective of this Chapter is to investigate the potentiality of complex systems' temporal structures to activate a consonance with identity-related aspects and what personal issues may emerge connected to time epistemology. It is also examined to what extent specific choices at the basis of the activity may create the necessary (but not sufficient) conditions for such consonance (or even dissonance) to be established.

This Chapter is divided into 5 sections.

Section 1 is devoted to a brief overview of time conceptualizations and strategies of time management, mostly recalling from the sociology of time.

Section 2 recalls the formal discussion of complex systems done in Section 1.2.1 (Chapter 3), focusing specifically on the temporal structures conveyed by the complexity paradigm. Section 2.2 reports the formulation of operational markers able to distinguish between the Newtonian and the complexity time, which originated within the master thesis of V. Ilari (which I co-supervised), who also actively collaborated in the Kairòs project.

In Section 3 is described the project (Kairòs) and a little follow-up activity (ONSCI), again elucidating design choices and related motivations, the disciplinary contents and details about the implementation. There is also a discussion of post-implementation reactions, taking both from the teachers' interviews and students' feedbacks. The second part of Section 3 is then dedicated to presenting the steps of data analysis.

In Section 4 the outcomes emerged from data analysis are discussed, illustrating how the findings from single analytical steps have been interpreted and evaluated in a comprehensive way.

In Section 5 the conclusions are drawn and the Research Questions are addressed (see the Figure below for a general overview of the Chapter).

The description of the design and the implementation of the project have been presented within the SIG5 symposium at the last ESERA Conference (<https://www.esera2023.net/>).

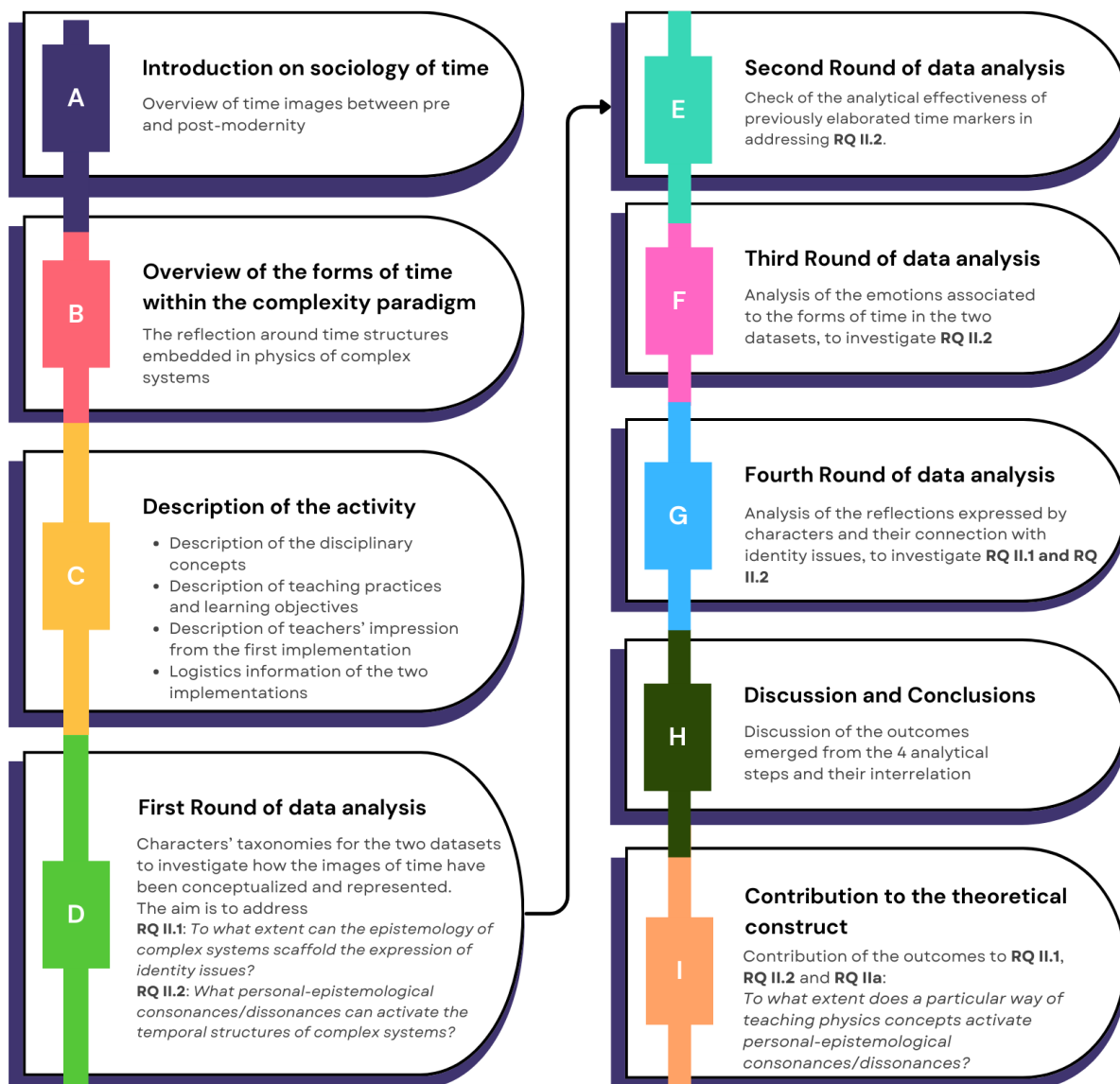


Figure 1: An overview of the parts of the Chapter.

1. Time from pre-modernity to late modernity

In pre-modern societies, time was intimately connected to natural rhythms and cycles, and it was perceived as something intertwined with the natural world, the cosmos, and the spiritual domain (Adam, 2006). Time was measured in terms of natural phenomena and events, such as the position of the sun, stars, the seasons, the alternation of day and night, and life and death. Moreover, the relationship to time was largely "task-oriented," meaning that work and daily activities were organized around the completion of tasks rather than adherence to a specific, measured timeframe. In addition, pre-modern time was usually linked to the sacred and the communal. Religious and mythological frameworks often provided the primary understanding of time, something both cyclical and eternal at the same time, repeating under divine orders.

This led pre-modern societies to develop a sense of time as something cyclical, linked to seasonal and daily agricultural cycles, and with a strong religious connotation (Thompson, 1967). Such a time was not meant to be measured nor to be controlled.

Then, with the industrialization and modern era, time shifted from being nature-related and task-oriented to being linear, standardized, and deeply intertwined with technology. The spread of industries raised the need for synchronized time across different locations to ensure the smooth operation of factories, transportation systems, and markets (Galison, 2003; Thompson, 1967). Regulation of work and workers became of crucial importance, hence the need to measure time and the consequential spread of clocks. The urgency of time synchronization across vast distances led to huge technological improvements, resulting in revolutionary technologies such as the telegraph and the railroad. As a consequence, these technologies were revealed to be essential for managing global empires, showing the political nature of time control.

Nonetheless, the need for time-synchronization brought to a profound philosophical and epistemological questioning of the concept of time itself (Thompson, 1967). Opposite to pre-modern time, modern time is linear, characterized by a forward progression that is divided into measurable units crucial for technology and logistics. Unlike the cyclical time of pre-modern societies, modern time is seen as a resource that can be spent, saved, or wasted, aligning with capitalist values of efficiency and productivity (Adam, 2006). As argued by Urry (2009), modern time became the "clock-time", a kind of time more similar to space, measurable, invariant, reversible, and detached from previous natural and supernatural connotations. The modern time has been abstracted, standardized, and integrated into the structure of modern life. It is no longer just a backdrop to human activities but a central element that structures and governs social, economic, and political life. The shift from natural, cyclical time to quantified, linear time reflects the broader transformations of modernity, where efficiency, synchronization, and control have become paramount.

With the transition from modernity to late modernity, time and time management strategies have changed again. Particularly relevant is the reflection carried on by Hartmut Rosa about the acceleration of post-modern society (Rosa, 2010; 2013).

In his critical theory of time in late modernity, he defines society as the "*society of acceleration*". Acceleration is accused of being an insidious totalitarian time regime, as while appearing as completely natural it is instead altering how individuals relate with each other, with space, time and their way of

“staying in the world” (Rosa, 2010). Quoting from Lübke (2009), Rosa argues that there is a constant shrinking of the present time, the only temporal period during which we can find a sort of orientation, make evaluations, and develop expectations (Rosa, 2010). Present rapidly becomes anachronistic, transforming into past - *what does not hold anymore* - and future - *what does not hold yet* - rapidly becomes present.

This is boosted by technological acceleration, which with the false promise of saving time doing the same tasks in less time, demands to do much more than before, with a paradoxical consequence. Coupled with the fall of the afterlife’s promise (late-modern humans are more and more willing and encouraged to satisfy their desires in this life) and the increased capitalistic competition (late-modern criterion to allocate resources such as money, power, friends, family, status...), technological acceleration ends up accelerating life rhythms. The consequence is an accelerated life experience, where changes occur faster and faster but are frantic and fragmented, with a non-clear direction. The very concept of identity is profoundly questioned then. If modern humans based their sense of self upon pillars such as work (getting a job and doing it for a lifetime), a family (getting married and staying together until death), a house (buying a house and never moving out), assuming stability over at least a generation period, late-modern people are asked to reconsider this plan as the pace of change shifted from *inter-generational* to *intra-generational*. Identity then becomes *situational* (Rosa, 2013), with the tendency to live as many experiences as possible even though they do not add up towards the same life direction.

The time authoritarianism of late modernity, as Rosa claims, deludes individuals into believing they can achieve their dreams, when the acceleration itself is what is preventing them from doing so, by replacing the idea of life projects with the principle of fluidity. The goal implicitly imposed is “being competitive enough to pursue a project” rather than actually pursuing an objective.

The most urgent outcome provoked by acceleration is for Rosa the spread of *alienation* from time, a de-synchronization pathology (Rosa, 2010). Building on the work of scholars such as Giddens and Marx, Rosa interprets the technological and social accelerations as the causes behind different forms of alienation: i) from space, as we change place more and more often, preventing us from establishing an intimate connection with spaces; ii) from objects, as we use them without knowing how they work (because they are increasingly complex) and preferring substitution to repair; iii) from our agency, as more and more options for everything (insurances, restaurants, travels) require to make more and more evaluations for which we do not have time, hence we do alienate from our ability to evaluate; iv) from the others, as we get to know more and more people that we end up being saturated and detaching from strong and deep connections (Rosa, 2010).

However, the most interesting kind of alienation for the reflection of this Chapter is the alienation from time. Quoting Walter Benjamin, Rosa recalls the difference between the German terms *Erlebnis* and *Erfahrung*. *Erlebnissen* (plural) are episodes which seem never-ending but leave little trace in the individuals (long-short episodes) whereas *Erfahrungen* are episodes which seem to run away but leave a profound trace in the individuals (short-long episodes). Alienation from time in this sense means that late modernity is dominated by short-short happenings, which run away faster and faster because of the shrinking of the present and still do not leave traces in the memory as we struggle to make sense of them. As Levrini and colleagues comment: “*Time seems to escape from both the sides: it goes fast, and it does not leave traces in the memory. Consequently, the episodes of present remain alien. We are not able to appropriate them and make them “ours”, in the sense we are not able to turn them into events that are*

significant for us" (Levrini et al., 2021; p.5). This kind of time appears meaningless and directionless, hence is not an *appropriated* but rather an *alienated* time (Rosa, 2010).

Given that we use our relation with actions, objects, space, time, and others to develop narratives of ourselves, these many forms of alienation result in an alienation from ourselves too. Rosa indeed recognizes *identity* as determined by the capacity to *appropriate* the world (made of people, places, episodes, etc.). Alienation instead provokes the dissolution of identity, which becomes situational, as we deactivate our "axes of resonance" (Rosa, 2019) with the world around us.

Time and identity

Thus, identity development is strictly correlated with the way we deal with time. The feeling of the present's contraction, frenetic standstill, and the experience of directionless episodes, inform how the individuals create narratives of themselves (identity development) in the space-time structure (Levrini et al., 2021; Rosa, 2013). As evidenced in a work inquiring about time management strategies for upper secondary students in Denmark (Ulriksen & Nejrup, 2021), the conceptions of time influence time management options. Sometimes time can be more conceived as a quantity, sometimes as a quality, and according to the case, it activates different ways of dealing with it. Surely, time is "far more than a one-dimensional quantity" (Ulriksen et al., 2021; p. 181). That is to say that, to my opinion, the emergency of *time alienation* raised by Rosa is crucial as it may be faced, and not irreversible. If the issue appears to be an alienated time management trend, an option could be to work on the time images. Given that present common time images lead to widespread examples of *alienation from time*, why not suggest alternative time images, which may lead to *appropriation of time* rather than *alienation*?

In the next section, I present alternative time images originating within the study of complex systems. These time images were at the basis of the activity further described and analysed, whose goal was indeed to introduce a reflection about the possibilities for *time appropriation*.

2. New forms of time

As seen in the previous Chapter, complex systems and their features brought to a deep epistemological shift from the classical newtonian physics. This holds for space-related issues (the role of interactions, the global emergent properties, phenomena of bifurcations) but also for time structures. I thus (Section 2.1) discuss the link between time and the complexity paradigm, mostly recalling from the notable reflection done by Ilya Prigogine starting from the '80s.

In the second part (Section 2.2) I briefly outline the work done by V. Ilari as a way to introduce the time markers elaborated in her thesis and considered in the following data-analysis.

2.1 Structures of time of complex systems

In Section 1.2.1 of Chapter 3 I described some examples of complex systems, focusing in particular on the new aspects they embed, which questions the primacy of classical physics pillars such as reversibility, linearism, etc.

Recalling the discourse about the bifurcations, for instance, I showed how dynamical systems out of equilibrium may present new emerging solutions other than the thermodynamical solution. In this sense, the bifurcation breaks the symmetry, hence modifying the space (even if it is not a proper space but a “space of the solutions”). Nonetheless, limit cycles, bifurcations or even deterministic chaos lead also to the development of new temporal structures.

The Van der Pol model or the logistic map are good examples in this sense. Indeed, the solution of Van-der-Pol equation is represented by a limit cycle, representing an asymptotical stable state for the system. A cyclical temporal structure then emerges.

Also in the logistic map seen before, beyond a specific value for the control parameter $r \approx 3$ the system starts to oscillate between a number of solutions, which increases as the parameter increases.

With $r < 3$, the system is uniquely determined in its evolution, hence reversible. With the raise of bifurcations instead, the system starts oscillating around different solutions, and the linear time evolution is replaced by a cyclical loop structure.

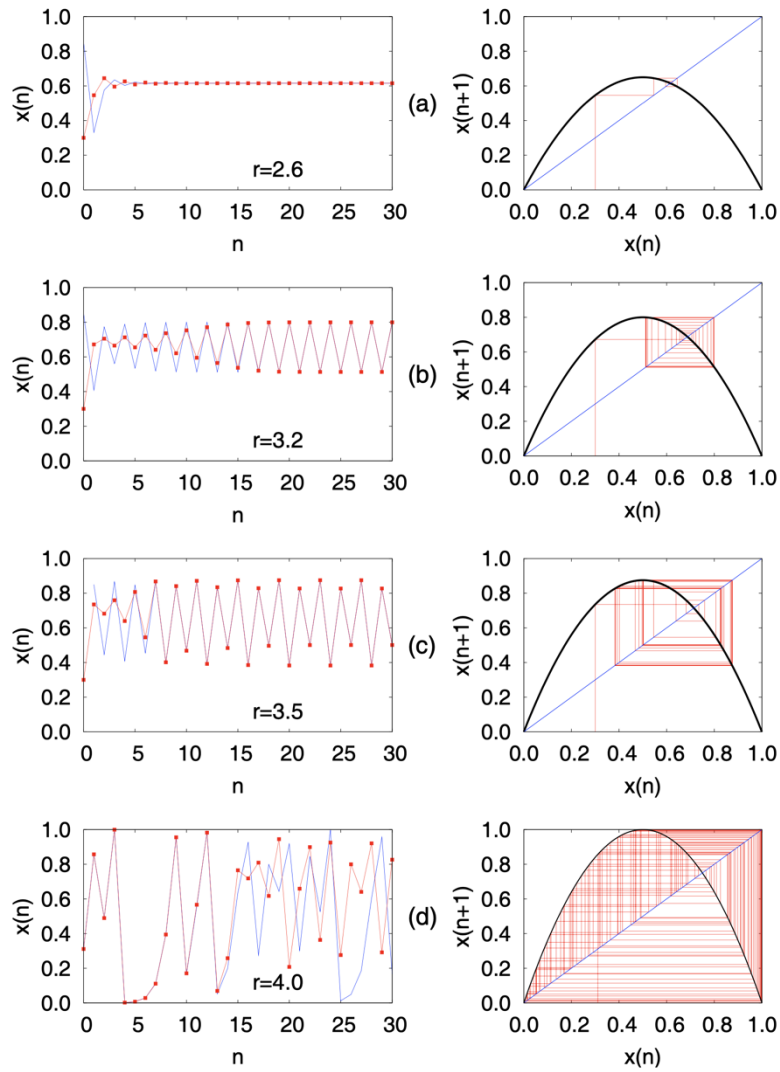


Figure 2: On the left the value of x at different time-steps “ n ”. As the control parameter exceeds 3, the system starts to have a periodical behaviour, with increasing modulus (on the right), until it reaches a chaotic behaviour ($r=4$). (From Simonetto, 2023).

With $r < 3$, the system is uniquely determined in its evolution, hence reversible. With the raise of bifurcations instead, the system starts oscillating around different solutions, and the linear time evolution is replaced by a cyclical loop structure.

If we consider the case of Bénard cells, an example of the pitchfork bifurcations seen previously, the instant at which the cells emerge is a crucial one, as it marks the transition from reversibility to irreversibility. The phenomenon hence destroys time homogeneity, creating a “before” and an “after”.

Following Prigogine reflections (Prigogine, 1980; 1997), the emergence of irreversibility as a new time feature or the emergence of cyclical forms of time (limit cycles) witness a sort of dualism in the temporal description. There is an “*external time*” governing the equations, reversible, homogeneous. On the other

hand, when dynamical non integrable systems (as the ones seen above) detach from the equilibrium they present new behaviours which claim for another kind of time. A kind of *“internal time”*, eradicated in the phenomenology of the system out of equilibrium. As Ilari (recalling Prigogine) correctly points out, *“external time is a parameter t that represents a quantity that can be measured with the clock, internal time is defined as an operator that takes into account the structural and irreversible change of states of a system”* (Ilari, 2024).

Such phenomenology is central for Prigogine, as it is constructive of new forms of life, new destinies for the system. As he states: *“for a long time such phenomena were excluded from the fundamental description of physics. All time-oriented processes were considered to be the effect of special, “improbable” initial conditions”* (Prigogine, 1980; p. 12). Though, he claims for an inversion of the logic, considering homogeneity and reversibility as “special cases” within a description which prioritize the realism of these emerging spatial/temporal structures.

Quoting the work of Poincaré about integrability of dynamical systems, Prigogine highlights that most of the dynamical systems are non-integrable because of resonances in the degrees of freedom, which do not allows the computation of trajectories. This problem goes under the name of “small denominator problem²¹”, first noticed by Poincaré (1899).

Despite KAM theory (Arnold, 1963) partially overcame the “small denominator problem”, resonances in the system and persistent interactions among the constituents forces us to abandon a determinist description in terms of trajectories but rather embrace a statistical one. Nonetheless, a statistical description satisfies the “realism” requirement as it allows to include the non-negligible phenomenology of irreversibility, as in diffusive behaviors (Prigogine, 1997).

Taking the premises from thermodynamical out-of-equilibrium systems, Prigogine builds his argument demanding a new comprehensive mechanical theory which includes irreversibility as the norm and reversibility as an extreme case. Parallel to irreversibility and reversibility stand the two kind of times suggested by Prigogine, *internal* and *external*. Indeed, the classical spatialized kind of time (external) ceases to apply in complexity since, with the formation of dissipative structures, the internal dynamics of systems can destroy the homogeneity of time, as well as the homogeneity and isotropy of space.

The project of Prigogine was indeed to unveil that what seems a forced shift from trajectories to statistical distributions, as in the case of thermodynamics, was instead a chance to go beyond an outdated approach, which relegates emerging phenomena - “episodes of life-creation” - (Prigogine, 1997) to theoretical shortcomings. Furthermore, these new temporal structures push for the consideration of also an *internal* kind of time, grounded on the systems’ features. It is evident the inadequacy of the universal temporal structure conventionally measured by the clock (the ‘external time’) in describing the qualitative changes in the evolutionary states of a complex system.

This dualism is suggested to overcome the primacy of the “alienating” (Prigogine, 1997) reversible and homogenous time as it does not leave space for anything new, without proposing at the same time a totally randomic kind of time (also alienating).

²¹ A mathematical formulation can be found in Appendix C.

2.2 Markers for time

One of the objectives of Ilari's master thesis was to resume the main features of the two kinds of times, *internal* and *external*, as conceptualized by Prigogine, and use those to read social times. In particular she was working on essays written by two samples of upper secondary students, which seemed to display two diverse images of time and issues related to *alienation* and *appropriation* of time (see Ilari, 2024 for further details). Thus, we proposed to develop operational markers to help us out characterizing what was emerging by the essays.

We developed markers associated to the features of *internal* and *external* time with the help of two nuances of ancient Greek times recalled also by Tonelli (2021): *Chrònos* (the chronological time) and *Kairòs* (the time of chance). Thus, we tried to transpose them from physics into *sociology of time*, and use them as lenses (with related markers - Table 1) to inquire students' perception of time.

These markers have been then used to analyse the two samples of essays from students (see Ilari, 2024 for more details about the essays) and were intended to be used also for the data collected within *Kairòs* implementation, described from next section onwards. In Section 3.3.3 I show the outcomes of using these markers on the new data.

Internal time features	Features description	External time features	Features description
Time of Irreversible trajectory	Life is created because there is a before and an after separated by a critical moment. You have a moment when you resonate with a noise within the system and create the conditions for a new future structure: a change is created. E.g. "Now the time has come to make this decision..."	Time of the reversible trajectory	It is time that regulates movement in homogeneous space-time. Assuming reversibility, it is a movement that does not create history, that does not create life. E.g. 'I'm going on with my day, everything's fine, nothing new'.
New and non-homogeneous structure	A new time is created within the phenomena, which causes a discontinuity in the regularity and the homogeneity of time. It is a structure susceptible to change. E.g. "something happens that disrupts my life".	Modular and homogeneous structure	Time is regular and divided into homogeneous modules. There is no qualitative aspect of time therefore. It is an invariant structure and not susceptible to change. E.g. "my days flow like this"

Structure internal to events not regulated from outside	It is the characteristic time of the system. The event is characterised and not put in an order with the others, there is a quality given to the event. E.g. "I take my time to do this".	Conventional structure which organizes events	External time is a conventionally constructed structure outside events. It serves to organise/plan the events of the day. E.g. "from 9 a.m. to 1 p.m. I have a commitment, then I have a one-hour commute, then I have a visit to the doctor, then a coffee with a friend of up to 1 hour, etc.".
Time actor	Time seen as something that can be determined. Perception of the ability to create a direction, a future. Eg. "I feel I know what I can do with my time".	Spectator of time	Sense of strangeness to time, seen as something that exists to which one looks on from the outside. E.g. "Things happen and I can only watch". "Everything goes by so fast and I don't know what to do".

Table 1: Markers for external and internal time developed by Ilari (adapted from Ilari, 2024). Four features have been identified, showing how they vary between the two kinds of time. Three markers refer to the time-structure, whereas the last one refers to the observer. Furthermore, since these are intended to be operational, examples of sentences that could be coded with the related category are given.

3. Kairòs (“*La sottile deriva dei giorni*”)

The “Kairòs” project was an interdisciplinary activity between physics and literature and conceived as a follow-up of the project “Physics of Clouds” merging concepts from the physics of complexity with creative writing. The same two²² teachers involved in the previous project designed and conducted the activity, in the same school and with the same principal still in charge. So, the cultural frame is still like the one described in Chapter 3, even though this time there was a shift both in the contents addressed and in the techniques used for the writing part.

Kairòs has been conducted between March and May 2023, involving a class of grade 10 at “Liceo Scientifico A. Einstein”, composed by 12 males and 12 females between 14 and 16 years old. It is worth to mention that the project was done within the curricular hours, mostly SM’s ones but also borrowing some hours from the chemistry and physics teachers of the class. The choice to use curricular hours is to reinforce the idea that it is possible to leverage formal education not only to learn concepts but also to develop instruments to live and navigate the present society. Indeed, by highlighting the concept of time from the perspective of physics and literature, the teachers wanted to engage students in reflecting about the many ways we have to think about and manage time, hence treating disciplinary concepts to transform them into helpful *lenses* for students to make sense of the *accelerated* world (Rosa & Trejo-Mathys, 2013; Erduran, 2023; Rosa & Trejo-Mathys, 2013).

The first part (lectures and experiments of physics plus an introduction to the writing part) lasted around 9-10 hours, while the writing spanned over diverse moments within literature curriculum hours (in May) but also continued at home. The design was guided by the two teachers in collaboration with prof. Olivia Levrimi.

For the physics lectures also Veronica Ilari was involved in the design. In addition, the physics teacher - Nicola Ialeggio (later abbreviated with NI) - and the chemistry one – Daniele Ridolfi (later abbreviated with DR), have been involved in designing part of the theoretical lectures and experiments. A school chemistry technician – Emma Gabellini (later abbreviated with EG) - was included in the design of the laboratory part and she herself did the chemical reaction shown to students.

The structure of Section 3 is as follows. In section 3.1.1 are presented the disciplinary contents at the basis of Kairòs, then in Sections 3.1.2 and 3.1.3 are described the teaching practices and in Section 3.1.4 are reported the class features and outline each single lecture.

In section 3.2 are shown both teachers’ and mine (as an ethnographic observer) impressions about the project, focusing on the reactions of students and other teachers. Building on that, there is a discussion of the second and shorter implementation of Kairòs, which I refer to as ONSCI, which has been done in September 2023 again by the same teachers but with a different design and with different students.

In section 3.3 is finally presented the data analysis.

²² Prof. Paola Fantini (physics teacher) will be abbreviated with PF and prof. Sara Moresco (Italian literature teacher) will be abbreviated with SM.

3.1 The philosophy behind Kairòs

This subsection aims to display what were the intentions of the teachers and how they tried to achieve their goals through the design process and the practices held in the classroom. The narrative that will emerge is the outcome of four different data sources:

- the fieldnotes that I took while attending each lesson of the course
- the transcription of each lesson
- an extended semi-structured interview done about one month after the end of the course with the two teachers and prof. Levrini. This is the same interview mentioned in Chapter 3.
- a presentation of the whole project done by PF and SM to the school's teacher council some months after the project's end (March 2024), also this partly considered in Chapter 3.

3.1.1 The disciplinary concepts

The goal of Kairòs project was to engage students in thinking about time with contents coming from Physics and Italian literature.

This choice is related to a discussion started in the paper “The Present Shock and Time Re-appropriation in the Pandemic Era” (Levrini et al., 2021), of which one of the authors is PF. In this paper, the authors investigate how students were dealing with time during an historical period – pandemic – where space (due to isolation) and necessarily also time (due to the forced changes in routines) were profoundly questioned. In their analysis the authors found that, instead of preparing young people to navigate a rapidly evolving and complex world, school science often isolates learning from broader societal issues by creating “ritual bubbles” that disconnect educational content from real-world concerns (Levrini et al., 2021). Thus, school ends up being a setting which detaches students from society rather than supporting them in finding their positions within it. The paper ends by stating that this represents a missed opportunity for science education to more effectively contribute to students' preparedness for contemporary societal challenges and call for “*designing materials and enacting teaching strategies that enable students to play with their own ideas and make them feel that their personal search for sense is legitimate and welcome also within the classroom culture*” (Levrini et al., 2021, p. 27). In this sense, the Kairòs project, focusing on time, could represent a kind of teaching which supports students' search for sense, given the strong relation between time and identity. An education that presents multiple ways to conceptualize and manage time is an education that is ultimately creating a space for identity development (Rosa, 2010) and make students feel that “their personal search for sense” can be done also at school, through disciplinary contents.

Thus, the idea for the project was to start by focusing on the diverse time-structures which are present in physics, as PF commented during the post-course interview:

“But there are various temporal forms, various temporal structures that science has dealt with and still deals with, that also give you a richness of interpretation here, always in that perspective that we were

saying before ... to be able to experience it personally, to not only, as you say, think about time, but also experience time” (PF).

The images of time in this case were discussed within the big frame of the physics of complexity, because complex systems exhibit time structures different from those of classical mechanics (see Section 2.1 for details), with the aim to question the primacy of Newtonian time image. This was a shared intention by PF and SM, which have developed over the years the sense of students being dominated by the idea of time as linear and passing away, implying a unique way to relate to time.

The objective was to untie students by this single kind of time and engage them in thinking about new forms of time; but also, to create the conditions to relate in a new way (creative writing) to different time. To PF and SM, this operation could lead to develop a larger and more nuanced image of time, hence a richer set of time-conceptualization and ultimately time-management strategies (Ulriksen, 2021), strongly needed in the society of acceleration (Rosa, 2013).

In the following, I present how the physics teacher (PF) used disciplinary contents to trigger the discussion about time, how these contents were reconceptualized with the support of the ancient Greek times and how time nuances were finally merged with contents coming from the literature curriculum of grade 10, specifically theatre.

Complexity and time

PF in the first three lectures settled down the main features of physics of complex systems which can be considered the “pillars” upon which build the discussion around the different time images (similarly to what she did within Physics of Clouds).

Thus, complexity was first introduced from a theoretical²³ point of view. PF explored the difference between complex and complicated systems, using metaphors like a bird's nest and origami to illustrate the idea of complexity as something that cannot be explained or reduced to its components, in contrast to something complicated, which can be instead explained and understood through its parts. In addition, PF continued by highlighting the different scales that are inherent when we deal with complex systems: i) the micro-scale where we can look at the single agent and its features; ii) the meso-scale where we consider the relationship between each agent and its neighbors; iii) the macro-scale which let us focus on the whole system and look at its global properties. This paved the way for the concepts of emergent properties and unpredictability which was discussed in comparison with the predictability and linearity typical of classical systems.

Connected to interactions, PF discussed with students the new kind of causality which emerges from complex systems. On the one hand the interactions between agents provoke the formation of macrostructures and let global properties emerge, but also such global properties can have an impact on the microscopic interactions themselves. Sometimes this retroactive effect inhibits the interactions (*negative feedback*) sometimes it enhances them (*positive feedback*), in a circular causality. PF also connected the “new causality” to the unpredictability that we see complex systems displaying under certain conditions: indeed, for example, by acting on some parameters which characterize the system, the negative feedback effect can turn itself into a positive feedback effect, leading to an unpredictable behaviour of the system. This was discussed both from a theoretical point of view, by using Netlogo

²³ Theoretical here refers to the “theory aspects” rather than the “practical” ones handled in lab sessions.

simulations (Wilenski, 1997), explaining the logic behind the Lotka-Volterra model (Volterra, 1926) and also by engaging students with two hands-on laboratory activities. In the first session they joined the chemistry laboratory to observe a chemical oscillating reaction, where a compound displays a periodic change of colour under certain conditions; this is similar to the well known B-Z reaction by Belousov-Zhabotinsky (see next section for details). In the second one, they dealt with Bénard-cells experiment in which a fluid is differentially heated and above a threshold it displays a cell-like structure, where the cells can be left-handed or right-handed. The choice of such experiments was to let students see how the combined effect of the relationships between single agents and an “external noise” :

- can lead to a bifurcation of the final state into two possible states (Bénard), with the system choosing one of the branches in a totally unpredictable way,
- may let emerge spatial (Bénard) and temporal (chemical reaction) new structures, due to the peculiar kind of interactions.

Greek times

We have seen that complex systems introduce an epistemic shift in learners’ perspective (Barelli, 2022). The techniques of inquiry, the questions, assumptions and inferences which can be made about complex systems are indeed quite different from those concerning the classical mechanics ones. While within classical mechanics we can follow the “chronological” evolution of a system and predict what will happen at a definite time, when dealing with complex systems we must be open to accept also unpredictable behaviors..

Hence the physics of complex systems make us confront with phenomena of irreversibility (bifurcation) or even the rise of periodical time structures (the periodical change of colour in the chemical reaction), which question the linear time image of classical mechanics. Thus, we are surrounded by a kind of time which displays itself in many ways, quoting Steven Jay Gould:

“We live embedded in the passage of time—a matrix marked by all possible standards of judgment: by immanent things that do not appear to change; by cosmic recurrences of days and seasons; by unique events of battles and natural disasters; by an apparent directionality of life from birth and growth to decrepitude, death, and decay” (S.J. Gould, 1988; p. 10)

Reality has unveiled to ourselves as made of different images of time: time as absolute (*“immanent things”*), time as circular (*“recurrences”*), time as a contingency (*“unique battles and disasters”*) or time as a linear direction (*“from life to death”*).

These different “faces” of time remind the ways by which ancient Greeks used to refer to time itself. Indeed, ancient Greeks had four different words to describe time: Kairòs, Eniautòs, Aìòn and Chrònos. Each word was presenting time in a different shape, hence the connection with our activity which aims to unfold time in its multiple nuances. These four conceptions of time have been recalled by the physicist Guido Tonelli within his book *“Il sogno di uccidere Chrònos”* (Tonelli, 2021).

For this reason, PF mapped the concepts of complexity and classical mechanics seen in the first lectures into the four times presented by Tonelli, that from that moment became the references for time images:

1. Chrànos refers to linear, chronological time, marking the measurable, sequential flow of events from past to future. This time reflects the linearity of classical mechanical systems, which respects the paradigm of predictability and a unique causal direction, but also the irreversibility, the time's arrow which is brought into physics by the second principle of thermodynamics. The interaction between the constituents of a system determines a past and a future which are different.
2. Aìon represents transcendent, absolute time or eternity, highlighting time's potentiality before it unfolds into reality. This time represents a "spatialized" kind of time, where reversibility dominates being time just a mere parameter, which does not imply any specific flowing direction. Such time is close to the newtonian systems, such as a ball rolling down of a table, which do not imply emergent behaviors.
3. Eniautòs signifies cyclical time, reflecting the natural recurrences and rhythms of life and the universe, akin to the seasonal cycles and life's inevitable returns and repetitions. But it is also the kind of time that emerges from the oscillatory chemical reaction, the periodical time of the changing colour.
4. Kairòs is described as the moment of the chance, emphasizing the importance of catching opportunities within the flow of time. In this sense it resembles the time of bifurcation of complex systems, the chance for the system to develop a new possible future, due to having reached a critical point. Is the moment when irreversibility starts to appear, where something new, for example cells, emerges.

The ancient Greek times were introduced in connection with physics, to give new words and provide a further "tool" to think about time adopting a larger perspective, as PF says during one of the lectures:

"... it is clear that these (ancient Greek times) are a bit of a forcing, guys (addressing the students), in the sense that they are a bit like... images. This forcing, in the sense of juxtaposing [ancient] Greek times with the times of physics, (is a) forcing in the sense that it helps us to understand that they are different things. But they help us to understand that physics also has many faces of time".

To sum up, first the concepts of physics of complex systems were introduced, both theoretically and experimentally, with the focus of the kind of nuances to time they add with respect to classical mechanics. Then the features of both classical and complex physics were rephrased by using the ancient Greek times: Kairòs, Aìon, Eniautòs and Chrànos. This step was crucial to pave the way for the literature concepts to enter into the playground. Indeed, the italian literature teacher - SM - had to find a connection with the physics topics constrained by the boundaries of the Italian literature grade 10 curriculum, since the whole project was conceived as a curricular activity. She ended up choosing theatre, since "Critics of Theatre texts" is part of the curriculum of grade 10.

Theatre

One link between theatre and complexity is that theatre embeds an intrinsic tension. Indeed it contains an inner dichotomy between the "representation of reality" and "reality" itself, on the other side of the stage. This recalls the tension between reality and fiction that Luigi Pirandello addressed in his masterpièce *"Sei personaggi in cerca d'autore"* (Pirandello, 1921).

Furthermore, another layer of connection that SM introduced is the dualism of humoristic and comic, introduced again by Pirandello in his treat *"L'umorismo"* (Pirandello, 1920). According to Pirandello, the comedy rises with the audience's reaction to something which does not fit, and it unfolds in two different

ways. On the one hand we can *feel* that something does not fit, as Pirandello say we can *feel* the contrary (“avvertimento del contrario”); this is an immediate and non-rational response, presiding over a “comical” situation. An example of this can be the laughter of someone looking at a clumsy person falling down, like in a Charlie Chaplin movie. On the other hand, we can *perceive* that something does not fit, we can *perceive* the contrary (“sentimento del contrario”); this is instead a less-immediate and more rational response, which involves a “reading the room” process, presiding over a “humoristic” situation. An example can be the expression of inappropriate sentences or behaviors within a particular context, which we decodify as inappropriate through a cognitive process (let’s think about mockumentaries such as the sitcom “The Office” or many others).

This duality of the comedy was re-interpreted by SM in light of the concepts discussed in the physics part. Specifically related to the “comical” is the idea of linearity: a character is walking and we expect him to keep walking as a consequence but then he suddenly falls down and we laugh because the linear causality we were expecting is broken. Alternatively, related to the “humoristic” is the idea of circularity: we read the context and then we see a character saying or doing something which does not fit with the context we have examined. There’s a non-linear and cyclical back and forth from the analysis of the character to the analysis of the context which finally provokes a sense of humor. Thus, the “comical” which is paired with the idea of linearity, is related to the linear time, Chrònos, whereas the “humoristic” which is paired with the sense of non-linearity and circularity is related to the circular time, Eniautòs.

Therefore, we see here that the disciplinary contents displayed by the teachers were all connected with a logical link by PF and SM, to establish the interdisciplinary material to be used in the second part of the activity (the writing part). The way such concepts have been practically used is described in sections 3.1.2 and 3.1.3.

3.1.2 The teaching practices

This section elaborates more on the description of the project by focusing on the practices embedded in the activity. In particular, I discuss the reason behind the choice to engage students in writing a pièce and the ways the disciplinary contents have been discussed and presented to students.

Experiencing the contents: complexity

The teachers had a very conscious perspective regarding how they wanted students to relate with the contents. The goal was to make them not only *learn* the contents, but also *feel* them.

“And this also applies to the scientific concepts that were proposed, complexity was spoken of and certain concepts characterising complex systems, etc., were enucleated. But then, with these key words, with this structure that had been built (epistemological structure) ... I with them called them key concepts, key words. And these keywords, these concepts, for them did not remain abstract things... on these concepts, they had to gain experience, thinking about the class, thinking about their being on the web²⁴ ... And even

²⁴ PF refers here to a metaphor she discussed in class, comparing Internet and some dynamics occurring in the web to those of complex systems.

the laboratory tests that were done afterwards were still translated into an experience-making within a conceptual structure” (PF commenting in the interview).

This excerpt is exemplary since PF expresses her intention to not leave the contents just on a theoretical level but rather to make room for students to experience them, to feel them. The way this “experiential connection” was sustained was for instance by highlighting the epistemological structure of the concepts, in continuity with what has been done in the activity described in Chapter 3. In this sense focusing on the epistemology, hence highlighting the structure of mechanisms such as the feedback effects or the logic behind the idea of irreducibility, allows students to get the inner meaning of the contents without being bounded only to the physics domain. As a consequence, it is possible to experience the disciplinary contents by experiencing other things which share similar mechanisms or similar epistemology.

As an example of this “epistemology-centered” attitude, PF in the first lecture asked students as a homework for the following lecture to go around the city and take some pictures of things that in their opinion, but accordingly also to what was discussed in class, were displaying some features of complex systems. Thus, for example two students came up with a picture of sand-dunes, arguing that a dune is made of thousands of grains of sand, but if you just look at them (so at micro-scale) you “loose” the macro-structure. This is in resonance with the idea of irreducibility which was at the core of the first lecture. Another interesting example of irreducibility shared by one student was a flower because flowers have petals which have their own connotation but if we just look at them, we are missing the concept of a whole flower. This exercise, which I reckon is a metaphorical way to look at scientific concepts, nonetheless allows students to unpack the concepts seen within the disciplinary part, grasp the features and then try to feel them by recognizing them in different fields.

The idea to create the chance for experiencing the contents was also supported by the choice of engaging students in writing a theatre pièce. Theatre was not only a choice to link - on a conceptual level - the Italian curriculum to complexity, but also on a structural strategy. Students were asked to gather themselves into five groups of 4-5 each, and then to write an act of the whole pièce. Within each group, each student was in charge of a scene. Hence, here we see that complexity was conceived a “structural constraint” since students had to relate first with their classmates within the groups, but then all the groups had to discuss together to make the whole structure of the pièce coherent and find the proper connections between each act. This collaboration was a “constraint” since the teacher asked to think about events that had implications in more than one act. So, for example if something falls off of a window in one act, in the other acts students had to consider that event and embed it in their act if their scene was happening at the same time. Students were somehow “forced” to reproduce themselves a circular causal mechanism: they had to come up with a scene by themselves and then discuss all the scenes within their group, but then after confronting with the other groups they had to come back to their scenes again and adjust them for the sake of global coherence. We see here an example of the inner agent-to-agent relationships at a micro-level (groups writing scenes) determining the macrostructure (the whole pièce) which ultimately acts back in a circular relationship upon its very source, influencing the single scenes to change.

Therefore, a collective writing structured the experience for students, in this case through a feedback effect; an epistemological-structure which informs an experience-structure.

Experiencing the contents: time

Theatre was a kind of language that, with some additional constraints, allowed students to feel the complexity but it also was a “space” to represent the different images of time and to feel them.

The idea indeed was to write a story about a condominium as an example of a complex system, where the agents interacting are the residents; so, students were divided into five groups and each group was assigned a floor of the building, except for one group that was assigned the annexe. Each group had to imagine their characters (which were the residents of each floor, or the people appearing in that floor at that moment) and to think of possible events happening.

The writing constraints also supported the reflection around time. SM, as reported in the project sheet and during the seminar done in the last March, decided that each character had to represent a specific kind of time, so their features (psychologically, physically...) and/or the ways they interacted with other characters had to represent the characteristics of one of the four Greek times. With this constraint SM intended to support a process involving:

- The **conceptualization** of times: in order to develop characters that represent diverse kinds of time students had to recall the properties and nuances of the specific times (picking from the interpretation of temporalities within physics, literature or even both of them) and re-conceptualize those nuances in order to be re-used for the creation of figures. Hence first a **conceptualization** which sets the stage for a **representation** of times.
- The feeling/experiencing of times: since the way to represent different times was done through humans (characters), this process added an emotional layer to the **conceptualization** of times, leading students to relate with those times by activating an emotional dimension. Indeed, by developing characters students took care to delineate a psychological profile and this profile had to reflect some nuances of the kind of time: such connection between characters psychology and the four times was intended as a constraint to help pupils develop a sense of “emotional times”, again with the idea to support a reflection about themselves and their way to think about time.

It is noteworthy to remind that SM helped her students in this delicate process of translating the features of the four times into features of characters, for instance by providing inputs and examples. The Aion could have been represented for instance by a character with a static rather than a dynamic connotation resonating with its “absolute nuance”; or Eniautòs could have been a character that repeats over and over its routine, in resonance with its “cyclical nuance”.

So, each act was populated by characters representing different time images. Also, as mentioned before, there was the connection Eniautòs-humorous and Chronos-comical that was conceived as a further layer to embed in the characterization of the characters.

Lastly, the idea of pushing students to experience and not only think about different conceptions of time was stimulated by the whole activity temporal structure itself. SM and PF proposed students with an activity that lasted from March until the end of the school, spanning over different lectures, sometimes during hours borrowed by colleagues of other subjects. The colleagues NI and DR made indeed available a few of their hours to host Kairòs activities. But the process did not finish with the end of the school, since SM asked the principal to keep the class also the following year to continue the pièce editing with the intention to reach a final version that students could also play in front of the school. Both the teachers expressed many times how much they see their students constrained within a temporal-mechanism

grounded on a chronological sequence of actions. There is a sociological tyranny from the present time (Hassan, 2003; Rosa et al., 2013) but other ways of conceiving time are possible, as we have discussed. The way the schedule of the project itself was conceived represented a rupture of the canonical time structure of school, where time is a quantity that has to be subdivided into precise slots and optimized (Liao et al., 2013). At school indeed students are presented with a very normative and strict experience, where lectures are taught by one voice, involving one subject and divided in slots of hours. The Kairòs project instead is an experience which aims to question the image of time as a resource to optimize, focusing on keeping the process of writing and reasoning alive rather than reaching a perfect output before a deadline, and with a temporal span that even overcomes the end of the school.

The students were constantly reminded by the teachers of the importance of the process (writing) rather than the output (pièce). This was done in a very explicit way: for example in one lecture just before the end of the school when PF asked students to reflect about the whole project, with specific prompts to which students were asked to answer (see Appendix B). The aim of the discussion was to gather students' impressions about the activity and specifically the writing part, and this led the class together with the teacher to unpack the writing process and to deepen its purpose for time reflection. The objective of this "meta-reflexive" moment was to highlight Kairòs as an activity "process-oriented" rather than "output-oriented", aimed to "defocalise" school activities from the output.

Explicit the intention

The educational perspective of the teachers is to make evident to students the potential of disciplinary contents as tools to make sense of society and navigate it. The concepts are dealt with in such a way to make them *lenses* through which look at the world. As I will argue later this is a signature aim of the Bologna Physics Education research group of which PF is part, but is shared also by SM.

Nonetheless, what I wanted to show here is that such intention not only informed the whole design of Kairòs, but was constantly shared with the students. Indeed students, from the very first lecture have been made aware of the goal of Kairòs:

"Experiencing means that even in an explicit, shared way, it does not simply remain a concept of physics. It does not remain a concept that I tell you related to physics, that physics has studied because it has studied complex systems, because it has done simulations on birds, it does not remain a concept of physics. It remains almost a "method," a structure that you build for yourself, that you need to think about something else and then to gain experience about yourself as well" (PF in lecture 1).

Here PF encourages students to not enclose the concepts within the disciplinary boundaries of physics; such concepts have to become a way to reason about different things that go beyond physics and science itself. Also, she discloses the connection with identity which was one of the reasons of picking time as a content: the concepts must become lenses to conceptualize personal issues, to think about oneself, about the own identity. This perspective was constantly shown by PF in her lectures, by making a comparison between students as a class and a complex system, where the individuals are the single agents:

"Think of you in saying to each other, "but I have to build my own identity because I am a unique and unrepeatable person. Single." It's true! You are a unique and unrepeatable and single person, but you are also a person within a complex structure, where there is a dynamic interaction with everyone else, so identity construction, for example, is this continuous interplay between individual and collective. What I

want of myself and how others represent me, and how I represent myself to them, in this continuous interplay between being inside and being outside, between being an individual and at the same time being part of a collective" (PF in lecture 2).

Here PF recalls implicitly some results that we have seen emerging from the previous Chapter, trying to activate the same reflection. This, in resonance with the goal to foster a reflection on the contents which goes beyond the disciplinary domain:

"Think of you as a small complex system [...] There are rules also that individuals follow in a more or less conscious or more or less deliberate way. But out of the behavior of individuals in this relationship between individuals, collective behaviors emerge [...] properties of the class are given, emergent properties, but these are derived from the relationships between individuals, and the change of a relationship can change the emergent property" (PF in lecture 3).

From this point of view is also interesting to look at the construction of the three lectures done by PF. In the first two lectures she introduced the concepts and in the third lecture students participated in experiment sessions, but at the end of each lecture she summed up the contents in light of their potentiality as lenses to look at society, to help find a sense of agency in the society as well as to find the personal positioning and nurture identity development:

"These things become thought structures, let's try to look at it that way. I think often about this accelerated world, full of advancing technology, so dematerialized, which is changing fast, (and) you are the protagonists of the change. I experience it through my grandchildren, however, I wonder what thinking skills I have to make myself" (PF in lecture 3).

In this regard, the science of complexity - because of its epistemological structure - can help in providing useful skills:

"Then we must have a vision of complexity, otherwise we are engulfed by this complexity of today" (PF in lecture 3).

The message that PF wanted to deliver is that sometimes adopting a vision informed by the ideas of complexity, rather than being stuck in a classical and linear view, may turn out to be much more useful to deal with some issues which appear as inextricably complex.

Finally, in the last lecture, PF wrapped up with students the whole process of Kairòs, engaging them to reflect about the broader implications of their creative writing activity with the support of written questions students were asked to answer at home, some days before the lecture. The questions were intended to trigger a reflection about the goal of the writing process and its link with the concepts of physics; in particular they made evident the parallelism between the pièce and an emergent phenomenon of a complex system, mapping the agent-to-agent interaction into the students collective discussion to produce both coherent acts within the group and a coherent play as a class.

The intention here was to make explicit that students, even unconsciously, impersonated themselves the behavior of a complex system:

"So we can think of two levels of complexity [...]: the complexity within the work, so in the management of the characters, of the characterization of the characters... and the complexity of the relationship between the writers, which is you. You can see it on two levels, you know what I mean? Theatre work is a complex

work, where there are characters interacting between different levels, where you had to manage time. However, there is also a complexity of managing the relationship between you, because the work itself has a structure[...] There is also a complexity of managing yourselves here, because everyone wrote a scene, then you did the groups, the group wrote the act, and all the acts have to contribute to an overall work that has to take into account the individual scenes, that has to take into account the individual acts. But the individual scenes and individual acts have to take into account the overall work.... Which is not done by one person, it is done by many people interacting with each other. So you displayed precisely a process of complexity in writing..."

And again, while prompted by a student question about the general objective of the course, PF adds:

"It's obvious that the moment you write a play, having the scientific thinking of complexity in the back of the head, you don't really go into the play to tell complexity, however, you have a tool for reading and constructing your additional work... And we think that having tools related to scientific concepts, which is not the formula of motion, but which are really the basic concepts of science, related to space, time, collectivity, what it means to be able to predict, what it means to manage time and space... (these tools) also help you to interpret the present in the other areas, which are not scientific, and help you to imagine futures..."

These excerpts again witness the extent to which both the teachers disclosed the whole design and its general objective, grounding on the belief that students must be aware of the ambitions of the activities and must be aware of the rational behind the choices. Making evident in this sense is not a normative process. Indeed, teachers did not tell students that they had to use complexity as a lens, but rather presented the possibility to use them as instruments to make sense of the world:

"To me the power of these projects is that all of this was made explicit, that is, in the sense that it's not that they, over time had to understand that that concept of complexity could come in handy when... That is, they were able to touch on it right away that this was important to them" (PF during the final interview).

3.1.3 A signature way of dealing with the contents

Previously I mentioned that there is a signature way of dealing with the concepts emerging over the last years within our Research Group, which aims to re-generate the physics concepts into something *thicker* than just disciplinary concepts.

The underlining assumption is that physics education is at a turning point since the way it has been taught so far has produced a serious detachment between school and what happens out-of-school. The lack of personal relevance that I recalled at various times is still a huge question. Hence, two solutions seem possible: either we²⁵ acknowledge that physics education, the way is done, is still provoking deep inequalities (Avraamidou, 2021; Hazari et al., 2015; etc.) and so we boycott physics education at all, choosing to teach something else; either we acknowledge that there is a serious problem related to the image that the disciplines have at school and we try our best to *re-generate* scientific disciplines. Our

²⁵ The use of "we" here is to refer to the physics educators community. However, it is true that a reflection on the relevance of the physics taught at school could not be shared in general. In this case it represents a position of our Research Group that is suggested to the large community.

choice was then to focus our efforts on thinking about solutions to give new life to a “seemingly dead” school physics.

Regeneration is the word that embeds the reflection we are carrying as we are constantly stimulated by questions as:

- Are there ways to identify conceptual structures within the physics discipline that may help students in answering deep personal questions?
- How can we transform such conceptual structures into thinking tools for students to navigate and make sense of society?

These are bottom-line questions which continuously feed the group-reflection but at the same time they are refined and improved according to the empirical outcomes that we get through data collection within the activities we implement.

Such questions show the ambition to thicken the disciplinary concepts with an epistemological and metacognitive layer.

In Figure 3 it is shown what we named as a “4-layer scheme” for science education. The first layer involves the learning of concepts but constitute just the premises for a “more ambitious” learning objective. There is a second epistemological layer, in which the concepts are unpacked in their epistemological structure used as a proxy to get an image of the nature of disciplines, how these develop knowledge and what kind of structure lies behind it. Hence, a third metacognitive layer is represented by the steps three and four: in these phases the students are guided to reason about the concepts that they have seen and reflect about their potential utility for different issues, beyond the boundaries of the disciplines.

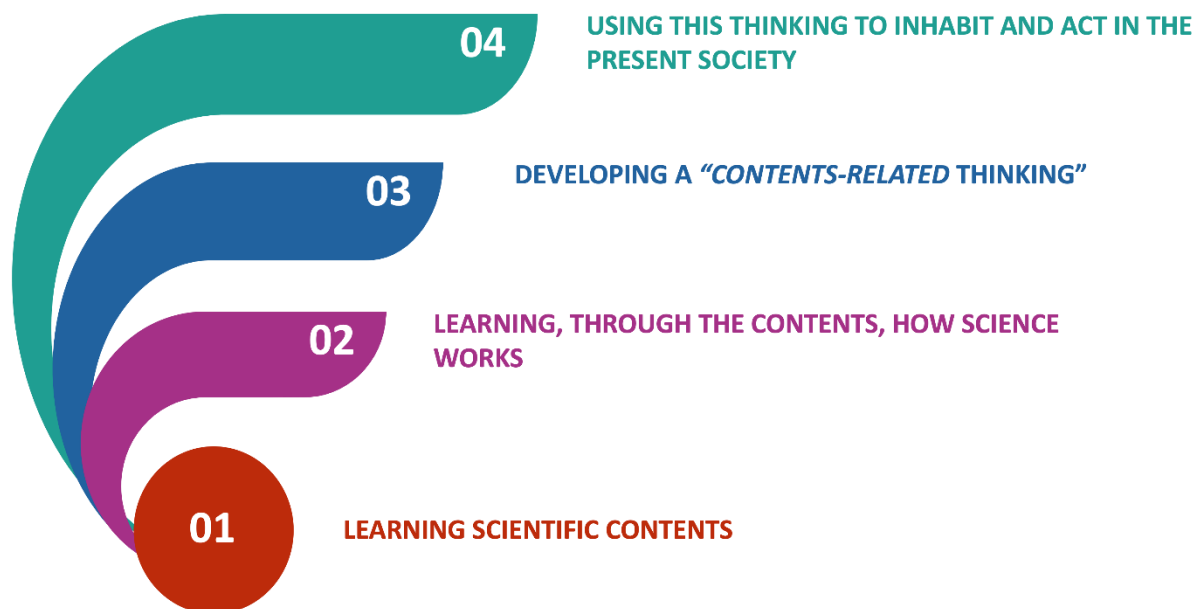


Figure 3: The dimensions of the 4-layer scheme.

It is evident here a general similarity with the educational aims of *Bildung* pedagogical framework. Originating from German Enlightenment thought (as the work of Wilhelm von Humboldt) and later carried on by theorist as Wolfgang Klafki (Klafki, 1995), *Bildung* encompasses a comprehensive approach to

education that focuses on the development of individuals, integrating intellectual, moral, and cultural growth. A *Bildung*-informed education is not only aimed at acquiring knowledge but also about fostering personal development of autonomy, critical thinking, and a sense of responsibility and societal transformation through engagement with cultural and intellectual traditions (Klafki, 1995; Sjöström and Eilks, 2018; Ulriksen, 2023).

According to Ulriksen (Ulriksen, 2023), *Bildung* can represent a profitable instrument to reflect about the meaning of school scientific literacy and so reduce the gap between science at school and science outside school (De Zuani et al, 2023). In the context of science education it could mean to integrate scientific practical and utilitarian knowledge (step 1 in the previous scheme – *learning scientific concepts*) with broader educational objectives, promoting not only a narrow technical understanding (Sjöström et al., 2017) but also a critical reflection on the societal and ethical implications of science (step 2 in the previous scheme – *learning how science works*). In addition, it could also mean to foster a deeper understanding of the role of science in shaping our worldviews and identities encouraging students to engage with scientific concepts in ways that are personally meaningful (step 3 in the previous scheme – *develop a “contents-related thinking”*) and socially relevant (step 4 in the previous scheme – *use thinking to inhabit society*) (Klafki, 1995; Ulriksen, 2023).

A further point on the proximity between the 4-layer scheme and *Bildung* is shown by the fact that also the Model of Educational Reconstruction (Duit et al., 2012), at the basis of our research group (as discussed in the first Chapter), was developed starting by *Bildung*. All these frameworks - MER, 4-layer scheme and *Bildung* – share the belief that scientific knowledge can go far beyond the simple learning of topics, including support for identity development:

“We underestimate what science can contribute (to education). It is perhaps not surprising that a discipline that deals with nature and the world around us is particularly concerned with what lies outside of us; but by leaving the inner life of human beings to the humanities, we neglect the formative experiences that can offer encountering both topics and methods in the natural sciences. Science contributes to understanding and interacting with the world around us, but it can also contribute to our understanding of ourselves” (Ulriksen, 2023; p.13).

A 4-layer scheme for time-education

The framework illustrated in Fig. 3 is the general version of the 4-layer, which then has to be “projected” into the core concepts of the specific activities, in this case time (Fig. 4).

The different forms of time encountered in the physics of complexity and then within the ancient Greek tradition and discussed with respect to literature, are used to highlight the diverse nature of the two disciplines, as they illustrate how the same concept is diversely treated. At an operational level, this has been supported by creating an interdisciplinary environment and by asking students to embed the physics features of each time in the writing process.

The third layer sets the objective to support students’ span of time management solutions: as they have one unique image of time they are led to manage time in a single way, but what if they develop a multifaceted image of time? The assumption is that a more nuanced image of time can likely enlarge the time management options, since each “face of time” requires a related management. In particular, the

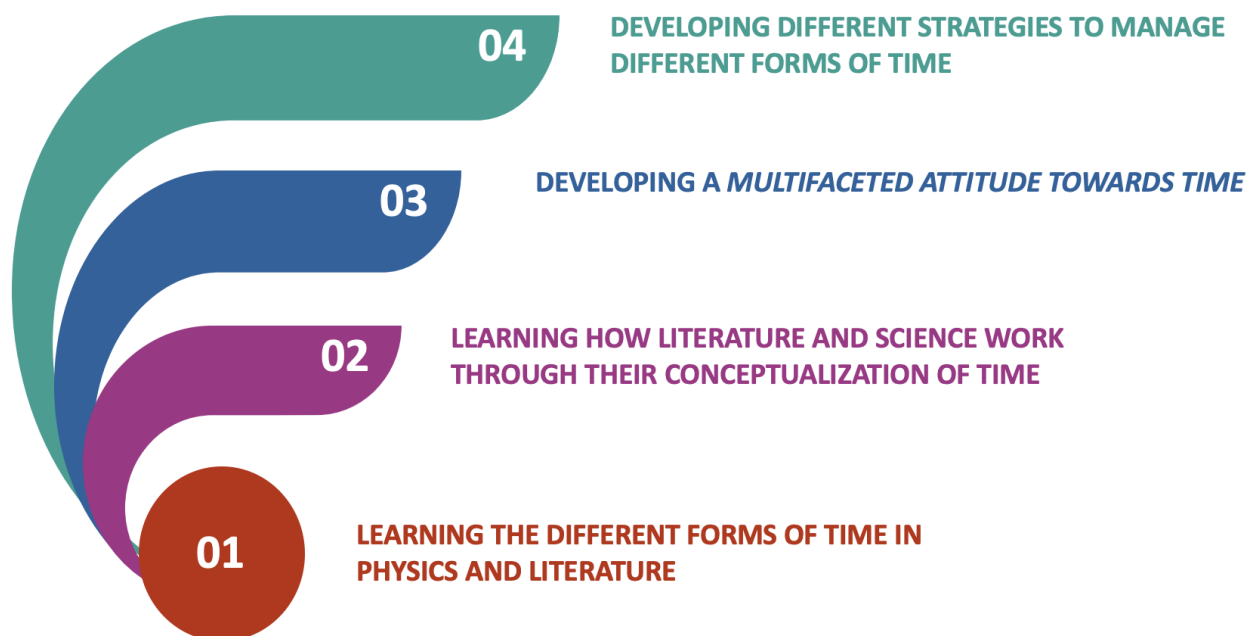


Figure 4: The 4-layer scheme for the concept of time.

teachers decided to make students experience the conceptual structures of time and complexity, as a way to support a specific way of thinking and an attitude towards time.

The last layer has the general ambition to use the updated “thinking about time” (in the figure: “developing different strategies...”) as a resource to inhabit the post-modern society and develop a conscious positioning toward its acceleration. This is a crucial point (and hope) for both teachers, promoted continuously by sharing their intention with the students (Section 3.1.2).

One further comment about the *4-layer* scheme. The teachers share the strong belief that knowledge (literature, physics...) is able to help people (students in this case) making sense of the world. This can sound trivial but is more subtle than it looks; it reflects the conviction that is possible to regenerate school education by investing in the concepts rather than dismissing them, by making them thicker rather than transform them in their shallow version. Concepts can be so rich to be also experiential structures, scaffoldings for thinking development and put the premises for agency in the society, and it would be a big waiver to just treat them as something to be told by the teacher.

3.1.4 Lectures’ outline

Lecture 1:

The first lesson introduced students to the complex systems in physics, led by PF, with assistance from FDZ, VI, and supported by NI, the physics professor. This session focused on theoretical aspects of

complexity and aimed to lay the foundational understanding necessary for grasping the paradigm of complexity. In particular PF explored the difference between *complex* and *complicated* and the concept of emergent properties. At the end of the lecture, students have been assigned to observe and document with pictures examples of complexity in their daily lives.

Lecture 2:

The lesson began with a recap of previously discussed complexity concepts. Then PF revisited the homework assignment, with students sharing photos capturing examples of complex systems. The lesson progressed with a hands-on session with NetLogo, exploring complex behaviors such as flocking birds and ant foraging (Wilensky, 1997; 1998). A guide was provided to suggest students how to manipulate simulation parameters and what to pay attention to.

Afterwards, students watched a video titled "Feedback loops: How nature gets its rhythms" by Anje-Margriet Neutel (<https://www.youtube.com/watch?v=inVZol1AkC8>) which delves into feedback loops in natural systems (with PF stopping the video to discuss its content). The video served as a concrete example to further elaborate on how feedback loops regulate natural and social systems, highlighting the dynamics of amplification and stabilization within complex systems.

Lecture 3:

In the third lesson, the focus shifted to a hands-on laboratory experience with VI, FDZ, NI, PF, and chemistry lab technicians, EG and her assistant, conducting two different experiments: the Belousov-Zhabotinsky (BZ) reaction and the Bénard cells. This session involved students diving into the practical application of the theoretical concepts previously discussed.

The lesson began with a recap of positive and negative feedback mechanisms, with students reflecting on these concepts through examples like the ecological impact of global warming and Lotka-Volterra predator-prey models, introduced by VI.

The first experiment showcased a chemical oscillation reaction, reminiscent of the Belousov-Zhabotinsky reaction, where a mixture of reagents periodically changes color when kept in motion. The reason behind engaging students with the BZ reaction is that it represents an example of non-linear chemical dynamics, offering insights into the behavior of far-from-equilibrium systems and the conditions under which complexity and self-organization emerge, with the help of changing colours to perceive it.

In the second part, the class explored the experiment of the "Bénard cells". Bénard cells represent a classic example of a self-organizing system in fluid mechanics, where a layer of fluid heated from below forms a pattern of convection cells known as Bénard cells. In the present context, the experiment served as an example of emergent phenomena, demonstrating how simple components under certain conditions can self-organize into collective emerging patterns (cells). See Appendix D for a detailed description of the two experiments.

Lecture 4:

In the fourth Kairos lesson, SM and PF interweaved the concepts of physics with elements of literature. At the beginning of the lesson PF presented a parallelism between the kind of temporalities present in physics and the four types of ancient Greek temporal concepts: *Aión*, *Eniautós*, *Kairós*, and *Chrónos*, previously introduced by SM.

SM then transitioned the discussion towards how these concepts of time can be expressed in writing through the lens of Luigi Pirandello's poetic aesthetics, setting the stage for the creative writing activity. Students were then organized into groups, each associated with a different floor of a condominium, and tasked with writing scenes populated with characters reflecting each one a different notion of time. These scenes collectively form acts that represent the various spaces of the condominium, and the acts form a whole pièce. SM also gave some hint about how to represent the features of the four times seen in the previous lectures (the scientific features) into the features of a character.



Figure 5: The organization of the building, with five different locations corresponding to the five acts of the pièce.

Lecture 5:

In this lecture PF and SM delved into the creative process and its outcomes, reflecting on the complexities of collaborative writing. The lecture began with SM emphasizing how the narrative started individually but naturally evolved into an interconnected ensemble, necessitating the integration of scenes from one act into another. They also recalled how the narrative construction, character development, and thematic exploration was not just about crafting a cohesive piece but also about the collaborative dynamics, decision-making processes, and adaptability to unforeseen narrative demands.

Lecture 6:

The final lecture was the collective “metareflection” moment mentioned above, where PF hold discussion aiming to delve into the students' experiences of the writing process, their interaction dynamics and the complexities encountered in integrating individual scenes into acts and the acts into a cohesive theatrical piece.

3.2 Post-Kairòs

In this section I present the diverse impressions that we had (me and VI as observers and SM and PF as teachers) about how students reacted to the whole project. This is also argumented by recalling diverse students' opinions explicitly shared during the final lecture, and the written answers²⁶ to the questionnaire delivered by PF before the lecture (Appendix B). Also, I report the teachers' sensations about the pièce, which ultimately led to some modifications in the following implementation (section 3.2.3).

3.2.1 General impressions about the activity

In the second lecture I was standing close to the front desk in the left row of the class, close to two students which from the beginning of the project up to that point had not been care that much of what was going on. One of them, during a little break shared with me that he was not enjoying the activity at all. He was also upset since to him their professors involved his class in such projects because they were considered as super passionate and studious, whereas none of them was either passionate or studious. Furthermore, he was envious of other classes that were not forced to participate in such activities.

During the last lecture, roughly two months and a half later, during the last lecture I casually placed the microphone close to the desk of the very same two students. While listening to the recording afterwards, these students spent most of their time still talking about other stuff and seemed completely detached from the ongoing discussion. Hence, I was surprised when during a small talk about soccer the same student who complained in the second lecture said to his classmate:

S1: "She's good, this prof, huh?" (referring to PF)

S2: "She's good!"

S1: "Anyway, it was good the Kairos project!"

S2: "I agree...we should do more often stuff like that"

And few minutes later:

S2: "We must thank SM for this amazing project..."

S1: "I agree... I hope she will stay"

S2: "Me too"

S1: "She is really good"

When I first read this brief exchange I was surprised, since I believe that they were really thinking what they were saying rather than "fooling the listener", given all the things that they said without any filter up

²⁶ Just six students answered the questionnaire, as it was not mandatory.

to that point. I rather believe that they completely forgot about the mic, which indeed was a simple phone placed on a desk.

The reason why I decided to start this section with this example is that I consider that quite representative of the general process students passed through during the project: a trajectory from an initial cognitive difficulty and emotional surprise towards a final engagement in the writing and the intention to continue the following year. In fact, for instance, two students showed SM the interest to continue the project in the following school year since they enjoyed that so much.

In the first three lectures students had to face the difficulty of completely new concepts, even though PF tried to discuss them in a simple way making references to examples from the living worlds and without entering into the details of a mathematical description. This led to some moments of confusion and distraction, especially during the second lecture in which students spent two hours in a row discussing about feedback loops, emergent properties and irreversibility. For example the first comment of the students reported above was done around the end of this intense lecture. Also, they had to understand the different forms of temporality embedded in physics of complexity leveraging also on the ancient Greek reformulation of different temporalities.

Furthermore, they faced another level of difficulty, namely to map the features of the diverse temporalities seen in physics within a writing artefact. This step was the most crucial yet delicate of the whole project, hence students were guided especially by SM over numerous lectures in SM's curricular hours. Still, at the beginning they had a hard time getting the goal of the activity: *"I don't understand what physics has to do with what I'm supposed to do (theatre writing)..."* was saying one student in lecture three. The literature teacher herself agrees that the transition between physics and literature was the most difficult part, as she commented in the interview:

"We presented the four times and asked them to imagine characters who lived guided by that temporality. So, we first tickled the imagination by thinking for instance about Aion...Aion, so this time that is a dilated time, is an expanded time, what does it mean? This was the step in March, April, the most difficult. They were learning things with PF and within them the first struggle was to find the connection, that is, what they had to do, and what a character actually living according to that time means. So first they had to get a good understanding of the aspects of the time, actually what that time entailed, and then combine them with character life choices" (SM).

On top of all these aspects, students dealt with the (designed) complexity of collective writing, where the scenes written individually had to match with the whole act, but also the acts had to fit into a comprehensive pièce:

"Personally, during the project I encountered situations in which scenes, acts, and the final product conditioned each other: it could happen that for a detail in one scene the entire act changed, or that in order to match the data in the final work a scene had to be rewritten" (student from the fourth Act, during the final discussion).

As discussed above, the teachers wanted students to *feel* the complexity, and the choice of theatre was done for this purpose; indeed, it makes a difference to study what feedback loops and circular causality are or making a direct experience of it. Related to this, it was not easy for them to inhabit the complex writing session, as they shared in the final discussion:

"Personally, it has been, on several occasions, quite difficult to find an agreement on certain decisions regarding interaction between groups or, rarely, single group" (student from the second Act).

However, after the initial dilemma, students started thinking about possible solutions both within and between the groups:

"We decided that we needed to make connections with the two groups that were attached to us in a plan sense, try to make the story as cohesive as possible, increasing the interactions and trying to maybe go and figure out how (were) the characters in the other groups..." (student from the first Act, during the final discussion).

and they began to come up with *interaction strategies* (as if they were agents interacting in a complex system) which could have let emerge a homogenous play at the end. SM also decided to use boundary objects as scaffolding constraints to smooth the transitions between the acts, that had to be embedded in two subsequent acts. Students instead, came up with the idea to first set a public time schedule of the events happening in their acts so everyone could refer to that while writing their scene (again for the sake of coherence):

"To facilitate organization in our group, we made a list where we indicated the time when the events took place, and before interacting with the other groups we made our time slots explicit to clarify right away whether they could match (with those of other groups)" (student from the first Act, from the questionnaire).

Another strategy adopted to provide coherence and support the idea of complex relationships was to let a character move between two acts (done by group 4 and 5):

"In addition, from the beginning to the end of the play the space was always supposed to be the annexe, but in the final part, thanks to a collaboration established with the terrace group, the apartment building itself was also included as a space thanks to the displacement of one of our characters, and I think this returns the concept of complexity very much" (student from the fourth Act, during the final discussion).

Besides the diverse strategies to handle the complexity, it is noteworthy that students recognized the similarity between the "writing session's structure" and the features of complexity and get the sense that they were collectively contributing for an emergent output. Here two students:

"Initially, each group worked exclusively on its own act, but over time it spread the idea that in order to best render the concept of complexity it was necessary to extend the work to the rest of the groups as well. So, I think the play can be called an emergent object in that everyone made their own contribution" (student from the fourth Act, during the discussion).

"Personally, I recognized the circular relationship that complexity speaks of, because from each cause, such as changing a scene, or even just a line an effect ensued, which in turn led to the change of another scene, necessary to bring the whole act back into balance. Each change then corresponded to an evolution of the work. In my opinion, the process was, indeed, complex, but as a group we were able to manage it as best as we could by modifying our product to make it as homogeneous as possible" (student from the fifth Act, in the questionnaire).

Students surprisingly refer to their experience by using the words of complexity. Even though they were triggered in such reflection by the questionnaire delivered in the last lecture, still they show to have

developed an awareness of the way they interacted and its proximity to the concepts faced in the first lectures.

To some extent, I claim that students here show to have developed a metacognitive thinking about the concepts of complexity, which is the aim of step 3 and 4 of the 4-layer scheme. Surely this is a germinal status, but still, I consider it valuable since it witnesses that by specific and strong design choices and with the care to guide students all along the way it is possible to let them start thinking *through* the epistemological structure of scientific contents.

To conclude, the trajectory of the two deskmates is representative of the class' general feeling in the sense that pupils were detached and bored at the beginning. Then, passing through the activity, finding their own solutions and engaging in the "free space" guaranteed by writing, they got to enjoy and appreciate the work done by the teachers:

"Then in my opinion (the writing part) it trained our brain in a different way. Because maybe studying all the dates of Italian, all the topics... maybe you even go by memory, instead this helped us more to understand how to think, to try to understand something that is different from what we usually do.... so good!" (student from the second Act, during the final discussion).

This positive result is shared by SM, who adds in the interview:

"So I noticed a growth as a class group more than in individuals [...] And this pleased me because so many (teachers) were saying that it was a closed class, it was a critical class, that didn't communicate right away and instead it showed that it could communicate well even with each other and especially to overcome then some neuralgic aspects that arise from who wants to do more and who wants to do less (about the balance the students had to find within each group)".

NI, instead, was impressed by students' reaction to the project to the point that he decided to introduce ideas of complexity in his 13 grade class, given the potentialities to become "thinking tools" demonstrated by his 10-grade class.

3.2.2 General impressions about Kairòs' images of "time"

All the groups but one decided to assign to each character a diverse face of time, whereas the fifth group just focused on the main character's temporality (Aiòn). Besides this, students leveraged the "structural constraint" of having characters interacting (allowed by the choice of theatre) to highlight the diverse time representations:

"We decided to assign each one (time) to a character whose characteristics, related precisely to those times, emerged as he/she interacted with the rest of the family. So, the focus was on one character, but in order to make his or her properties stand out best, he or she would relate to the other characters on stage, and to succeed in doing so as best as possible we curated and managed actions according to his/her behavioral characteristics " (student from the fourth Act, in the questionnaire).

To some extent then the result was achieved, having different characters representing the four kinds of time with a more or less structured characterization for each of them. Still, PF but also SM noticed that something was missing in the final pièce.

The starting point of Kairòs project was the intention to involve students into a reflection and experience of different forms of time discussed and managed in such a way that they could have then become personal instruments to make sense of themselves and the world around. The intention was to create the condition to feel the diverse temporalities and map them into the inner issues, use them to question and reconceptualize the personal way of managing the time (Levrini et al., 2020; Ulriksen and Nejrup, 2021). The ambition was to present images of time able to enter into students' realm of time-conception and management, dominated by Chrònos, and provoke a disequilibrium. The clash between a chronological time conception and new forms of time was intended as the starting point for the re-positioning of students towards time and develop new "time-habits" to live in the society of acceleration (Rosa, 2010).

Related to this, PF instead had the sensation that students mostly reported in the pièce (through the characters) a perspective of time as something external rather than internal:

"What I think they struggle with, because it is really a struggle that I think is of each one, was to experience situations where the imbalance is true. That is, their Kairos understood as contingency, only in the first act it emerges, (with) the character of Martina, who wants to seize the opportunity, who talks about her life whether to go or not to go to the university, so there is the short time of her grandfather reviewing his life and the long time of her that a few days seems like an eternity..., there it comes out (the imbalance/disequilibrium). But it's the only one that uses a Kairos like a somewhat personal time, where you have to regain a balance, you have to readjust and rebuild a new structure [...] for the others (characters) the contingency (disequilibrium) [...] they many times experienced it as something very concrete that changed what was happening, a glass breaking..." (PF commenting during the interview).

And further on she adds:

"Kairòs time comes up in her (Martina), as a personal time, it is a time experienced by the person, for others it is an external time, that is, it is an object that breaks down...that causes the story to take a different turn. But it is not in a context of true imbalance where I have to rebuild a structure of balance, it is not an internal time".

Thus, PF claims the lack of "internalization" of the four times, except for one character who displays through her words the internal process of time questioning which produces an unbalance and a following temporal re-positioning. To her, the main obstacles related to "learn to inhabit new forms of time" were two (again from the interview):

"There is a double difficulty: on the one hand the difficulty of experiencing different temporalities, so the Chrònos, Aìon, the Kairòs... The four temporalities that we have given, and to think that time is not (only) one time, but there are different temporalities. To recognize that there are these temporalities and to build their characters thinking about these different temporalities, which is not so trivial, is very important in my opinion. This was a very important discovery for them because for them time is the passing of time (Chrònos)".

Hence, one difficulty is to accept that time is a broad concept and new forms of time are available and can be used to think and manage time. But also:

"And then there is another step: to make time, that is to (be able to) make this (inter)play between external time and internal time. That is, these four times can be external and internal. And they have been

struggling to experience them as internal times... And it's one thing to make these times, times that help you manage your personal life phenomenon (another thing is to not do so)".

As I argue in the next section, this sense of dissatisfaction was considered as a central issue to “consider” in the follow-up implementation, a few months later.

3.2.3 Towards the second implementation: ONSCI

Since 2021 the Department of Physics and Astronomy of the University of Bologna organizes a summer school named ONSCI (in Italian “Officina di Narrazione della SCienza” - “Laboratory of Science Storytelling”) to enhance skills in science communication through storytelling, particularly aimed at aspiring researchers and educators (<https://site.unibo.it/officina-di-narrazione-della-scienza/it>). Participants (they can vary between bachelor students to higher education teachers or scientific communicators as well as journalists) learn to use storytelling in various contexts such as seminars and public engagement activities. The summer school emphasizes interdisciplinary approaches, combining science with fields like visual arts, literature, and philosophy, to better understand science's impact on society. The program covers fundamental aspects of crafting narratives that reorganize and enrich scientific content beyond the usual technical and logical-mathematical frameworks. The school, including experts in science communication and art-science from academic and professional backgrounds, features theoretical lectures and practical workshops where participants create their own science narratives. Evenings include performances and outreach activities, culminating in a public presentation by participants of their workshop results.

Within the 2023 edition (7-13 September) the FEDORA project hosted three out of the four ONSCI workshops (<https://www.fedora-project.eu/fedora-at-the-summer-school-onsci/>) : i) the AI Atelier, which explored the intersection of art, creativity, and AI (see here for more information: <https://www.fedora-project.eu/ai-atelier-a-co-teaching-school-activity-inspired-by-fedoras-principles/>); ii) the “Mocku for Change”, focusing on the mockumentary genre to address Climate Change (the same mentioned in Chapter 3); iii) a second version of the Kairòs project. These activities explored the intersection between art, technology, and narrative techniques to provide useful tools for science communication.

The structure, the contents, the learning outcomes and the general philosophy of this second implementation of Kairòs were the same of the first implementation, even though for time-constraints the four introductory lectures were concentrated in two sessions of 2 hours each. Furthermore, we didn't have the chance to do the experiments and to let “students” play with simulations²⁷.

Besides this, two major differences distinguished the first (which I will name from now on “Einstein”) and the second (which I will name from now on “ONSCI”) implementations:

- **The students.** In the first round a whole class was involved, with 24 people of the same age and with similar cultural backgrounds, guided by their literature teacher and embedded in a familiar environment (their school). The second round involved participants of a summer school open to

²⁷ Even though the physics lectures' have been condensed into just a few hours and also much less time was dedicated to writing, still the contents and the references to introduce time were the same of the first implementation. For this reason I will skip here the “wrapping up” section that I did for the first implementation.

anyone interested in the topic, willing to explore the creative writing technique rather than art or mockumentary or theatre. Ten people participated in the ONSCI implementation: two PhD students, four master and one bachelor students in physics, one philosophy master student, one geography upper secondary teacher and a physics/math upper secondary teacher. Participants age spanned between 20 and more than 50 years old.

- **The writing structure.** This time, SM decided to ask students to produce individual monologues instead of a whole pièce. Again, the objective was the same – represent different characters embedding one specific kind out of the four times – but students had to work alone. This reduction of complexity was certainly due to a lack of time (they were given just two-three afternoons of 3 hours each to write) needed to develop a comprehensive pièce; nonetheless this decision comes equally from the sense of dissatisfaction about time-internalization mentioned above. Indeed, the monologue is by default more suitable to host a self-reflection of the character, which was somehow missing in the first round. As SM commented in the interview: "*in an (individual) essay it is just you and more or less the traits of the individual are seen*", whereas in the collective writing "*the traits of the individual have intersected, then during the writing someone has stepped back to make room for something they would not really feel*". Hence, to trigger even more the process of reflecting about the four times internally rather than externally, SM chose the monologues to the detriment of a layer of complexity given by a writing done by many hands.

Therefore, the result was a collection of 8 monologues (two people did not complete the workshop) with the objective to represent within characters an “internal noise” introduced by one of the four temporalities and to narrate the interior process of listening and dealing with such noise. This internal noise was the caveat to push for the expression of a more internal kind of time.

3.3 The analysis

In this section I present the analytical process I did with the texts produced in the two implementations, Kairòs-Einstein and Kairòs-ONSCI. The objective of the analysis is to navigate the texts and see how the different kinds of time have been *conceptualized*, *felt* and then *represented* in the pièce/monologues by pupils. The rationale of such analysis is to inquire what kind of consequences can produce a reflection which questions the uniqueness of time by presenting new temporalities. Specifically, we were interested to see if and how the connection between time and identity was activated by students.

I first present the abstracts of each act of the pièce and each monologue, and then I discuss the process of data-analysis. The analytical method used is the following.

I did a first round of qualitative analysis, which produced some outcomes. Then I performed other analytical steps, with the aim of confirming or disconfirming the preliminary outcomes, providing new perspectives on the issues found (I named such process “pulling the threads”). At the end, I collected all the outcomes emerged from each step and discussed how they relate to each other, providing a general overview.

Data

The dataset used to perform data-analysis and triangulate the outcomes for the Einstein implementation is made of:

- Audio-recordings and transcripts of all the lectures (excluded the moments in which SM let students write part of the pièce during her curricular hours)
- My fieldnotes of all the lectures but one (the 5th)
- Written answers returned to PF in the last lecture
- A logbook made spontaneously by one of the groups
- An extended interview done with the teachers at the end of the course (see Appendix A for the interview protocol)
- The pièce “May 5th Street”
- Pictures taken in the lab activity

The dataset used to perform data-analysis and triangulate the outcomes for the ONSCI implementation is made of:

- Fieldnotes of all the lectures
- Monologues
- Commentaries written by the authors while introducing each monologue
- Informal discussions had with some authors

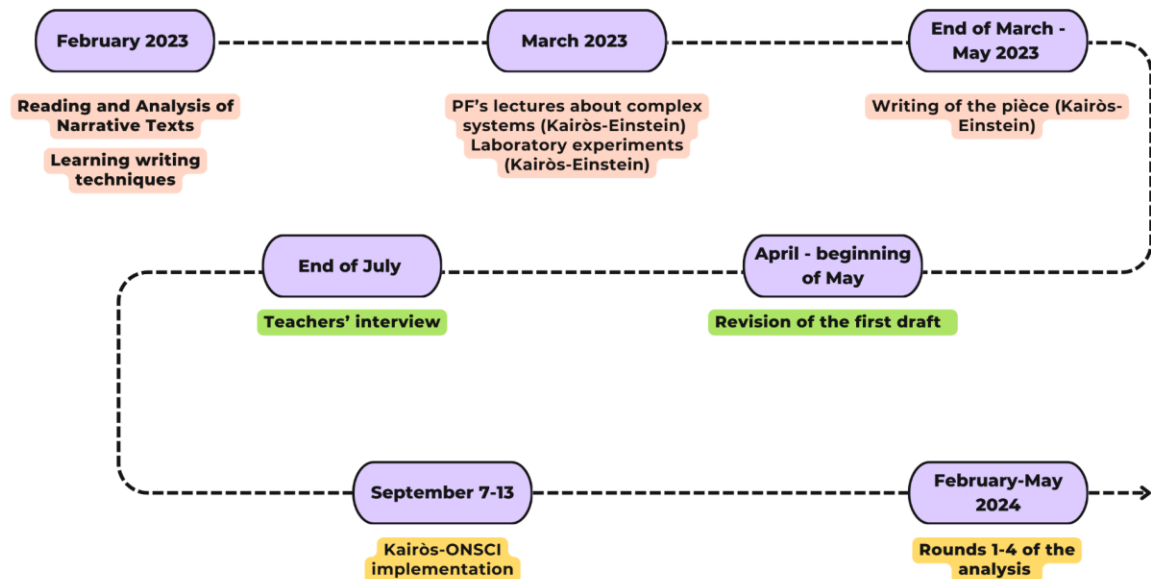


Figure 6: Timeline of the projects' implementation and data analysis.

3.3.1 Abstracts

In this section I present short abstracts for each of the five acts of the pièce “May 5th Street” (produced within the first implementation, Kairòs-Einstein) and also for each of the monologues written in the second implementation (Kairòs-ONSCI), which are collected in a book now in revision named “Above the sea”. The reason why the abstracts are here and not in the Appendix is to facilitate the reader to follow the analysis discussed in the next sections, where there will be many references to both the characters and the events occurring in the writings.

Kairòs-Einstein

“May 5th Street”

Act 1

The first act, set between the communal garden and the communal hall of the apartment building, begins with the residents gathering for their annual communal lunch.

The act unfolds with the characters interacting post-lunch, highlighting their distinct personalities and relationships. Karen, a snobbish supermarket cashier, despite her usual inactivity, complains about physical tiredness. Danish, a silent cook from Pakistan, and Martina, a brilliant and ambitious girl, remind Karen to help clean up. The scene also captures the moment when the shoe of the dog of Maurizio, a gentle yoga teacher for dogs, is stolen, adding a bit of chaos to the quiet situation. Loretta, a woman ever observant, resolves the mystery of the missing shoe with her detailed knowledge of everyone's habits.

In the next scene Martina, while reporting that she got a scholarship for the university, expresses her desire for a life beyond the routine of the building, reflecting on the repetitive nature of her days and her aspirations for something more unique. Loretta and Salvatore, porter of the building and Martina's grandfather, share their custom to fit in the daily routine but nonetheless encourage Martina to take the chance.

Later in the act, Danish shares a story from his life, in which he recounts his journey from Pakistan to Italy amid socio-political turmoil and his family's struggle to settle in a new country, but also the happy ending thanks to a scratch card found in the street. Then Maurizio complains about Karen's loud vacuuming disturbing the peace; afterwards, Maurizio joins Loretta in the communal hall where they both watch TV and discuss recent dramatic events involving the tumultuous relationship between Karen and her husband.

In the final scene a sort of explosion interrupts the calm but the residents soon realize that it was a minor incident; in the meantime an angry Karen fires some of her husband's clothes at the communal barbecue.

Act 2

The second act is set on the first floor of the building.

The act opens with Vittoria and her husband Giulio discussing at the community lunch we saw in the previous act; Vittoria is enjoying the gathering, but Giulio expresses concern their neighbor Aurelio and his invasive nature, as he seems particularly interested in another neighbor, Bolek Zajac, a reclusive Polish man. Vittoria suggests inviting Bolek to dinner to get to know him better.

Then we see Aurelio gifting Bolek with a plant with a hidden camera inside. Bolek, unaware of the camera, accepts the plant but later, while cooking, he accidentally discovers the hidden camera when the plant falls and breaks. This revelation shocks him to the point of going to Giulio and Vittoria's apartment and seeking comfort. The couple is supportive and tries to keep the atmosphere as normal as possible despite the tension. Aurelio knocks on their door to ask if they have seen Bolek, as the camera is not working and he can't anymore spy him, but they pretend not to have seen him. Aurelio leaves, but we then realize that he keeps listening behind their door while they talk with Bolek.

In the last scene Aurelio realizes that his actions have been exposed and that he might face serious consequences; hence he decides to quickly leave his place and to settle for a while at his sister's place. The act ends with Aurelio leaving the apartment troubled and anxious about the future.

Act 3

The third act is set on the second floor of the building.

The act opens with Carmen Bruni, a 65-year-old impulsive woman, enjoying a quiet afternoon when she receives a call from a friend, discussing plans for the dinner that Carmen will host that night. After the call, Carmen prepares to go shopping for ingredients and interacts with her young son Francesco, who mentions possibly staying in to watch a TV series that night. In the next scene we see her meeting and exchanging a few words with a neighbor, Pietro, while he is leaving in a hurry for a friend's (Leone) birthday.

Afterwards we see Pietro at Leone's party talking about his much younger partner Bianca, who remained at home, and getting drunk for too many drinks. In the meantime, friends arrive at Carmen's place, and they begin a card game, discussing local gossip and personal anecdotes. In the next scene we see Francesco visiting Bianca instead of going out with his friends. They watch a movie together and we understand that they are more than friends by their jokes and complicity. In the last scene, after that Francesco comes back to his place, taking care not to get caught by Pietro, Pietro arrives at home pretty drunk and exchanges a few words with Bianca, upset for him being in that status.

Act 4

The fourth act is set between the annex and the building.

The act opens with Sharon Monteri celebrating her tenth birthday at home with her mother Miriam, her father Mirko, her grandmother Annamaria and her brother Giovanni. The scene is warm and familiar, with Sharon blowing out the candles on her cake, but then Giovanni reacts badly at a sister's joke and locks himself angrily into his bedroom. In the following scene Giovanni is reprimanded by Miriam for his indifferent attitude towards his sister's birthday, but also about Giovanni's little help at home and his recent struggles at school. The discussion becomes a reflection on the mother's expectations, with Giovanni feeling misunderstood and alone. Afterwards we see Mirko, who was listening from behind the door, taking care of Sharon, who was left alone after the cake cutting.

In the following scene we see Miriam discussing with Annamaria (her mother in law) the challenges she has been facing so far to balance the career as a lawyer and the family life. In the scene we also get to know that Giovanni has another father who was addicted to alcohol and created a lot of troubles for Miriam, finally leading her to go away with Giovanni. In the next scene Giovanni is together with his grandmother, Annamaria, as she shares memories of her past. This intergenerational exchange deepens Giovanni's understanding of his family's history and values, helps him to understand especially his mother's perspective and reassures about how much she cares about him. The act closes with a final moment of relaxation: Miriam, Sharon, Giovanni and Annamaria share some biscuits that Miriam and Sharon just cooked and then all of them but Miriam bring some biscuits to the neighbors in the building.

Act 5

The fifth act is set on the third floor of the building.

The act opens with a dinner in a tense atmosphere at Davide's home. His father returns home to find the family already eating without him and the (unemployed and lazy) wife having done nothing for the house which is a mess. An argument pops out between Davide and his parents about his unsatisfying outcomes at school despite the private lessons he usually takes. The parents keep arguing despite him trying to stop them. Thus, Davide escapes to the communal rooftop terrace, seeking calm through painting sunshine, to cope with the family tension.

While painting, Davide is startled by Giovanni (from the previous act) who unexpectedly arrives with a tray of biscuits and they engage in a short conversation. Giovanni tries to lighten the mood, but Davide remains distant, reflecting on his isolation and the lack of familial connection, especially since his brother moved out for university. Davide's brother, Edoardo, calls to check on him, sensing something might be wrong. Davide struggles to hide his distress during the call. Edoardo decides to visit, and their reunion on the terrace is bittersweet, filled with mixed emotions. They discuss family issues and personal challenges, finding comfort in each other's company.

The evening deepens as Davide remains alone on the terrace. He reflects on his desire for a happier family life, symbolized by a red heart-shaped balloon floating into the sky. The act closes with a family reunion when both parents come up to the terrace to reconcile with Davide. His mother regrets her harsh words, and his father tries to explain his side, both acknowledging their mistakes. This emotional reconciliation is marked by genuine apologies and Davide expressing his love for them, hinting at a possible healing within the family.

Kairòs-ONSCI

"Above the sea"

Bus

Alfredo's monologue at a bus stop meticulously details his routine, emphasizing his life's circular pattern, dominated by the care for his ill mother and a monotonous job. He describes his day starting with a precise schedule: waking up, taking care of his mother, commuting to work on bus 57, and returning home to repeat the cycle. His routine is disrupted when bus 57 is late, causing him anxiety about being late for his mother. This delay introduces a moment of existential reflection as he observes another passenger choosing a different route, prompting him to question his own life choices.

Camilla

This monologue explores the return of Camilla, the protagonist, to her small-town life after a traumatic earthquake interrupts her university studies in anthropology. She reverts to a routine lifestyle, seeking solace in its predictability and safety. The writing captures her reflections on the simplicity and repetitiveness of her days, contrasting her initial desire for adventure - that had driven her to move out from home - with her current appreciation for stability. Another earthquake challenges this peace, prompting Camilla to question her assumptions about safety and routine. It symbolizes a new beginning, not just a return to the old, highlighting her evolving relationship with the concept of time and change.

Efrem's routine

Efrem, a 37-year-old from Bologna, grapples with emotional turmoil following an unexpected breakup. He decides to visit a sexual health center for the LGBTI+ community, which represents a literal and metaphorical test of his resilience and ability to manage life's uncertainties. As he prepares and makes his way to the center, he reflects on his relationships and the transformative nature of love, influenced by philosophical thoughts on how love challenges and enriches one's identity.

Post-visit, Efrem feels a mixture of relief and introspection, supported by encouraging messages from friends who reassure him. This reinforces his community bonds and the importance of such support in personal crises. Efrem then ponders the concept of routine, viewing it not as a strict schedule but as a dynamic comfort that provides stability and identity, especially when navigating changes in personal relationships. Through this experience, Efrem gains profound insights into himself, understanding the therapeutic nature of routine and the significant impact of love and relationships on personal growth.

Gigi

Gigi, a librarian, daydreams about the various lives he could have led—chef, musician, educator—while stuck in the monotony of his current job. Each day, as he randomly comes across a book left on library tables, he imagines possible futures, only to be taken back to reality by the sound of a bell signaling that the library is closing. The narrative reveals his struggle with regret and the fear of change, pondering over missed opportunities and what might have been. The bell, which typically snaps him back to his duties, eventually breaks, symbolizing a potential escape from his cyclic routine and the possibility of exploring new paths finally.

Lara, complex girl

The monologue features Lara, a young girl who is always governed by emotions, constantly improvising, and unable to reflect deeply until the last moment. Despite consuming vast amounts of knowledge through reading and observing, thoughts vanish when she tries to focus, but then apparently when she is under exam pressure or assignments, her thoughts and words spontaneously flow, creating "conceptual masterpieces." She nostalgically recalls her school visit to a library, where she was asked to do something that she loved so much like reading books, but also asked to summarize them. Despite the pressure and anxiety over potentially misunderstanding the deeper meanings of books, she has always managed to creatively fill out that assignment but also other ones – such as translating versions from Greek - using her imagination.

Lucio and Gaia

Lucio, a meticulously organized and appearance-conscious bank teller, prepares for a highly anticipated date with Gaia. His lifestyle is rigorously disciplined, characterized by regular exercise, a carefully curated diet, and a commitment to his appearance, including a passion for collecting pristine, often unworn shoes. This attention to detail extends to his professional life, where he is punctual and precise, albeit frustrated by a lack of recognition and advancement.

On the evening of the date, Lucio's preparation is disrupted by an unfortunate event—he steps in dog feces, ruining his new shoes. This incident plunges him into a flurry of anxiety and overthinking, fearing judgment and embarrassment in front of Gaia. Lucio's reaction to the accident reveals his deep-seated concern with maintaining control and perfection in all aspects of his life, from his physical appearance to his social interactions. Despite the setback, he tries to salvage the evening, showcasing his resilience and his ability to manage unexpected challenges, albeit with a mix of humor and distress.

Getting lost

The scene features Mario Bardelloni, a 95-year-old man, on a lonely Christmas morning at home. Surrounded by pictures of his past, he recalls to his mind the celebrations for his wedding day and a family

trip to the Grand Canyon. Mario pauses at a photograph of this trip, reflecting on his children and grandchildren, wondering about their lives now. As he continues, he stumbles upon an old black and white photo, struggling to remember a childhood friend from grape harvesting days. Frustrated and sad, Mario's memory fails him as he tries to place names and faces in his address book, so that we get to know that he is afflicted by Alzheimer disease. Finally, he resolves to ask his son Luca for help, hoping to share those cherished memories with his grandchildren.

Teodoro at the market

Teodoro, a man in his thirties, takes us through a day marked by an unexpected disruption during his usual routine. His intellectual work typically gives his days a predictable rhythm: market visits, caring for his routine needs, and enjoying quiet evenings.

One winter evening, as Teodoro walks through the bustling market, great confusion is created by the passage of a thief, and this breaks the flow of his day, evoking a rush of emotions. This event brings Teodoro to reflect on his life's monotony and the unpredictable nature of time, symbolized by the circular routine disrupted by the incident. As Teodoro observes the chaos, he experiences a moment of introspection and connection with a passing stranger, a young quiet woman walking on the beach which contrasts sharply with the surrounding turmoil. This encounter, brief yet profound, leaves Teodoro contemplating the larger meanings of his encounters and the paths not taken. The day concludes with Teodoro retreating into a quiet night and his thoughts going back to the experiences he had lived.

3.3.2 First round of data analysis

It is not trivial to analyze fictional texts with the goal of extracting some information about writers' perspective (Martella et al., 2013). Indeed, when it comes to interviews which are made of questions and answers, even though it is always useful try to read the "unspoken" and "unexpressed" and read between the lines of what is said (Kvale, 2007), the interviewer has anyway an explicit layer shared by the interviewee. In other words, it is possible to say a person has a specific perspective around something based on the fact that the same person explicitly reported that perspective.

With fictional texts this is not possible, hence we have to recall other strategies. In the present case though, being aware of the constraints that informed the writing was helpful in letting me enter the data. Actually, a very strong constraint placed by the literature teacher was to develop the features of each character upon the characteristics of a specific time. Hence, if one of the analysis objectives is to inquiry how the four times were *conceptualized* and *represented*, the starting point could be focusing on the characters and considering them as our "units of analysis":

"In order to bring out the different faces of the time, we have not made explicit references, everything lies in the actions and words performed and spoken by the characters " (one of the authors of the fourth Act, during a personal conversation).

To this purpose, I present two tables that are a taxonomy of all the characters, one for Kairòs-Einstein and the other one for Kairòs-ONSCI. Each table is divided into four parts grouping all the characters representing each kind of time. Then for each character physical information but also some psychological information are noted down in the first column.

Besides the first column there are two other columns (Table 4), one indicating the *representation* of the kind of time and one indicating the *conceptualization* of that kind of time. Because different kinds of time have been conceptualized and represented into characters by different people (for Kairòs-ONSCI) and by different people in different groups (for Kairòs-Einstein), we do expect a difference in the dual process of “conceptualization and representation”.

What do I mean by *representation* and *conceptualization*?

The first column – *representation* – gathers the “objective” data, in the sense that it contains the description of how a specific time with related features has been translated into characters’ traits or their personal stories. This column gives an overall picture of the mapping intentions for students, and it is objective in the sense that it is not an outcome of analysis but just a record. It comes indeed from the characters’ sheet that each group put as an introduction to their act.

In the table below is shown an excerpt from the detailed characters’ sheet of Group 4, which explicitly reports how the time was embedded in the characters. This is the most detailed, whereas the other groups not only produced less detailed descriptions but also sometimes did not mention how their characters were connected to the times (see Table 2).

Miriam Valletta	<i>Her mother, Miriam Valetta, is thirty-three years old and a lawyer. Until the age of nineteen she lived in Rome, her hometown, then moved to where she now lives to study law. In her life she has had to face many difficulties such as a pregnancy at the tender age of sixteen, with an eighteen year old boy who initially seemed the right one, so much that when Miriam came of age they went to live together to both take care of their son Giovanni. After a year, however, her boyfriend started going out every night, coming home drunk, he no longer cared about his son and began to be violent when Miriam tried to talk to him to improve their relationship. Miriam put up with the situation until the day she came of age and because in her heart she hoped everything would go back to the way it was before. Seeing, however, that things got worse the more time passed, she decided to leave him and take Giovanni away so that he could live in a healthy and happy environment. Miriam is very protective of her son precisely because she spent the first years of her life protecting him from his father's slaps and has given and continues to give him all so that he does not have to bear the brunt of what happened in the past.</i> <i>Because of what she had to suffer, she first denounced her fiancé and later moved with Giovanni to study law so that she could help all those in difficulty and above all to defend women who, like her, had to go through that kind of hell. After a few years, she met Mirko, a man with whom she fell in love, whom she married and with whom she finally spent the life she wanted.</i> <i>The time allotted to her is Kairòs, because Miriam is able to seize the opportunities that life offers her wisely.</i>
Mirko Monteri	<i>Her father, Mirko Monteri, is 35 years old and was born in the province of Terni. He was and still is very attached to his family, in fact he still lives with his mother, who, together with Miriam, is a fundamental woman in his life because she gives him security. His father, who was a soldier, died when he was just a child during an expedition in Afghanistan.</i> <i>Mirko is a slacker, particularly lazy in fact he spends most of his time in his armchair watching television, despite the fact that he is still young and could very well go out. He always remains impartial and only takes sides when forced to by his mother or wife. He worked for a long time in a supermarket as a butcher and it was there that he met Miriam, but then he was fired due to</i>

	<i>several absences, so he is currently looking for a new job. To make himself useful, he tries as best he can to help with the housework, but being very clumsy he often leaves it to his mother. Mirko, however, is very good at downplaying everything and always has a joke ready.</i> <i>The time assigned to him is Eniautòs, because it is the circular time linked to Mirko's ordinary routine.</i>

Table 2: The description of two characters in the characters' sheet from Group 4. As it is evident there are both a detailed description and an explicit argument for how and why that character represents a kind of time.

Karen Poledro	• 50 years old • Gossipy (always attentive to the movements of condominiums; always has a notebook nearby) • Control addicted • Barbara d'Urso (a famous italian TV host) fan • Wears floral dresses and flip-flops all year round
Loretta Campanello	• 72 years old • Supermarket clerk • Sporty (passionate about aerobics, Pilates and yoga) • Argumentative, snobbish and insufferable • Very bossy toward her husband (doesn't help much at home) • Goes out a lot with her friends • Claims to be 35 years old • Flashy clothing and makeup

Table 3: The description of two characters in the characters' sheet from Group 1. As it is evident the description is made by bullet points and it lacks an explicit argument for how and why that character represents a kind of time.

Hence, for groups as the one of the first Act I was forced to use additional material:

1. I contacted the students via e-mail and asked them if they could add some more information about their characters and if they could specify what time each figure was representing and why.
2. I used the written answers that some of the students produced for the homework delivered by PF in the last lecture. Indeed, in those documents they share here and there something about the characters and how they dealt with the time-representation.

For what concerns the second sample, Kairòs-ONSCI, the essays just involve one character each, so one kind of time. Furthermore, each of the essays has a commentary by the author which resembles the main aspects of the character and its connection with the specific time chosen.

The second column – *conceptualization* – is the outcome of an interpretative step of analysis, in which I unpacked the features chosen by students to represent their time and traced back to where such features were coming from. Behind this process there is the assumption that students could have represented in the figures' characterization only the features of time they did conceptualize over the lectures (both within physics and literature times' descriptions). Hence, it seemed interesting to check for each of them what features they conceptualized – associated to the different times – and what not (for exclusion). This inferential step allowed me to have a connection between a disciplinary feature of time (either from literature or physics) and the way it was represented.

Kairòs-Einstein table

The table below is linked to the Kairòs-Einstein implementation.

Main features	Representation: How the kind of time is represented (how features are displayed)	Conceptualization: How the kind of time is conceptualized (features chosen)
KAIROS characters		
Danish (Act 1): - 43 years old - Grumpy - Cook	Danish represents Kairòs because he made the difficult choice to leave his family and come to Italy, and it was a no-return choice.	Kairòs as the time of contingent events that lead to irreversibility (physics-based conceptualization).
Martina (Act 1): - 20 years - Intelligent and ironic - Open and sweet - Student	Martina represents Kairòs because she has a drive towards change, she wants to break away from the monotony of things and find her own path, which is unique. She wants to find a new "order" as a solution to her internal tumult, for example a new life at the university.	Kairòs as the break of time-symmetry. Also, as the time when new kinds of orders are generated within the system (physics-based conceptualization).
Vittoria (Act 2): - 36 years old - Gentle - In love - Florist	Vittoria represents Kairòs because every day she takes an opportunity to cultivate her love for her husband, by bringing a flower to him from her workplace.	Kairòs as the cure for every moment, however, to make a simple moment the chance for something special. Here the author seems to have conceptualized Kairòs mostly through literature rather than physics.
Francesco (Act 3): - 26 years - Shy and antisocial - Clumsy - Unemployed	Francesco represents Kairòs through unpredictability, being the least (non predictable) obvious person as a son for his mother and the least suitable lover for Bianca. It is unpredictable in the sense that "one would not expect it". A visible consequence of his being "less suitable" is that he is an awkward character, as he often stumbles and acts in a clumsy way. These choices have been made to represent a general sense of instability. He also has a hidden relationship as a new feature, order, of his life.	Kairòs as featured by unpredictability. Kairòs as the time of the "instability". Kairòs as the time for new order. All these elements show a physics-based conceptualization.

Bianca (Act 3): - 24 years - Elegant - Unfaithful - High-level cashier	Bianca represents Kairòs because she indulges in something new and unexpected - a romantic affair outside of marriage – deciding to seize the opportunity.	Kairòs as the time for the emergence of a new order (physics-based conceptualization).
Miriam (Act 4): - 33 years - resourceful - Lawyer	She represents Kairòs because she had to face no-return choices. Also she had to took the opportunities and being wise about her decisions.	Kairòs as the time for irreversibility and new order (physics-based conceptualization). Also, Kairòs as the moment in which we have to be wise and make a profound reflection (related to a literature-based conceptualization of Kairòs).
AION characters		
Aurelio (Act 2): - 69 years old - Intrusive - Snitch - Problematic - Retired	Aurelio represents Aiòn by isolating himself from the others. He isolates himself because he is afraid of other people's judgment.	Aiòn as an “absolute time” which is above the events (and hence by what occurs to people). Physics-based conceptualization.
Bolek (Act 2): - 41 years old - Introvert - Cook	Bolek represents Aiòn again by detaching himself from reality and people, driven by distrust towards the others.	Aiòn as an “absolute time” which is above the events and people (physics-based conceptualization).
Annamaria (Act 4): - 60 years - Youth - Positive - Retired	Annamaria represents Aiòn because she always seems young and not subject to the passing of time (she also has a positive and youthful feeling). She also represents Aiòn because the memory of her husband lives in her.	Aiòn as a time suspended, which does not flow; as a time “de-temporalized” (physics-based conceptualization). Also, Aiòn as the time of memories, which live for eternity (literature-based conceptualization).
Davide (Act 5): - 17 years - Sensitive - Sad - Lonely	Davide represents Aiòn because he isolates himself from hateful circumstances, namely his parents' quarrels. Aiòn is a time which loses its temporal connotation to become more similar to a space; the clock stops, because it is painful	Aiòn as an “absolute time”, as a time of suspension, de-temporalized (physics-based conceptualization).

- Creative - Student	to spend time with family and then it restarts only when the tension is resolved.	
CHRONOS characters		
Salvatore (Act 1): - 69 years old - Gentle - Doorman	Salvatore represents Chrònos because he feels time passing, he witnesses people arriving and then leaving in the building, whereas he always remains there. His uniform also shows the sign of time.	Chrònos as the time of human degradation, as widely described both in philosophy and literature (literature-based conceptualization).
Giulio (Act 2): - 57 years old - Gentle - Orchestra director	Giulio represents Chrònos since he is devoted to consolidating over time what he loves the most in his life: his wife and his job, music.	Chrònos as the arrow of time, as the time which marks an evolution, as for the physics interpretation (for instance in the second principle).
Sharon (Act 4): - 9 years old - Curious - Happy - Student	Students show to have an incorrect conceptualization hence this impact their representation: <i>"The time assigned to her is Chronos, that is, the time that holds within it the possibility of living beyond decay and the passing of time, which refers to the ability of children to know how to live with serenity, not minding the wickedness that lurks in the world"</i> .	Chrònos as the time beyond degradation: wrong "conceptualization".
ENIAUTOS characters		
Karen (Act 1): - 50 years - Snobbish - Authoritarian - Flashy - Cashier	Karen represents Eniautòs because of the repetitiveness of her routinary commitments, particularly physical activity. She also displays a sense of control of her routinary time which ends up faltering in the final scene where she burns her husband's clothes.	Eniautòs as a time of repetition, a cyclical time (literature-based conceptualization).
Loretta (Act 1): - 72 years old - Gossip and intrusive - Available to others - Simple - Retired	Loretta represents Eniautòs because she knows the routines of all the characters and helps them recall what they did if they forget about it. She represents the "idea of control" since she has the dynamics of the condominium under her control.	Eniautòs as the physical time of repetition, of things happening at the same time (literature-based conceptualization). Also, Eniautòs as a time you can use to measure events (the idea of clock) and so to feel things under control (physics-based conceptualization).

Maurizio (Act 1): - 32 years old - Simple - Dog related - Yoga dog teacher	Maurizio represents Eniautòs since he is subject to the routine imposed by his dogs.	Eniautòs as a time of repetition, of things happening at the same time (literature-based conceptualization).
Carmen (Act 3): - 65 years old - Elderly - Funny - Retired	Carmen represents Eniautòs because she relies a lot on the routine of gestures and timetables, to keep herself alive and manage her love disappointment.	Eniautòs as a time of repetition, of things happening at the same time (literature-based conceptualization).
Pietro (Act 3): - 34 years - Sporty - Winning - Financial investment entrepreneur	Pietro represents Eniautòs because he is identified with his work, which is depicted as very routinary. Pietro represents (as Loretta) Eniautòs' "idea of control": this is shown by his relationship with the body (he has a well-groomed body that must be constantly maintained through the gym). Indeed, the fact that he stumbles is just a parenthesis that happens when he is drunk (a loss of control).	Eniautòs as a time of repetition, of things happening at the same time (literature-based conceptualization). Also, Eniautòs as a time you can use to measure events (the idea of clock) and so to feel things under control. I see in this again a physics-based conceptualization.
Mirko (Act 4): - 35 years - Humorous - Lazy - Immature - Unemployed	Mirko represents Eniautòs because he has an ordinary routine (he used to work at the supermarket but now he spends every day at home, on the sofa).	Eniautòs as a time of repetition, of things happening at the same time (literature-based conceptualization).
Giovanni (Act 4): - 17 years - Negative - Depressed - He feels excluded - Student	Giovanni represents Eniautòs because he is mentally stuck in a negative loop, in the constant flow of days which appear to him repeating endlessly. The circularity is enhanced by being reproached by his parents for the same things whose meaning he doesn't understand.	Eniautòs as a time of repetition, of things happening at the same time (literature-based conceptualization).

Table 4: Characters' taxonomy from the first implementation.

After completing the table above, I started to look for patterns, especially within different time groups, but also considering other “cross-times” groups as gender or age of the characters. I report here the patterns.

Kairòs

Kairòs has been conceptualized by recalling diverse features mostly coming from the physics domain: the moment which leads to irreversibility, the moment of time symmetry-breaking, the moment of instability, unpredictability and the time preceding the emergence of new orders.

In particular:

- in 3 characters there is a reference to the time-moment leading to irreversibility (in the conceptualization column), which has been represented as a difficult choice to make, already taken (Miriam and Danish) or still to take (Martina).
- in 4 characters there is a reference to the emergence of new orders which are represented as changes in life, from having an affair to going to the university or separating from the partner. Furthermore, the features of instability and unpredictability are represented by Francesco being clumsy and stumbling all the times.

One aspect that stands out is that the Kairòs characters are all young, with the oldest character is 43 years old. This does not seem to be random since it is consistent with the fact reiterated by group 3 in one email exchange that the older people all have their own routine (and therefore in this case they are more likely Eniautòs): *“The routine that belongs to every elderly person of our time”*.

Aiòn

Aiòn has been conceptualized as an absolute and de-temporalized time, again mostly recalling its interpretation within the physics discipline. These features have been represented in the stories by characters who generally isolate themselves from other people. Related to this it seems that enhancing in the first lectures the idea of Aiòn as a time “without temporality” untied by the events (absoluteness), opposite for example to Chrònos which is the time that orders the events, brought students to conceptualize Aiòn more as a space than as a time.

That in particular opened the chance to represent Aiòn as a way out to temporal painful situations: indeed, in the stories we observe that the time-flow is associated to painful situations for all the Aiòn-characters (a fight in the family, anxiety for being caught, the advancing old age) who end up finding refuge within Aiòn. This aspect is described in Section 4.

Chrònos

Chronos’ characters are different between each other. Thus, we see one character, Salvatore, which is built around the concept of degradation, on the strand of a long literary legacy; on the other hand instead, we have Giulio which is developed around the physical idea of Chrònos as the time which marks the evolution, which describes the trajectory of the world.

Anyway, the table shows that Chrònos was the least picked time by students, proving the intention for both the teachers to focus on alternative images of time and to question Chrònos dictatorship (Hassan, 2003; Rosa et al., 2013).

Eniautòs

Eniautòs has been conceptualized as the time of routine. Also as the time within which things repeat themselves after a specific time-range (period).

Even though the conceptualization is pretty the same for all the characters, the representations change accordingly to groups and authors, proving the utility to differentiate between conceptualization and representation in the analysis.

For some characters indeed the repetition is displayed by routinary commitments, like doing physical activity or walking the dog. For other characters instead, as Giovanni or his mother Carmen but also Loretta, the repetition is not embedded in the things to do but in the way the figures feel their life is going on: for Loretta and Carmen starting every day with some sort of security given by the routine is a way to find a state of tranquility whereas Giovanni feels the repetition as a sort of prison made of daily reproaches from his parents.

In addition to repetition, Eniautòs has been associated with the idea of measurability. This was represented mainly by characters showing the “need” to control, both their daily schedules for example to optimize them and more generally in the sense of controlling everything that goes on around them (Loretta). I claim here that maybe the physical conception of periodical time (Eniautòs) that can be measured because of its period, while this period can be used as a clock to make time measures of something else, has been translated into the writings as “controllability”. In other words, the idea of “measurability” has been translated into the idea of “controllability”. I will elaborate more on this aspect in Section 4.

Across-time patterns

Some trends seem to emerge looking at the gender, the age and the jobs of the characters.

- 1) If we consider the very young characters (an age similar to the authors’ one) and separate according to the gender, we see that:
 - females display a positive attitude but above all are mature and wise. For example, Martina thinks about her future in a proactive way, able to verbalize consciously her inner tension but also capable of indicating what she really wants. Sharon, a 10 years old girl who is described as already very wise, manages to accommodate situations better than her 17-year-old brother.
 - males on the other hand tend to be characters in a negative and depressed phase. They are in conflict with their parents and as a consequence they isolate, finding refuge by locking themselves in their room (Giovanni) or escaping on the terrace (Davide). They are in a situation of unbalance, they don’t know what they want and seem prey to their destiny.

Also other two characters from Act 3, Francesco and Bianca, although a little older, mark this duality. Francesco is a little shy, clumsy and locks himself in his room whereas Bianca is already married, confident and works, even though they are the same age.

- 2) Looking instead at the age of the characters, whatever time they represent, I have the impression that those with a more nuanced characterization are either young or old, whereas the characters who could be (or are) of the same age of students' parents, are outlined in a more superficial way (apart from Miriam). It seems indeed that students did not pay that much care to develop characters in that age-range.

Even more indicative seems to be the case of the last Act. The main character is certainly Davide, who is witnessing a heavy discussion between his parents who are not even listening to him when he asks them to stop, hence he leaves. In this Act, even though the parents appear in two scenes, they are just mentioned as "Mom" and "Dad", not even given a name, whereas Davide's brother (a few years older than him, so close in the age) who appears in just one scene, is mentioned with his name (Edoardo). I claim that these elements suggest something which goes beyond the realm of chance, which is discussed in Section 4.

Kairòs-ONSCI table

Here I show the table from the second implementation, Kairòs-ONSCI.

Main features	Representation: How the kind of time is represented (how features are displayed)	Conceptualization: How the kind of time is conceptualized (features chosen)
KAIROS characters		
Lara "Lara, complex girl"): - Young lady - Passionate about books - Loves to create stories - Student	Lara represents Kairòs through her aptitude for improvisation. Also, Lara represents the emergence of a new order since she describes her inner psychological mechanisms that lead her every time to find out a new solution, different from the one expected by her teachers. For example, she doesn't translate the version or fill the character sheet but she uses the assignment as a chance to create stories.	Kairòs as the time of chance (conceptualization based on the Greek philosophy). Kairòs as the moment in which there is an unpredictable choice of the future states. Kairòs also as the moment in which a new order emerges (physics based conceptualization).
AION characters		

Mario (“Getting lost”): - 95 years old - He has Alzheimer - Nostalgic - Attached to his family - Retired	Mario represents Aiòn since he is forced to stay “out-of the time”, disconnected by events. He recalls pictures as a support to live connect again with the time of the events. His Alzheimer is making him loose his temporal connotation.	Aiòn as an absolute time, eternal and as a time “de-temporalized” (physics-based conceptualization).
CHRONOS characters		
No Chrònós characters		
ENIAUTOS characters		
Alfredo (“Bus”): - Middle aged man - Cares about his mother - Office employee	Alfredo represents Eniautòs since he repeats every day the same actions, at the same time, both at work and at home. Also, the presence of the clock is a way to reinforce the reference to Eniautòs (a periodic time that can be conceived as a clock).	Eniautòs as the time of repetition (literature-based conceptualization). Also Eniautòs as a time to measure events, related to the idea of a natural clock (physics-based conceptualization).
Gigi (“Gigi”): - Middle-aged man - Unsatisfied from his life - Librarian	Gigi represents Eniautòs because he has a routinary job, working in the library. Also, he repeats the same pattern every day, imagining a life that he did not choose to do but that in his mind he could have done.	Eniautòs as the time of repetition (literature-based conceptualization).
Teodoro (“Teodoro at the market”): - 30 years old - “Intellectual”	Teodoro displays Eniautòs because he is a worker that has his own routine, from office to home every day. The routine is something he really cares about as it shows his deep upset when an unexpected event “ruins” (as he says) his day.	Eniautòs as the time of repetition (literature-based conceptualization). The link to time-tables recalls the idea of clock and measurability (physics-based conceptualization).
Lucio (“Lucio and Gaia”): - 39 years - Healthy	Lucio represents Eniautòs through his very tight and repetitive schedule.	Eniautòs as the time of repetition (literature-based conceptualization).

- Loves shoes - Works in bank	Also, he represents the idea of “measurement” since he reports the timetables for each of the training sessions as well as for work habits and free time (e.g. “Saturday at the church”). The idea of measurement is embedded in his need for control that he expresses also during the appointment: he gets upset because he is no more in charge of time management.	Again is also connected to the idea of measurability (time-schedules), so more related in this aspect to physics-based conceptualization.
Efrem (“Efrem’s routine”): - 37 years - Coming out of a relationship - Deep person	Efrem represents Eniautòs through his intention to go back to his routine. This time the routine meaning is deeper with respect to other characters. Indeed, he questions the idea of an empty routine, still he shares the importance of having some sort of repetition as a “hand holding” to the sense of his identity.	Eniautòs as the time of repetition (literature-based conceptualization).
Camilla (“Camilla”): - 47 years old - Comes from a village - Works in her own farm	Camilla represents Eniautòs in the sense that she grounds her confidence and serenity on the expectations that every morning she will see the same places around her and she will have a positive and peaceful day.	Eniautòs as the circular time, as the time that makes things repeat every day (literature-based conceptualization).

Table 5: Characters’ taxonomy from the second implementation.

Kairòs

Kairòs here is conceptualized as the moment of chance (from greek literature) but also as the moment in which fluctuations and instability lead to the emergence of a new order. Such features of a Kairological kind of time are then represented as properties of the protagonist, Lara. She is restless and reveals to the reader her inner turmoil, especially with respect to school and homework.

This is new compared to the characters from the previous table. In the Kairòs-Einstein table characters had to take choices, whereas here we see no particular choices. In this case, Kairòs refers more to a time in which the internal noises of the system, coupled with external noises, determine the emergence of new orders. These new orders can be interpreted as the original stories that Lara creates in doing the sheet homework or when translating from Greek.

Nonetheless, we can notice that again Lara, a representation of Kairòs time, is a young character in continuity with the Kairòs-characters from the first implementation.

Aiòn

Aiòn is conceptualized with some of the features already seen in the other implementation, as the time which is eternal and is de-temporalized, even though it seems to miss the “spatialization process” that was emerging before. In that case we discussed how - in at least 3 out 4 examples - Aiòn was first de-temporalized and then spatialized into an “abstract space” where to take refuge.

In this second implementation, the de-temporalization does not lead to a spatialization, being a very different kind of de-temporalization. Mario can't help losing memories and his “time-connotation”, the ability to order the events of his life and place them in a time continuum. The pictures show events with a precise temporal-connotation, hence serving as triggering temporal objects to stimulate Mario's memory and let us readers to understand that Mario suffers from Alzheimer.

In the previous case the characters felt a pain associated to the time-flowing, they were aware of the events occurring one after the other. Because of that indeed, they were trying to stop the time that was torturing them and find another form of time - Aiòn - detached from the events. Here instead, we see an opposite trend: Mario has been forced to temporally detach himself from the events, and he suffers because of this temporal forced alienation.

Eniautòs

Eniautòs is the most chosen kind of time in this second implementation. It has been mainly conceptualized with the features of repetition and circularity, with references to days or weeks passing away all alike (in continuity with the previous implementation).

Furthermore, there is again the idea of controllability that emerged in the first implementation, specifically in two characters (Alfredo and Lucio); related to this it is remarkable that the controllability is pinned in their two monologues by the presence of a “clock”, the object that takes trace of the time and helps out to control it. Therefore, the clock as a way to exercise control over time, here expressed even more clearly than in the other dataset. These two figures are completely devoted to respecting the time schedules they created for themselves, without any sort of flexibility. Hence, when unforeseen events occur, they are confused (Alfredo) or upset (Lucio) because to them those mean not only a loss of time but also a loss of control over their life.

The other two characters, Camilla and Efrem, seem to experience Eniautòs at a more profound level, not as just a schedule used to optimize the days. The sense of repetition and circularity that these two characters show is strongly intertwined with their sense of self, of who they are and how they manage their life. For Camilla, coming back to the routine is a way to face her stressed period after the earthquake, finding peace of mind by repeating the same actions every day, whereas Efrem disclose a reflection about what routine is to him, not something to use for keeping the pace of days and ordering the events but something through which he can find again his inner balance after a moment of disequilibrium. In section

4 I discuss these nuances emerging from the monologues and build an argument about their relationship with identity development.

Overall considerations

In the first implementation two clear trends emerged from the table: i) the young females as strong, positive and mature characters compared to the young males, negative and depressed; ii) the young and the old figures nuanced in their characterization, whereas the middle-aged ones much less.

In this case, none of the characters has a very young age, but we can zoom out and check if there is any difference between male and female whatever their age. Apparently, there is no such difference in terms of awareness and maturity between males and females. If, for instance, there is Efrem which seems worried about his future and he needs to find again himself by coming back to the routine, on the other side Lucio has a strong and pro-active attitude towards life, taking care of himself both physically and socially. Also, Camilla displays a more confused behavior whereas Lara is strongly rooted in the awareness of her qualities and what she wants to do in her life.

For what concerns the second point, due to the constraints introduced both by SM (focus on the inner psychology of the character) and by the different nature of the writing (monologue instead of a play), all the characters appear as non-trivial and multifaceted. This difference does not surprise since in the previous case each group of students had to deal with more than one character whereas here each author had to develop only his character.

Finally, the difference in the composition of the group of participants may lead us think that maybe , at least the lack of differences between female and male figures²⁸ positively relates with the age and conditions of the authors. There could be good reasons to argue such pattern being a projection of a feature of that class. In other words, I am trying to sustain the idea that the activity as it was structured provided the participants with the “room” to express something related to them as a group, as a class (expression which is lacking when there is no group, as in the second case). I will discuss further this idea in Section 4.

3.3.3 Second round of analysis

The idea of this analytical-step is to use the markers elaborated within the master thesis of Veronica Ilari as a lens to investigate what positioning students assumed with respect to the new kind of times introduced by the Kairòs project. The bottom line of this is that whatever form of time we have, Kairological, Chronological, etc., is the way we relate to it that tells if that time is felt as an internal time or rather an external one. As PF reports in the interview indeed: *“All four times can be internal or external...”* and are internal if they *“...help manage the personal phenomenon of life”*. Still, as mentioned above, PF had the sensation that in Kairòs-Einstein students were still attached to external forms of time.

²⁸ The second point, as discussed, is instead due to structural constraints.

Hence, the goal here is to use the markers to check if the design constraints introduced in the second implementation, to support a more personal way to relate with time and scaffold the expression of what has been called an “internal time”, produced the desired outcome.

Data analysis

At an operational level, I coded both the data samples using as a top-down codebook the markers produced introduced in Table 1. Then, I reported to NVivo 14 the codebook and coded sentences. In the two tables are displayed the entries for each marker, linked to each act of the pièce and each monologue.

External time	Kairòs_Act 1	Kairòs_Act 2	Kairòs_Act 3	Kairòs_Act 4	Kairòs_Act 5
Spectator of time	4	0	0	2	0
Conventional structure which organizes events	6	0	8	6	0
Modular and homogeneous structure	4	0	0	1	0
Time of the reversible trajectory	4	0	0	1	1
Internal time					
Time actor	4	1	1	3	1
Structure internal to events not regulated from outside	1	2	5	2	2
New and non-homogeneous structure	5	0	0	6	1
Time of the irreversible trajectory	4	0	0	2	2

Table 6: Entries for each of the five acts.

External time	Bus	Camilla	Gigi	Teodoro at the market	Efrem's routine	Lara, complex girl	Lucio and Gaia	Getting lost
Spectator of time	1	0	1	0	0	2	0	0
Conventional even organising structure	1	0	3	0	1	0	4	0
Modular and homogeneous structure	0	3	2	5	0	0	0	0
Reversible time trajectory	0	2	1	0	0	0	0	0
Internal time								
Time actor	0	0	0	0	4	0	0	0
Internal structure not regulated from outside	0	0	0	0	5	0	1	0
New and non-homogeneous structure	0	1	0	2	1	0	0	3

Irreversible time trajectory	0	2	2	0	1	0	1	4

Table 7: Entries for each monologue.

The first thing to report is the difficulty I noticed when trying to code with this set of markers; even though I had the definitions as a support to decide if a sentence was more related to a marker or another, still I had the constant impression that these markers and their definitions were often too specific and narrow to be applied.

This, in my opinion, is related to a structural mismatch between the analytical instrument (the codes) and the unit of analysis (sentences of the texts). The goal of such codification is to map where and how students reported time as internal or external; this is something linked to the **way** students thought and positioned themselves with respect to time, whereas the present codes seems to be able just to see if the structure of the time displayed is closer to an image of internal or external time, as conceptualized within physics of complex system.

Such misalignment is evidenced by examples in which the codification mapped the kind of time associated to a character as internal or external and by checking students' commentaries about their work it emerged the opposite. Indeed, there is a tendency in the codification to code Kairòs mostly as an internal time, because its features are "interpreted" by these markers as features of an internal time, whatever the ways students represented it. Though, as said above, it is the way it is reported rather than its natural features that determine if a time is internal or external. At the opposite times as Eniautòs or Chrònos are mostly "interpreted" by the markers as external even if in some cases they seemed more internal if looked through different lenses.

This misalignment seems to be the reason for a non-clear difference in terms of the entries of internal and external time between the two implementations, as the table below shows. Indeed, we would have expected a prevalence of internal time entries in the second implementation and of external times in the first one, according to teachers' sensation. Of course, one could argue that the codification is reliable and is disconfirming the hypothesis; still I claim that the constraint introduced in the second implementation in a way really supported a more pronounced expression of internal times, but these codes are not able to show that.

Thus, in the following section I discuss and present an alternative strategy to unveil traces of internal/external time and argue why the methodology just presented was not able to validate the hypothesis.

Data source	External time	Internal time
Total ONSCI	26	27
Total Einstein	37	36

Table 8: Total entries for both the implementations.

3.3.4 Third and fourth rounds of analysis

The analysis with the first version of markers for the internal and external time did not show much efficacy in providing insights about how students felt and reported the time faced during the process. Thus, we need to adopt alternative strategies.

The discourse around the duality “internal-external” time involves identity related issues, since it involves how the individuals conceptualize time in relation to themselves and ultimately manage that according to such conceptualization. Hence, is connected to identity-development.

The intention here is to check if and how the design choices of the two implementations allowed students to reason about their personal way of thinking about time and dealing with time, or if they just gave the chance to reason about the forms of time that we see in the phenomena that happen outside us. In other words, I want to find a way to investigate if and how the boundaries of the creative-writing in the two implementations helped students to both think about and experience their inner mechanisms, their “internal fluctuations” leveraging a metaphor from complex systems.

According to this intention, I focus in this section on two aspects:

- the **feelings and emotions** associated by students to each kind of time (via the characters)
- the **directionality** of the characters’ reasoning while expressing their temporality: I am interested in checking if the time structure embedded in the story supports the characters to “look out” at the world or “look in” at their inner dynamics, questions, issues. I reckon that is a strong assumption to disentangle what happens outside and inside a character, but I will note if the “trend direction” is inwards or outwards, grounding the discussion on some excerpts.

The results emerging from both foci of attention will contribute to the final discussion (Section 4).

Third round

I show here the mapping of the “affective expressions” that have been associated to the four kinds of time both in the Kairòs-Einsten and in the Kairòs-ONSCI implementations.

The goal of this procedure is to see if any patterns emerge, hence for example if one kind of time is more likely associated to expressions that have a generally positive connotation or a negative one (with the attention to keep open the coding to all the possible nuances).

To do so, I created four categories (named as the four times) and then I followed an “open coding” procedure creating codes for the feelings that I saw associated to the diverse times (using the software NVivo 14). Many scholars studied the differences between emotions, feelings, dispositions, moods, etc., (Scherer, 2005b; Zembylas, 2007; Ekman, 1992). Being aware of such debate, I mainly focus on taking trace of the general “semantic profile” of affective states associated to the diverse times, to whom I will refer to as “Affective categories”. From a procedural point of view, each time that in the writings there was a reference to a “face of time” I coded that excerpt with two types of labels: one indicating the time

(so one of the four categories) and one indicating the affective category associated, trying to interpret both the words and the actions of the characters. For the second type of label I sometimes used multiple affective categories.

In a first round of analysis I considered only the excerpts in which a character was expressing something related to its temporality and not to the temporality of others characters²⁹.

At the end of the first round I ended up with 31 different affective categories. Some of these shared similarities, while others were not exactly representing an affective state but maybe rather the consequences of a specific affective state. Hence, as a second step I recalled the codebook “Geneva Affect Label Coder” - GALC - introduced by the Swiss Centre for Affective Sciences between 2004 and 2005 (Scherer, 2005b) and fitted the previous categories within the ones from GALC. The GALC codebook includes 36 affective categories (Fig. 7) which have been empirically founded through surveys about emotion terms done in different contexts and involving different languages³⁰. This instrument is presented with a set of words that have been found as correlated with a specific emotion, so I crosschecked the words coded in the excerpts to check the possible match between my personal codes and the GALC, while projecting the old categories into the new ones. This process is backed by the assumption that *“the occurrence in verbal reports of any label or expression considered as being part of the family of affective states can be taken as evidence for the presence of a feeling state that is closely associated with the fuzzy category identified by the central concept”* (Scherer, 2005b; p.716).

The previous 31 categories have been therefore mapped into 19 categories out of the 36 of the GALC list. In this process some of the excerpts changed the associated category, so this can be considered a refinement process.

In a following phase, I plotted the entries for each “Affective Category” against the different kinds of time, producing 8 histograms (see Fig.8 and Fig.9). As an additional tool to examine the outcomes of the categorization, I decided to color the histograms in two different ways, according to the connotation that each category **generally** has (red for negative connotation, green for positive connotation). However, it is true that dividing emotions into positive and negative is risky since sometimes particular affective categories, as for example “Turmoil”, can have both a positive and negative connotation. To prevent this, I checked in the text if the sense of the coded excerpt was positively or negatively connotated and changed the codification when needed.

²⁹ This choice is motivated by the idea that, when a character speaks about someone else’s temporality, the description could be biased by the need to have conflict in the story (a literary constraint) and not being representative of the students’ perspective about that specific form of time.

³⁰ The semantic reference can sometimes change according to the language.

Affect categories	Pertinent words or word stems
Admiration/Awe	admir*, ador*, awe*, dazed, dazzl*, enrapt*, enthrall*, fascina*, marveli*, rapt*, reveren*, spellbound, wonder*, worship*
Amusement	amus*, fun*, humor*, laugh*, play*, rollick*, smil*
Anger	anger, angr*, cross*, enrag*, furious, fury, incens*, infuriat*, irate, ire*, mad*, rag*, resent*, temper, wrath*, wrought*
Anxiety	anguish*, anxi*, apprehens*, diffiden*, jitter*, nervous*, trepida*, wari*, wary, worried*, worry*
Being touched	affect*, mov*, touch*
Boredom	bor*, ennui, indifferen*, languor*, tedi*, wear*
Compassion	commiser*, compass*, empath*, pit*
Contempt	contempt*, denigr*, deprec*, deris*, despi*, disdain*, scorn*
Contentment	comfortabl*, content*, satisf*
Desperation	deject*, desolat*, despair*, desperat*, despond*, disconsolat*, hopeless*, inconsol*
Disappointment	comedown, disappoint*, discontent*, disenchant*, disgruntl*, disillusion*, frustrat*, jilt*, letdown, resign*, sour*, thwart*
Disgust	abhor*, avers*, detest*, disgust*, dislik*, disrelish, distast*, loath*, nause*, queas*, repugn*, repuls*, revolt*, sicken*
Dissatisfaction	dissatisf*, unhapp*
Envy	envious*, envy*
Fear	afraid*, aghast*, alarm*, dread*, fear*, fright*, horr*, panic*, scare*, terror*
Feeling	love, affection*, fond*, love*, friend*, tender*
Gratitude	grat*, thank*
Guilt	blame*, contriti*, guilt*, remorse*, repent*
Happiness	cheer*, bliss*, delect*, delight*, enchant*, enjoy*, felicit*, happ*, merr*
Hatred	acrimon*, hat*, rancor*
Hope	buoyan*, confident*, faith*, hop*, optim*
Humility	devout*, humility
Interest/Enthusiasm	absor*, alert, animat*, ardor*, attenti*, curi*, eager*, enrapt*, engross*, enthusias*, ferv*, interes*, zeal*
Irritation	annoy*, exasperat*, grump*, indign*, irrita*, sullen*, vex*
Jealousy	covetous*, jealous*
Joy	ecstat*, elat*, euphor*, exalt*, exhilar*, exult*, flush*, glee*, joy*, jubil*, overjoyed, ravish*, rejoic*
Longing	crav*, daydream*, desir*, fanta*, hanker*, hark*, homesick*, long*, nostalg*, pin*, regret*, wish*, wistf*, yearn*
Lust	carnal, lust*, climax, ecsta*, orgas*, sensu*, sexual*
Pleasure/Enjoyment	enjoy*, delight*, glow*, pleas*, thrill*, zest*
Pride	pride*, proud*
Relaxation/Serenity	ease*, calm*, carefree, casual, detach*, dispassion*, equanim*, eventemper*, laid-back, peace*, placid*, poise*, relax*, seren*, tranquil*, unruffl*
Relief	relie*
Sadness	chagrin*, deject*, dole*, gloom*, glum*, grie*, hopeles*, melanco*, mourn*, sad*, sorrow*, tear*, weep*
Shame	abash*, asham*, crush*, disgrace*, embarrass*, humili*, shame*
Surprise	amaze*, astonish*, dumbfound*, startl*, stunn*, surpris*, aback, thunderstruck, wonder*
Tension/Stress	activ*, agit*, discomfort*, distress*, strain*, stress*, tense*
Positive	agree*, excellent, fair, fine, good, nice, positiv*
Negative	bad, disagree*, lousy, negativ*, unpleas*

Figure 7: The list of the GALC codebook for emotions and related stem-words. The emotions highlighted were the 19 into which the initial 31 codes were mapped; the green and red are respectively for those generally positively/negatively connotated (adapted from Scherer, 2005b; p. 714-715).

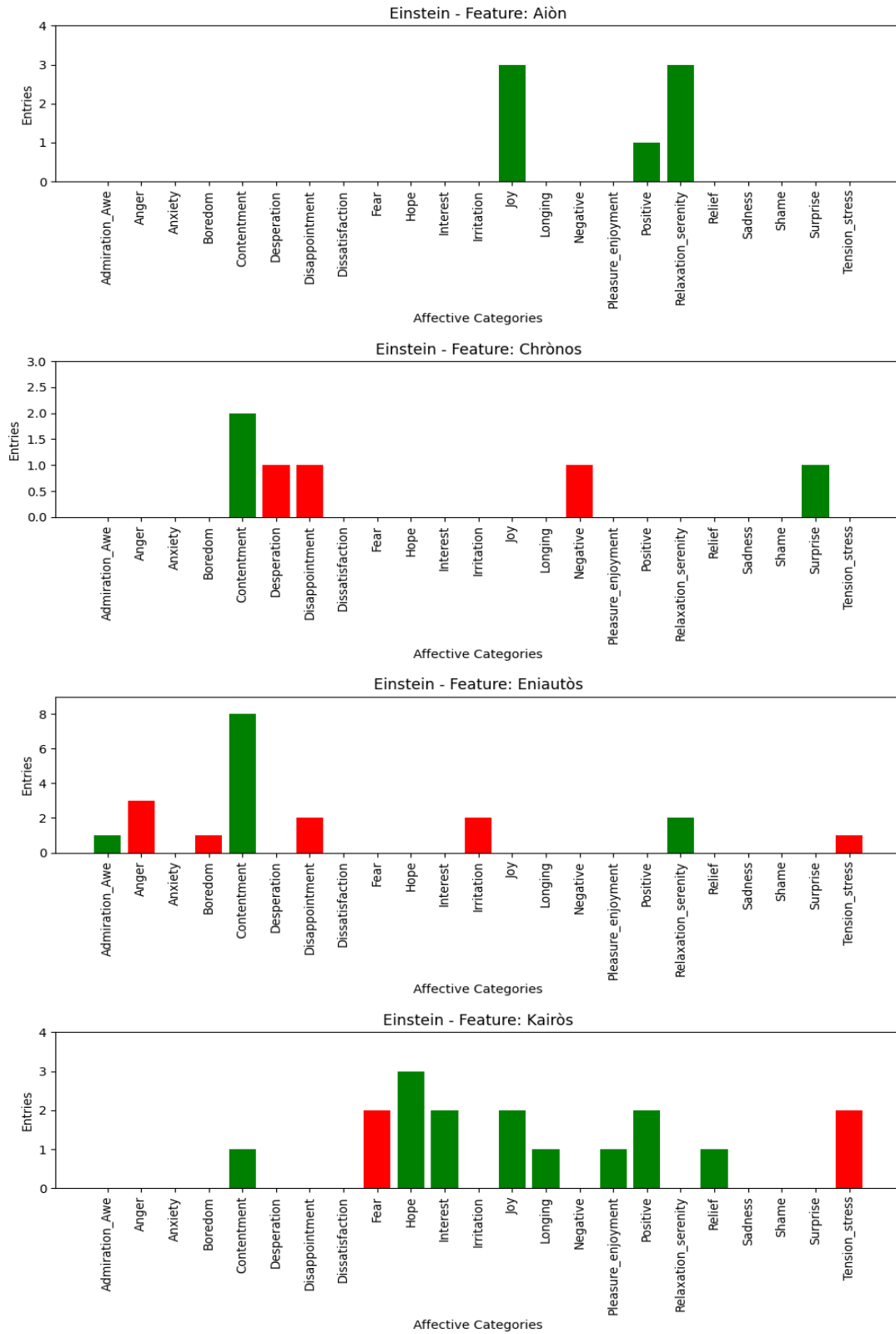


Figure 8: Histograms for affective categories of Kairòs-Einstein implementation.

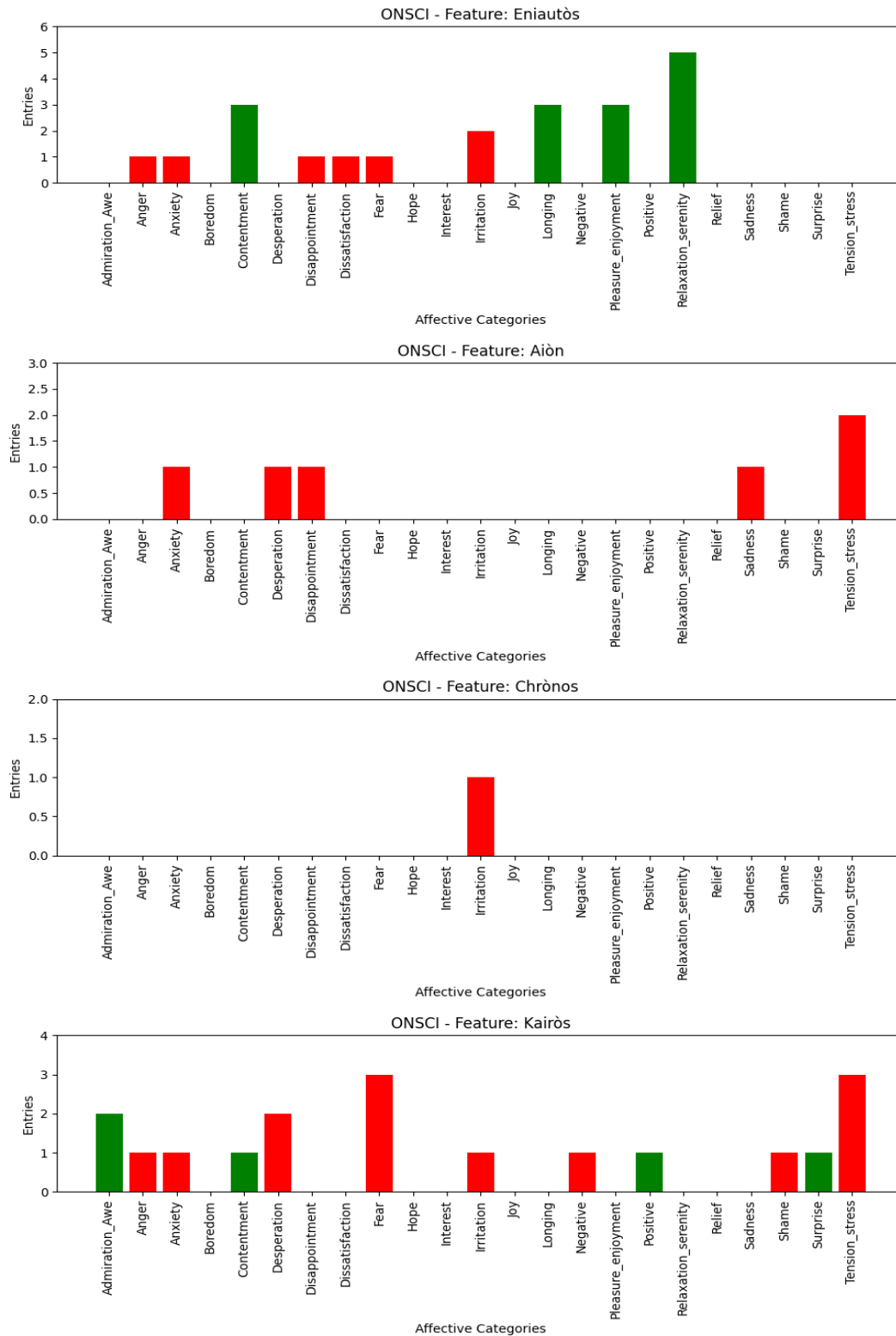


Figure 9: Histograms for affective categories of Kairòs-ONSCI implementation.

By looking at the histograms it is possible to notice that the first three forms of time have few entries, with the exception of *Kairòs* which is quite populated in both the data-samples. Still, this is not an issue as the goal is observe the distribution and the data itself does not allow for numerous entries. Also, having few entries thus is the consequence of being mostly concerned in getting as many nuances as possible in the affective categories, rather than building a statistically solid argument (Scherer, 2005b).

Concentrating on the single forms of time, I point out that few differences can be noticed between the two datasets.

- **Aiòn** has no overlapping categories between the first and the second implementation. This means that none of the affective expressions displayed by the characters in the implementation done with upper-secondary students are displayed by the characters developed within ONSCI. Furthermore, in the *Kairòs*-Einstein dataset all the categories have generally positive connotations whereas in the ONSCI implementation they are all negatively connotated.

Taking into considerations that the only “free variables” that changed were the people involved and the structure of the writing, it could be reasonable to deduce that one of them is correlated with the outcome. In section 4 I argue why I consider having had different authors is the affecting variable.

- **Eniautòs** is mostly correlated with the affective category of “Contentment” in the first implementation; this category is populated also in the second implementation although the categories of “Longing”, “Pleasure_Enjoyment” and “Relaxation_serenity” are at least equally populated. Overall, although there are several categories (little populated) that are negatively connotated, it seems that *Eniautòs* is more likely correlated with positively connotated affective expressions, in both datasets. Unpacking these three categories into the ones of the first round (indeed the 19 codes are composed by one or more of the previous 31 codes), we see that the codes were mostly “Security”, “Solidity” and “Comfort”. This is in accordance with the general sense of “taking things under control”, “being able to master the daily-time” that was emerging also from the two tables (Section 3.3.2) and will be discussed in Section 4.
- **Kairòs** is generally associated with positively connotated affective categories in the first implementation and mainly negatively connotated in the second dataset. Even though categories as “Fear” and “Tension_stress” are populated in both the datasets, in the second one “Desperation”, “Anger”, “Anxiety”, “Irritation”, etc., are populated as well. I claim that this difference could be mostly related to a structural constraint introduced between the first and the second implementation by SM. Indeed, probably because the teachers had the impression that the students did not express their “internal time” that much, SM insisted extensively with the second set of “authors” to leave space for the description of the internal time of their characters. The internal time was often referred to as the inner dynamics triggered by a stimulus (*Kairòs*), which then becomes a “inner noise”, and part of the task was to describe how the temporality of each character found a new balance “oscillating around the noise”. Hence, the noise has been represented as something which questions a balance, activating a process which ultimately led to a new balance. Thus, a noise has to be troublesome to cause a disequilibrium and I claim this is

the reason we see the prevalence of negatively connotated affective categories associated to Kairòs.

In general, it seems that Kairòs is more populated than other times, which could suggest the suitability of this temporality to accommodate more dispositions towards it.

Fourth round

I proceed by discussing the “look-in” and “look-out” mechanisms for the two datasets.

Kairòs-Einstein

For what concerns the first dataset, even though the vast majority of the characters show a face of time embedded in their words, actions and behaviours, still only few characters manifest a discussion about their internal dynamics, questions, issues. In fact, most of the times the discussion about time is anchored to something which happens outside the figures and the different shapes of time are mapped into the reaction to the events surrounding the characters³¹. Hence, just three characters seem to display a “look-in” mechanism: Martina and Loretta (to some extent) from Act 1 and Davide from Act 5.

Martina

She uses the temporal duality between Kairòs and Chrònos/Eniautòs to unveil her inner tension between the need for uniqueness and self-determination and the fear of leaving home and her family.

There is a clear emphasis to an annoying sense of repetition, *“I get up, work, eat and go to sleep, I feel like I have already discovered everything there is to explore - [she says in a fed-up tone, almost grumbling] - ”* and the tension toward something new, *“In the repetitiveness I see normality, and instead I want uniqueness, a novelty in the usual life” [she says as if enlightened, looking at the horizon]”*.

Martina engages in a discussion with her grandfather Salvatore (Chrònos) and Loretta (Eniautòs), in which the three characters represent different forms of temporality and the comparison triggers a self-reflection about the difficulty of changing time-management habits. “Chrònological” and “Eniautological” time habits can still be somehow good and comfortable *“After all, I have had so many good times here. Maybe I am really taking them for granted!” [joke referred to and heard only by the audience]”* compared to new and unknown “Kairological” time habits: *“yes ok I know, now you are going to tell me that I deserve it, that I have been patient and that I have to take this opportunity that life gives you only once. But what if I don't want to? What if I feel obliged to choose the scholarship, I've been waiting so long for this opportunity that I thought it was unattainable and so I imagined my life in this building, with you. What if I was afraid of something so unexpected and uncontrolled?”*.

³¹ It is nonetheless true that the genre played a major role in this, activating theatre more often discussions or preferring actions rather than inner reflections. However, we are here more interested in the potentialities offered by the context of the activities.

Martina really shows to the audience her psychological troubles in taking the decision to leave or not home and to accept the scholarship. The temporalities are used as props on which to rest her turmoil, which is finally solved with her accepting to leave and to face her fear of discomfort: *"You are right! Mum also told me, I have always looked for something else, I have always loved change, I have never repeated something so boring two days in a row. Why do I have these doubts? The me of a year ago would already be packing a suitcase!"*.

Loretta

This character impersonates the time of Eniautòs by being attached to a routinary lifestyle and the attitude to take under control whatever happens around her (see the connection between Eniautòs and controllability discussed in the previous Sections).

While discussing especially with Salvatore and Martina she highlights her temporality to disclose something about her inner "life-mechanisms", reflecting an internal way of living her time: *"I observe! Is it simple boredom of an old retired lady? Or the need to have everything under control at all times? Personally, I think this building has somehow enchanted me. I heard what you said earlier (Martina complaining about living the building's boredom) and I'm sorry that you, in this place, don't see nothing special" [she says admiring the apartment building with shining eyes, as if enchanted, looking almost mad]"*. To her, repetitiveness is not boring, but rather is something that have enchanted her, something special: *"You (Martina) are underestimating the importance of the everyday, if you look too much for change, you will end up losing what is around you, perhaps obvious but essential!" [she says with a raised finger, in a tone mixed between reproach and warning]"*. Loretta is so anchored to Eniautòs since it helps her to be centered, to preserve her image of herself.

Nonetheless, Loretta finally shows the awareness that the sense of security provided by "Eniautological time habits" is only a façade, a shallow security behind which there are feelings of sadness and melancholy: *"...Listen to your grandfather Martina, it's true that the repetitiveness of things gives you security because you already know what's going to happen, you almost feel as if you're cheating time, but in the end it's time which is cheating you. I spent my retirement here, having waited anxiously for it, every day the same, and I am happy with that, with my everyday life. But Martina, if I was 20 years old again I would do the opposite, accept the scholarship, take this chance"*.

This final sentence is a further proof that Loretta is living her temporality as an internal time, since she is using the time-related features to guide her into a very deep and personal reflection about herself and her way of living time.

Davide

The fifth act of the pièce revolves around the figure of Davide, which daily suffers for the conditions of his family. His personification of Aiòn - a time detached from the events, *absolutus* - displays itself both in his actions (take shelter on the rooftop) and his words, which show to the reader his internal turmoil due to the family situation and the pain that a time-flow in such situations provokes for him.

Since the initial description of the character we witness how students used the time connotation to shape Davide's behaviour and identity: *"When he is sad and angry, he listens to music, which helps him calm down and drives away the bad thoughts that constantly invade his head. In fact, he lives in a difficult family situation and his parents' quarrels torment him on a daily basis. Davide goes up to the terrace to be alone, away from the constant shouting. For him, the terrace means peace and freedom, a place where he can be himself [...] Around his neck he always keeps headphones in case they come in handy to 'disconnect' from the world".*

From these few lines of description, it is evident the tension between a daily painful routine and the need to escape from it, going to the terrace or using headphones, and finally find the calm to be "oneself". This continuous detachment mechanism, which is the way Aiòn has been embedded in the act, is not only contextual for the sake of the story evolution but is used as a proxy to let emerge Davide's personality. For instance, when Davide is on the terrace he says: *"How I wish there was that feeling of passion between my parents that they have been missing for so long. How much I would like memories of happy moments with my family as all people usually have. How much I would like to live a normal life.... How I wish".* The readers are brought within the "stream of consciousness" of Davide wishing for a Chronological peaceful time while instead he is forced to find his tranquility within Aiòn. Later on, also the painting which he is doing begins to speak, as if it was an extension of Davide's feelings:

"[After a few seconds, the painting begins to speak and in its simplicity expresses all the complexity of the thoughts and moods of a sensitive teenager like Davide].

"Please stop time, stop time for children who laugh until they can't breathe, stop time for children who don't yet know the value of the verb to love, stop time for grandparents who tell their grandchildren about life, for parents who love their children immensely. Stop the clocks on carefree summer evenings, stop the calendars when it snows at Christmas, stop the stopwatches when everything is going swimmingly. Please stop time, I need to breathe this moment, I need to imprint this evening's sunset on this canvas."

Since in the daily painful routine the peaceful images quickly fade, Davide and his painting exploit Aiòn to "freeze" and enjoy them.

Also in this case the character shows his tendency to use time to "look-in", to conceptualize and give voice to his internal feelings.

Furthermore, the temporality are used again to represent a **tension**, as it was in the previous two cases (Martina - Kairòs vs Eniautòs/Chrònos and Loretta - Eniautòs vs Chrònos); this seems interesting because both the similarity of the procedure and also the diversity of temporalities used from time to time to showcase such tension. I discuss this aspect later on in Section 4.

Kairòs-ONSCI

For what concerns the second dataset, since the introspection was much more explicitly supported by choosing a new format and also because of the introduction of the "internal noise" of the characters as a constraint, most of the characters present a "look-in" dynamics. In particular the characters are: Lara

("Lara, complex girl"), Gigi ("Gigi"), Camilla ("Camilla"), Alfredo ("Bus"), Efrem ("Efrem's routine") and Mario ("Getting lost").

In the following lines I will wrap up what kind of reflections are supported by the "look-in" mechanisms of each character.

Mario ("Getting lost")

Mario, the main character, embeds the time of Aion. As it was emerging also from the table in Section 3.3.2, his temporality is represented by a forced condition of detachment from events (in this sense Aion) due to Alzheimer. Even though this could appear as an external way to showcase Aion (projecting a disease), still we are guided within the increasing stream of emotions that Mario feels while trying to remember his past times. Thus, in this case the constraint of the monologue seems to work efficiently as support for an *internal* kind of time representation:

"Oh God, this day! We used to play on the wagon after harvesting, me and ... and (some agitation could be heard in his voice) oh God, what was that child's name? We used to play together when we were harvesting, we used to press grapes together and run away from wasps. (With increasing agitation and confusion in his voice) Luigi? No, Luigi no! Then maybe Michele? No, Michele was the mayor's son. Was it perhaps Giuseppe? No Giuseppe no, no, no (almost angry, for the anxiety of not remembering this name, and with much sadness). How long has it been in the end? How can I not remember that name? (With a note of relief)".

Being an Aion figure, detached from the events and recollections because of a lost memory, has consequences which unfold internally in Mario's mind:

"No, no, I can't find it! I can't remember! And who are these people? Whose names are these? Who was Angela? And Gianni? Who were these people?"

[Increasingly in shock, he approaches the window and confusedly looks out, his gaze seems to see again the colours of the countryside from when he was young, which contrast sharply with the grey of the concrete, he sees the farmsteads and fields that are now replaced by buildings and roads].

And what is that steel building? Was it always there? No, no there used to be a park... (with bitterness and resignation).

Hence, it seems that living his temporality triggered for Mario a "look-in" mechanism in the sense that strong feelings emerge and he has to deal with them and struggle to find a new possible equilibrium.

It is nonetheless interesting to notice what the author said in the commentary:

"Mario's character was born out of a flash of inspiration I had during the exposition of the workshop themes, and in particular of Aion, the eternal time, in particular to the question 'in your opinion which part of life is most represented by Aion?' which stimulated various discussions [...] and all of that went very well with my inability to write except about things that touch me directly, and in fact Mario mirrors what my poor grandmother is going through, who has been suffering from Alzheimer's for a few years now and

constantly lives in a dream world in which she has not clear what time it is [...] and this is precisely the noise, the suffering, that drives in Mario the need to get out of the status quo (his condition)".

In these words, the author shows to what extent writing can help sometimes to give shape to internal thoughts and emotions. He was not able to write about anything but something personal, in this case the pain of his grandmother. Thus the writing structure (monologue) and the constraint to insert a "noise", ended up in a "look-in" mechanism for the character which is strongly informed by personal issues of the author itself.

Lara ("Lara, complex girl")

Lara represents the face of Kairòs as discussed in Section 3.3.2, as she can't help but improvising and following her instinct moment by moment:

"I can't think things through. I just wait for the last minute, wait for that word, that image, to go and trigger all those things that I have here, in my head".

But the peculiarity of such monologue is that it is entirely expressing inner mental loops, thoughts sparkling and then turning off soon after, in a confused structure. Within this stream of consciousness it is visible how the idea of time contributed to determine such look-in mechanism, and it is again through a tension, a dichotomy. Lara loves reading and she usually does it whenever she has the chance; the way she reads is non scheduled rather is erratic, without any sense of a direction or learning objectives, as could be for example reading books of a specific field to nurturing a passion. In this sense it fits with her being a Kairòs character, as she reads whatever comes to her hands, without thinking about it. This kind of reading is done in a "free time" schedule, whereas when the teachers ask her to read specific books, within a specific time range and with the objective to fill also character sheet, she becomes anxious and starts to feel uncomfortable about that: *"To read? What? She³² has to read a book!? But she enjoys reading. For her it's an hobby. But, wait a minute... if you enjoy it... maybe it's not quite to read the way you know how to read".*

Even reading, which she loves, when framed within a different structure in terms of time and objectives (doing a commentary), becomes something questioning Lara and her abilities: *"will she really be able to do that? What if she ruins a beautiful story because of the rubbish she writes about it? What if the teacher and the librarian Claudia have already read the book and realise that she is not at all capable, because she certainly is not, of grasping its innermost meaning, its most important aspects? - you know, my little girl really likes to use big words - what if it turns out to be too banal? SUPERFICIAL?"*.

When the reading is free and triggered by random books occurring as manifestations of Kairòs, Lara feels joy and a high-level of self-efficacy, whereas when the reading is "trapped" within a schedule (Eniautòs), it loses the Kairological connotation and Lara starts to feel at odds with that. Again the look-in process

³² The monologue oscillates between an inner and an external voice.

unveils how two times (Kairòs and Eniautòs) have been used to describe a personal tension of the character.

Gigi ("Gigi")

Gigi is another character embedding Eniautòs since he is prey to his daily routine which repeats the same day after day provoking him a sense of continuous dissatisfaction. He would be brave enough to follow some of the many possible scenarios whirling in his head, but he just can't find the right determination.

Hence, even though the commentary confirms that the main temporality is Eniautòs, again there are many traces of a dichotomy between Kairòs and Eniautòs. Kairòs as the chance to change life and follow his dream triggered by a random book found on a table, and Eniautòs as the comfort zone of his monotonous life. These two forms of time are used to display the doubts that torment Gigi and constitute the pillars upon which his turmoil is shared with the audience:

"When I think about it, what jazz, what cuisine... I've always liked doing this: helping others, helping them, making myself available. Making myself available for the intellectual and material growth of people, as much as possible. Yet when it came down to it, I didn't end up being a professor. But why? [...] I mean... actually I could still do it now. Who's stopping me, I have the titles at the end....DRIIIIIIIN!"

Gigi oscillates between many possible scenarios, but he always ends up closing the book and coming back to his life, when the bell reminds him that the library is closing. As the author reports in the commentary, this is a metaphor for the concept of logistic map: *"a logistic map is in fact a map that describes how a non-linear but deterministic equation, which for example can represent a population dynamic, can, depending on the value of a parameter, oscillate between several possible solutions, even infinite ones"*.

To conclude, Gigi is another example in which both a tension between two forms of temporality is displayed and activates a look-in mechanism.

Camilla ("Camilla")

Camilla embeds Eniautòs but mostly by displaying traces of a "look-in" process.

The monologue indeed can be interpreted as an alternation of two different kinds of time, Eniautòs and Kairòs. At the beginning Camilla escapes from her routine at home because she feels the need to discover the world outside her village and she thinks that her routinary life is an obstacle. Hence, she "betrays" her "Eniautological habits" by taking the chance - Kairòs - to go to the university. Then, after a while, earthquake comes (Kairòs again) and forces her to come back to her previous life, her "Eniautòs like" life. Though, this time Camilla exploits the repetition of the routine as a source of security and peace of mind; she was traumatized and needs a sense of calm ensured by doing every day the same things, waking up in the same place, eating the same things at breakfast, etc. The repetition of the actions is what prevents instability but apparently this is not true, as she experiences with the second earthquake (again Kairòs that breaks the Eniautòs time structure). She realizes indeed that even by doing the same things each day, life can still turn upside down at any moment and so it is pointless to ground our security upon the sense of repetition.

From this brief description it is evident how the alternation of two times informed the monologue in terms of structure, but still every time we witness a shift from one temporality to another one, Camilla looks inside herself and shows us her effort to find again a balance and position again with respect to time (as she says after the first earthquake):

“Who knows what I thought I would achieve by leaving here, this strange idea of discovering the world... but what is there to discover when I can have all the serenity I need by staying here? [...] no, really, now that I'm a grown woman I know how important it is to have a stable, regular, repetitive life... to have stability! Of course it's boring though... but no, but no! To say that is just not to realise how reassuring it is to hear that alarm clock every morning announcing the beginning of a new, perfect, identical day...”

and so, after the second one:

“Sure, this time it was the kitchen in my house and not the lecture hall at the university that collapsed... but that means that now I can't go back home and... that means starting all over again... but starting all over again is reassurance, is peace of mind, is salvation... does that mean that starting all over again may not mean that everything goes the same way?”.

Kairòs represents the chance to escape from the routinary life which becomes too tight sometimes, but it is also the earthquake that changes life completely. Into Eniautòs is projected the idea of comfort zone that needs to be questioned by following the Kairòs (out-of-comfort zone); then Eniautòs seems to guarantee comfort again when there's need, but this turns out to be wrong.

“Does this mean that even repeating everything all the time, all the same, doesn't necessarily mean that those mountains of mine are there ready to protect me? [...] Maybe ... I don't know ... maybe it can mean that that little girl beguiled by the future a second chance I can give her? After all, 27 years have passed but in reality not a minute has passed...”

Also in this case the look-in process unveils how the same two times of before (Kairòs and Eniautòs) have been used as metaphors for conceptualizing and expressing an inner tension.

Alfredo (“Bus”)

The author of the essay, in his afterword to the tale, writes the following:

“The monologue shows the moment when Alfredo is presented with Kairòs, the time of the occasion, related to the 57 bus not arriving on time. This event represents the “background noise” that bothers the character because it challenges his routine, but simultaneously allows him to rationalize and unhinge it in its pathological aspects”.

These words report a deliberate intention of the author to display a “look-in” process for his character, in agreement with the writing constraint asked by the teacher. The Kairòs is the chance that comes to break the daily routine of Alfredo but more importantly provokes an internal reflection about the meaning of Eniautòs for the character. Hence the clash between two time-structures here lead the figure to deal with an “increasing internal noise”, which questions his way of living the time and his way of living life as well (in this sense he intends the *pathological aspects*).

For example, here the Kairòs is represented by the bus being late and by a woman, who was waiting for the same, finally taking another one instead of the 57. Alfredo asks himself if he could have been brave enough to do the same: *“She knew where to go. Garibaldi Square. Do I know where to go?”*

Then there is a second Kairòlogical moment because when the 57 finally arrives there is also another bus just behind:

“1:15 pm: the 57 has arrived. But there is also another bus all red. I’ve never seen it before. (Addressing the audience) I know where Garibaldi Square is? (Pause)

Why don’t I change bus?”

Here Alfredo reflects about being able or not to change the plans and question the custom of Eniautological habits. But something more can be read between the lines if we compare it with the afterword; indeed, this very simple question is the “tip of iceberg” for Alfredo, is a question that scales up to questions such “Why do I do this every day?” or “What is the sense of what I do every day?”.

Efrem (“Efrem’s routine”)

Efrem is an Eniautòs character (Section 3.3.2), who comes back to his routine after having done a test that could have changed his life completely.

Nonetheless, he also expresses his particular conception of routine which is not determined by the time displayed on a clock but rather by the meaning of the things that must be done. Reasoning about a personal meaning of routine is the path through which Efrem shifts to reason about himself and the way he lives and conceptualizes time. Hence, this shows again the presence of a “look-in” process

“Here, I think I need to start from here. Perhaps for the first time in my life I have realized what having a routine is really for. A routine for me has nothing to do with something static, repetitive and aseptic. It is not a set of things to be done, a kind of procedure to be followed in order to have the feeling at the end that one has accomplished one’s duty toward self-realization. Routine for me is that safe beach on which you know you have built in the past, with effort and commitment, a warm and welcoming tent by the sea”.

There is a conscious expression of the meaning that time has for the character:

“Routine in my opinion has the function of reminding us of who we are in the moments when we think we have forgotten what arouses in us the smell of the sea and the starry sky that were so familiar to us when we spent the days in our tent. Routine is dynamism...”

The proof that the character is looking inside himself and reflecting, activated by a thinking about time, is that he doesn’t accept the routine as an empty time-structure, he does not accept Eniautòs the way it is. He struggles so much instead, to find a personal and idiosyncratic way to stay within the time-structure, squeezing it accordingly to what he is and the things that are important to him.

“Routine, in my opinion, has to be a place we enter and leave again and again. We get into it to find who we are but as soon as we can we have to get out of it to make room for something new”.

4. Discussion

In the previous sections I pointed out what emerged from the different steps of the analysis, with some outcomes being confirmed and some new coming out at each step.

This analytical process can be described by using the metaphor of “pulling the threads” (Figure 10). At the beginning I developed the table of the characters (for the Kairòs-Einstein implementation) and from that few results came out. Each result can be considered a thread of a different color.

In the following analytical steps (the ONSCI table, the affective categorization and the collection of “look-in” mechanisms) further results emerged, sometimes confirming the initial ones, sometimes adding new elements.

- The confirming results can be considered threads of the same color (when exactly confirming) or similar one (when adding similar aspects).
- The new results instead constitute new threads (of new colors) that may be enriched by the following steps of analysis.

Hence, the **first step** (Kairòs-Einstein’s characters taxonomy) produced four main outcomes, which constitute the initial threads:

- Aiòn as a refuge (red thread).
- Eniautòs related to the idea of control (green thread).
- The different characterization of youngs and adults (grey thread), probably due to the creative writing structure.
- The different characterization between males and females (grey thread³³).

The **second step** (Kairòs-ONSCI’s characters taxonomy) did not confirm the image of Aiòn as a refuge but did confirm the link between Eniautòs and control (so it added a green thread).

The **third step** (affective categorization) added similar results to the issue of Eniautòs and control, but also showed how Aiòn was mapped positively in the first implementation and negatively in the second one, confirming the idea of Aiòn as a refuge. So, this step added a redish and a greenish thread.

In the **last step** (“look-in” mechanisms) we have different results, some of them also new:

- Loretta expressing a kind of Eniautòs again related to a sense of control (add a green thread)
- Davide expressing Aiòn as a way to take shelter (add a red thread)
- Martina, Lara, Gigi, Camilla, Alfredo and Loretta expressing personal tensions exploiting from time to time two contrasting temporalities: new result (add a blue thread)
- Mario’s expression of personal issues (add a greyish thread)

³³ Again the same colour (grey) but slightly different, since they are outcomes related to the structure of the activity (creative writing) more than to four times. This will be discussed later.

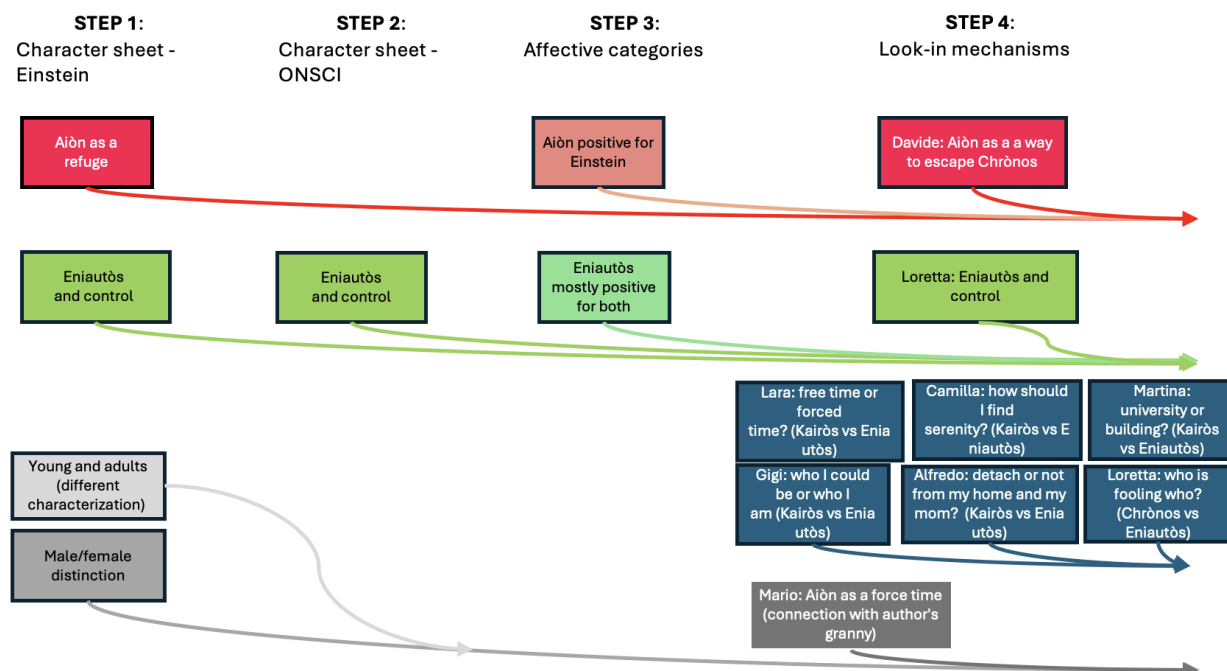


Figure 10: The mechanism of “pulling threads”.

I will now discuss each of set of threads (red, green, blue and grey) which constitute an overview of the outcomes emerged in the analysis.

Aion as a refuge (redish threads)

Three analytical steps out of four have contributed to illustrate how Aion has been represented as a time in which the characters find refuge, but only within the Einstein implementation. As the characters taxonomy shows and in particular the story of Davide resembles, the Aion characters were living its *absoluteness* feature to untie themselves from the painful laces of other temporalities. In this sense, having only positively connotated affective categories related to Aion (as it is shown in the histograms) is consistent with the Table’s outcomes.

The fact that young students decided to represent a tension between a daily time which is difficult to manage and the need to find some rest by stepping out of time recalls what Levrini and colleagues named “time bubbles” (Levrini et al., 2020). In that paper the authors were inquiring how students were rearranging their daily lifetime rituals within the pandemic period and some of the students they were studying shared experiences of a time “suspended”: they were creating and placing themselves within a personal “space-time bubble” to escape from the society, which was completely re-shaped by Covid 19. As the chronological temporality they were accustomed to was passing through huge changes, they were having hard times in finding their sense of agency and positioning with an increasing sense of discomfort. That’s why some of them felt the need to step-out of time and lock themselves in “space-time bubbles”. As in that study some students were exploiting a different kind of time, a suspended time, to escape from the Chronological time full of uncertainties, here we see these characters leveraging upon an Aion like structure to escape the tough Chronological time.

In this case it seems that creative writing provided the space to express personal issues about the need to have another temporality to “phase-out” from Chrònos when it is too difficult to handle, as it was in the case of “bubbles” for Levrimi and colleagues (2020).

It is evident here the role played by the 4-layer structure of Figure 4. Students first encountered multiple time structures, and they started reasoning about science and literature through these time images. But specifically by creating “time-characters” they had the chance to reflect both individually and collectively around the possible attitudes towards the multiple forms of time, and the possible strategies to cope with them. Thus, the fourth layer created the conditions to “reinterpret” and “display” a personal process whereby sometimes the everyday (represented by Chrònos or Eniautòs) becomes unmanageable and emerges the need to look for a position where to catch a breath (Aiòn) and the need to find a way to “alienate oneself” from time (Rosa, 2010).

However, Aiòn as a refuge does not hold for the second dataset. Even though we have just one monologue embedding Aiòn, still it is remarkable that in that case the temporality is not at all a way out from misery but rather the opposite, a prison which makes the character suffer. I claim that this can be explained by recalling the different ages of the authors between the first and the second implementation. Noticing that people of the same age produced a coherent representation of Aiòn different from the one in the second implementation, I am led to conclude that the writing process was so open that starting from similar premises, i.e. the conceptualization of Aiòn, it created the space to embed issues characteristic of authors’ age.

Eniautòs and control (greenish threads)

The analytical steps illustrated how Eniautòs was associated to a sense of control. Nonetheless, when presenting Eniautòs within physics and literature lectures, hence from both a scientific and literary perspective, PF and SM did not emphasize Eniautòs as the time to control but rather as the time of circularity, of repetition, the time of the clock.

One possible interpretation could be the one introduced in Section 3.3.2., namely a process that led to shift from the idea of measurability (Eniautòs as the time of the clock which is a measuring instrument) to the idea of “controllability”.

It is interesting to notice that this is the reverse of the historical process that happened between the late 19th and early 20th centuries, when a rapid technological advancement and the spread of long-range communications set the need to take time “universally” under control, leading to the creation of modern synchronized clocks (Galison, 2003). Nonetheless, as discussed in the first Section, our understanding and regulation of time are deeply influenced by the technologies we develop, hence the industrial transition and the birth of modern clocks fundamentally changed societal perceptions of time. As Thompson highlights (1967), the shift to industrial capitalism “imposed” a specific perception of time to enhance labor discipline and productivity.

It seems here that students manifested an historical and social (and probably introjected) culture of time as something to control, emerged from the data as associated with positive feelings (see Eniautòs histograms of Section 3.3.4). Eniautòs is a kind of time that gives a sense of security (see Loretta), even

though I see here some differences with respect to the sense of shelter provided by Aiòn. Aiòn was a refuge from other forms of time and it was the manifestation of a discomfort for a specific age; here the fact that we do not find differences between the two datasets leads us to interpret this sense of security as a more general and transversal attitude of modern and post-modern humans to conceive time as a quantity to control.

Nonetheless, by tuning the analytical sensitivity something subtler becomes visible. Looking at the first implementation and checking the affective categories associated to Eniautòs character by character, it emerges that Giovanni - the only young Eniautòs character - was always associated to negatively connotated emotions whereas all the other Eniautòs characters (adults) were always associated to positively connotated emotions. There is an exception for Mirko, even though the only excerpt coded for him is in his initial description and describes his daily laziness which ends up being boredom.

	Carmen	Giovanni	Loretta	Mirko	Pietro
Admiration_Awe	0	0	1	0	0
Anger	0	3	0	0	0
Boredom	0	0	0	1	0
Contentment	2	0	4	0	2
Disappointment	0	2	0	0	0
Irritation	0	2	0	0	0
Relaxation_Serenity	0	0	2	0	0
Tension_stress	0	1	0	0	0

Table 9: I coded all the excerpts already coded with Eniautòs label with a new label corresponding to the character's name. Then I looked for the affective categories associated to Eniautòs for each character and filtered to get rid of the affective categories with zero entries (in total). The colours represent the general connotation for the corresponding affective category.

What does this mean? I use PF's words to help me in the answer. She was arguing about her sensation of students expressing a sense of discomfort with respect to adults, when she reported (during the interview):

"I can say that (this discomfort) emerges from their work quite strongly and I therefore believe that it is a reflection of their being, what SM said, but also understood as this being in a cage in some way with respect to the adults which are once again worried about the product, worried about spending for maths lessons [...] And so this control that comes out very strongly of the adult in relation to the boy (Giovanni), but it's an external control, is a control over the routine, is a control over what he (the young) does...[...] and so it almost seems (that control) repeats itself in the routine at home with respect to the things to be done [...]"

(and) the same thing repeats itself in the school routine, so (young people are) trapped at school and trapped at home...”

What PF is saying here is that the control expressed mostly by the character of Giovanni is a control that is a manifestation of the adults' world, into which students are transitioning. In that world in which the routine and the control are intertwined as the most evident expression of the society of acceleration (Rosa, 2010), adults have already accepted and appropriated the clock-oriented time-framework (indeed the emotions for them are positive). Students (young people transitioning into adults' age) are in the process of discovering and dealing with this kind of time management and are here expressing their sense of discomfort through the voice of Giovanni, who is plagued by Eniautòs and the sense of control (negative emotions in the categorization).

Hence, I finally claim that through the representation of Eniautòs students are making visible two important issues:

- How much in the modern and post-modern society time is conceived as a routine to keep under control (and students are able to reproduce this because they live and are immersed in such society)
- Youngsters' difficulty linked to phasing into a “chronoscopic society” (Hassan, 2003) dominated by this kind of time-management

Dualism of temporalities to showcase personal tensions (blueish threads)

In the previous section I have been illustrating how students displayed characters' inner tensions by leveraging the tensions between different forms of temporality. The most common choice was the contrast between Kairòs and Eniautòs, representing each time specific tensions of the characters (Gigi, Martina, Lara, Camilla, Alfredo). Another dualism is the Loretta's one, namely Chrònòs vs. Eniautòs. The use of temporal dichotomies to represent inner tensions and polarizations seems to be interesting for the following reasons.

Providing students with the chance to reason and discuss about time is generally something useful for increasing awareness of how they can deal with time, and thus is strongly correlated with issues regarding their identity development as citizens. Here again emerges the importance of presenting time (within physics) as a multifaceted concept, as PF was commenting above, *“there are various temporal structures that science has dealt with and still deals with, that also give you a richness of interpretation”*. Still, not only present many scientific images of time besides the Chronological one, but also creating interdisciplinary activities to *feel* the forms of time, *“to be able to experience it personally, to not only, as you say, think about time, but also experience time”* (PF). The effects of this way of dealing with time (again recalling the 4-layer scheme in Figure 4) enlarged the references to time and supported to use this metrics as a “space for representation” of different tensions.

The writing activity in this sense, created the condition for students to express also issues that go beyond time and time-management, confirming the potentiality of creative writing emerged within “Physics of clouds”. I refer here to the **grey threads** of Figure 10.

Specifically, at the end of Section 3.3.2 I noticed how in the Einstein implementation the young female figures were always depicted as positive and mature whereas the young male ones were described as negative and depressed but also not that much mature.

This seems related to what their literature teacher said speaking about the class, *“it is a class whose demographic identity is greatly influenced by the fact that they are half male, half female and half of the females are two or three years older than half of the males. I am referring to age, awareness, determination... not all males, but the vast majority.”*

This example about female being more mature of their age was something that the teacher noticed but probably not every student was enough aware to recognize it and be able to express if asked about; nonetheless the writing activity was surprisingly able to “borrow” the words to express it.

This is also the case for another issue emerged again through the Einstein analytical table. The figures who are either young or old were more nuanced in their characterization, while those of an age comparable to students' parents were generally portrayed more superficially, with the significative example of Davide unnamed parents in the last Act. My interpretation is that students are using the pièce to represent a feeling of tension that they have or at least see around them, between young adolescents and parents. In this sense, the fact that adults (parents) are less nuanced characters could be a way for pupils to deny and refuse them. One additional element supporting this interpretation is the fact that in each scene featuring adolescents they have an argument against their parents, so this tension seems to be at stake.

These issues (and also the case of “Mario” and its author’s comment) demonstrate how creative writing in itself has the potentiality to let emerge identity issues, as it is an activity that involves individuals to such a profound engagement which often ends up being a mean of expression.

5. Conclusions

In the previous sections I reported in detail the datasets, the analytical steps done and related results. For what concerns the outcomes I developed a “metaphorical” image of threads that are thickened along the analytical process, to represent the way outcomes have been dealt with at each step and the meaning of having different results to integrate. The basic assumption is that an outcome emerging from a specific data-analysis done on a selected fraction of the whole dataset (which comprises here the pièce and monologues but also the recordings, the fieldnotes, the interviews) can (and should) be enriched by adding other perspectives from other data-analyses using other fractions of the dataset (Seale, 2002).

Concerning the outcomes emerged, it is visible how a particular way to teach physics concepts can leave space for the expression of personal issues. Time is a core content of physics knowledge, upon which many epistemological reflections can be done. Recalling PF’s words, science has been dealing with various temporal structures, and the Kairòs project represents a possible way to introduce them in class. This is crucial as discussed also by SM and reported by much literature, since reflecting about time and time-management necessarily activates questions related to the sense of ourselves (Adam, 2006; Rosa, 2010; Rosa et al., 2013;).

Still, introducing new time-images and questioning Chrònòs dominance is not enough. I showed indeed the efficacy of the design structure (four layer scheme) - which led to the creative writing activity for instance - to scaffold students’ personal reflections about time and their relationship with it. As PF commented in the interview *“they immediately had experience of a conceptual structure that allowed them to express themselves [...] I found a lot about them in reading their work, that is, I found a lot about their being in the world. One could almost make a sociological reading of what is there”*.

Based on the outcomes discussed, I claim that the Kairòs project is a concrete example of the potentiality of physics education to provide relevant knowledge to students, in the sense that can resonate with them and stimulate questions about themselves in the world (layer 4 of the 4-layer structure). This is also what Ulriksen (2023) looks for: *“Through science education that makes students tremble and contributes to fundamental experiences, students can change and open up their understanding of who they are”* (p.9)³⁴. Scientific concepts carefully reconstructed can be effective triggers in supporting students’ research of their identity, as they can represent a “space” for expression of personal issues.

Therefore, regardless of any discourse involving the contextuality of the implementation (in terms of school, teachers, students, etc.) already discussed elsewhere (De Zuani et al., 2023), the Kairòs activity stands as a reference for all the science-educators interested in inquiring their students’ positionings with respect to time, but also to present them the many possible ways they can *re-position* towards time, hence sustaining Dolin’s point that science subjects must provide tools for a reflection that ensures and support an identity-developing perspective (Dolin et al., 2016).

³⁴ Original translation from Danish.

One crucial point still requires to be mentioned, for the sake of the *Zeitgeist*. I ground here the results on the multiple analysis performed on essays written by students between March and May 2023. If I had to conduct now this activity, I could not ignore the potential role of AI and thus rethink about the analytical strategies. In this and the previous Chapter indeed, there is a strong assumption on the supreme value of the words populating the essays, which are considered ways of expression for students' inner feelings as well as traces for their learning. Based on this assumption we "took the risk" to carefully evaluate single words and analyze them looking for themes. Though, if these essays would have been done with the help of ChatGPT (not available at that time but now incredibly spread in Italy), then our interpretations would have been at least non reliable, pretending to "read" students implicit choices or questions but in fact trying to interpret words generated according to an algorithmic coherence for narrative texts.

Thus, I believe these activities still have a strong educational potential, but a deep reflection of the possible analytical methods seems mandatory.

5.1 Contribution to the theoretical construct

The outcomes of the analysis, in particular the representation of tensions exploiting time dualisms, is in continuity with the previous outcomes discussed in Chapter 3. In that case, students shared their tension between the need for self-affirmation (outside the group) and the fear of leaving the comfort zone (inside the group). This was triggered by the discourse around the different perspectives by which a complex system can be looked at: focusing on the agent-to-agent relations (inner point of view) or on the global emergent property (external point of view).

Having found again the efficacy of complexity themes in activating reflections about identity is a further important result of Kairòs, which addresses RQ II.1 (*To what extent can the epistemology of complex systems scaffold the expression of identity issues?*). In fact, it reinforces the idea that it is possible to educate citizens and create "room" for identity development through scientific disciplinary concepts coming from the physics of complexity. I claim here the importance of such result, recalling Ulriksen (2023): *"The formation of the individual through self-reflection and introspection, which has been a consistent part of the different conceptions of education across variations over time (Horlacher, 2016), has not really found a place in science education"* (p. 14).

As regards RQ II.2 (*What personal-epistemological consonances/dissonances can activate the temporal structures of complex systems?*), two results seem to mostly contribute to answering. The "patterns" emerged show that Aìon was associated to the need for shelter whereas Eniautòs was associated to the sense of control, showing also some traces of resistance especially in the young character (Giovanni). These were interpreted as generational outcomes, also exploiting the ONSCI dataset as a "control" sample. Beyond this, it is interesting the use of time-polarizations to convey very specific tensions; this, in particular, suggests that such a "large" image of time is epistemologically rich enough to accommodate diverse examples of tensions.

Then, regarding RQ IIa (*To what extent does a particular way of teaching physics concepts activate personal-epistemological consonances/dissonances?*) I claim that the variety of personal instances seen through the analysis result from the huge effort of *educational reconstruction* of the concept of time (Duit, 2012) and the specific multilevel activity structure. In different examples, the authors shifted from discourse around their time-management toward discourses around profound problems linked to reflections about who they are, how do they perceive the world around them and who they want to become. Introducing to the concept of time and struggling to create the conditions for time to be much more than a content to learn, reveals to be productive for students' reflections about their identity.

This in particular suggest keeping investing in the 4-layer scheme of Figure 3, demanding for new implementations to test its efficacy with other physics contents. This will be the starting point for the study of Chapter 5.

To conclude, two following RQs from the first Chapter can be considered. For what concerns RQ I (*What methods and analytical lenses can be used to identify the connection between physics epistemology and identity development?*), a brief comment can be done. The analysis done in this Chapter suggests the importance of triangulating diverse data, of different kinds, to best catch episodes of *consonance/dissonance*. The “pulling the threads” metaphor used in the analysis clearly shows the need to multiple perspectives to be used for converging on the interpretation and at the same time consolidate the argumentation.

RQ III (*“What role do epistemic emotions play in link activation?”*) still remains unaddressed, as it is not clear the role of epistemic emotions in the mechanism of consonance/dissonance activations. Still, Section 3.3.4 paves the way for a possible analytical choice for the further implementation, that is trying to focus on them as an analytical tool and use them as markers to disclose possible underlying processes.

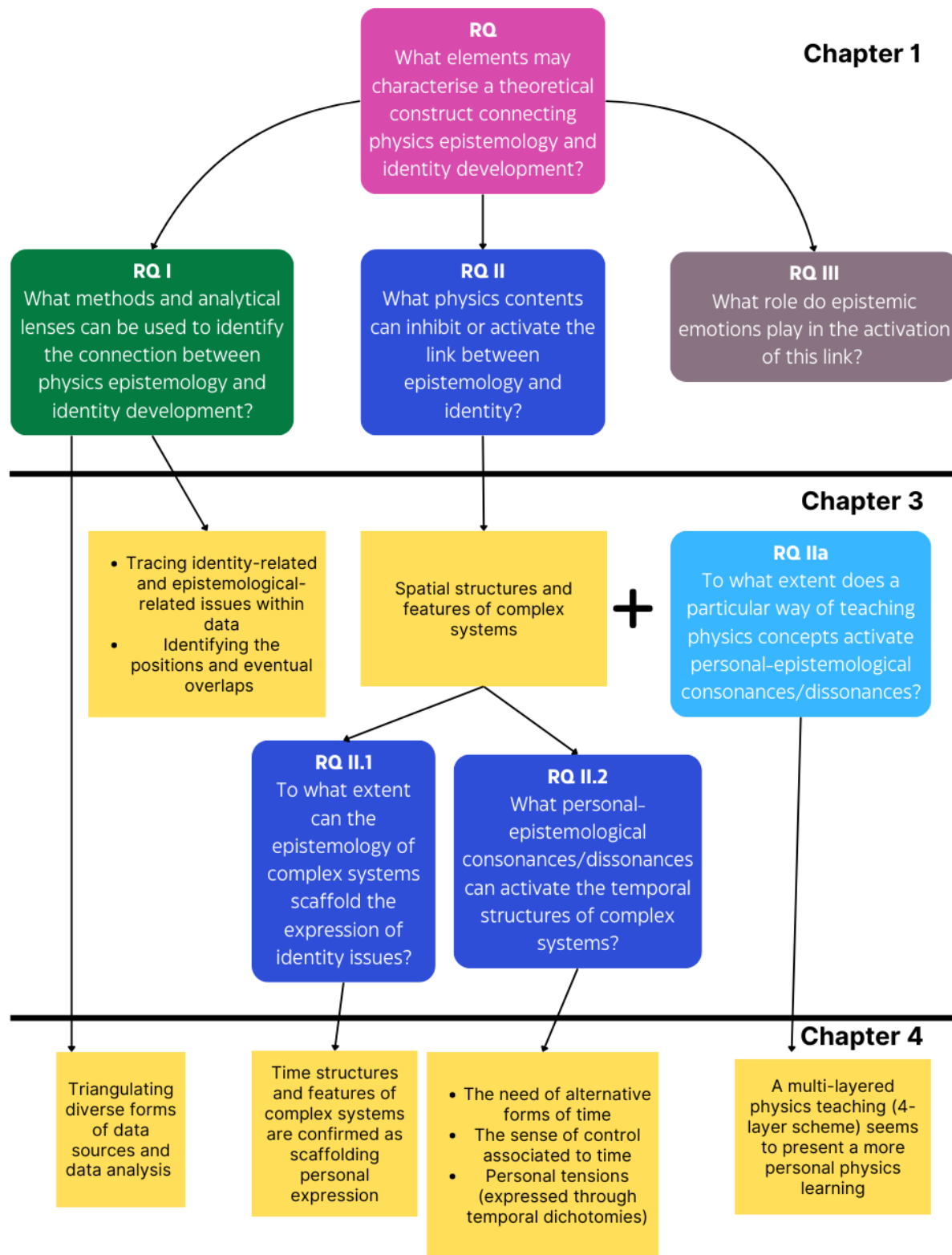


Figure 11: The evolution of the scheme presented in Chapter 1 and recalled in Chapter 3. This Chapter provided outcomes related to strand I, strand II and strand IIa, represented by the yellow stickers.

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Appendixes

Appendix A

We report here the text of the interview protocol used with PF and SM. Specifically, we sent to the teachers the questions and the themes we intended to tackle during the interview, some days before meeting them. The goal was to trigger and feed a larger reflection rather than a situational one.

The interview has been done on July, the 25th, 2024.

Dear PF and SM,

we would like to go over with you the experience you had in your classrooms with Kairos. We think it was a very rich and articulate experience, starting from the design but also in terms of the implementation and what it elicited in the students, as well as in the colleagues who intervened.

We would be interested to know what your expectations were, what you noticed in the students but also around you in the school, and how you experienced the experience in general.

The reflection we have hypothesized is divided into 4 parts:

- A part centered on the motivations behind the activity and content choices: what role knowledge plays for you, what form you wanted to give it in the classroom, what aspects you wanted to emphasize and deepen and why
- A part centered on planning: how you organized the activity, what choices you made (the use of simulations, experiments, playwriting, etc.)
- A part centered on artifacts: what you expect to find in the play and why, and some reference to the discourse of re-appropriation of self through re-appropriation of time
- One part centered on school aspects: have you noticed any new dynamics emerging among students, or among teachers, or at the school level? Also, we would like you to share your impressions with respect to the challenge of incorporating a project of this length within curricular hours

Reflections on the motivations and deep-seated beliefs underlying the experience (role of knowledge)	Tell us about the main motivations that led you to "jump" into this experience, and to place it in the curricular hours? How did the activity fit into the Italian curriculum? That is, which concepts were "disciplinary"? What others, instead, came from your belief in the cultural value that your discipline can have for the education of boys and girls of that age? What role can/should the elements of disciplinary knowledge play for students?
	What strategies have you used to bring knowledge to life and make sure that studying in school does not

	remain a separate and entirely separate experience from adolescents' growth experiences?
Time: Why, what its educational value, and what "faces" of time	In the module, the central topic is time. What value and meaning do you attach to an education on time?
	How can science (physical) education be a resource for educating about time? Why was the focus on complex systems chosen?
	In what ways can literature be a resource for educating about time? Why was a form of theatrical writing chosen?
	Can you tell us, briefly, what acceptions/forms of time were covered in the module? How did you coordinate to deal with them?
Other design related issues	Can you tell us how you created a space where students could put their own ideas and thoughts into play?
Reflections on artifacts, activity outcomes and dynamics among students	What did you expect/expect to find in the writings? What do you suggest to observe in the texts, also in light of the discussion done in class at the end of the activity? What aspects did you notice that might be outcomes of this work? Specifically, what did the students take home (in your opinion) in terms of knowledge or attitude toward knowledge? How about you?
	Have you noticed any particular dynamics emerging (positively or negatively) among the students during the activities?
Time and re-appropriation of self	A recent research paper by the Bologna group (which Paola also authored) highlighted how students tend to separate personal time (time of self-building) and social/collective time (time in which the world progresses, in which things happen). In your opinion, are these two different dimensions of time traceable in the module? Is there anything in the design or implementation in the classroom that can contribute to how these two forms of time can align?

	The same article highlighted how students construct their idea of time through daily rituals and the directionality of time. Did you notice during the work, in the writings or discussion, anything that could have enriched our reflection on personal rituals and the need to regain a sense of directionality? Do you have any reflections on what, if any, this directionality might have meant? (prompt: in the paper, directionality takes the form of "preparing for future profession with tutorials, opening personal research you sense or simply making plans...)
	During lectures (especially physics lectures), were explicit references made to recognizable aspects of identity? If so, which ones? Do you have reflections on how, if at all, educating about time can help support students in their identity formation?
Reflection on dynamics among teachers and at the school level.	Did you notice any particular dynamics emerging (in a positive or negative sense) among the cooperating/participating teachers? Did you notice any particular dynamics emerging (in a positive or negative sense) at the school level, during or as a result of the activity?
Reflections on the module and relationship with curriculum	Going back to the beginning, you pointed out during the activity how it was a challenge to be able to fit the project within the curricular hours, especially in terms of the Italian curriculum. What structural and institutional difficulties/problems do you think an activity like this would encounter? Would you do it again? What important aspects, institutionally, have you noticed?

Appendix B

I attach here the suggesting questions that PF delivered to students for the last lecture.

The writing process and the final product (Via 5 Maggio)

"Words have their own meaning (or rather a multiplicity of possible meanings), but they acquire a precise, relatively precise, relatively stabilised meaning only within the context of the sentence, depending on its global meaning. The sentence in turn consists of words: equally legitimate, therefore, is it to say that it takes meaning from these, and not vice versa. The same applies to the relationship between the sentence and the possible overall text of which the sentence is part, between that text and its context [...] we are in the presence of a "dialogical and recursive relationship", according to a fine definition by Edgar Morin, between text and context. We encounter once again the circular relationship as a fundamental creative process not only in the physical universe and the biological world but also in the sphere of thought itself". (G. Zanarini)

The writing process with the interactions between you above all in mind

A new circular relationship between the whole and the parts:

During the writing phase, you encountered the difficulty of writing and integrating scenes (product of an individual student) within an act (product of a group) and acts within the complete work (product of an entire class). In this process, did you recognise the circular relationship that complexity speaks of? If so, in what sense? How did you personally or as a group experience this process? What difficulties, what strengths...?

Emergent property:

Can the theatre work be considered an 'emergent object' from a process of interaction of a multiplicity of individuals, in this case of you 24 students? Did you follow predetermined rules for interacting with each other? If so, which ones? Did the rules of interaction change or did new ones emerge during the writing process?

The writing process with the end product in mind

Getting in and out of a system, knowing how to look now at the particular now at the whole, making explicit and recognising the interweavings:

How did you manage and take care of the fact that all the characters in the scene are 'single' and at the same time are all 'on stage'? How did you manage the words and actions of each individual character to realise the scene as a whole?

In constructing and managing the dialogues and actions of the characters, did you take into account certain complexity words/concepts such as, for example, instability to bring out new structures i.e. 'new situations', unpredictability, circular causality.... If yes, in what way?

In the construction and management of the dialogues and the actions of the characters, did you explicitly take into account any changes in the space-time scale typical of complexity?

In the construction and management of the dialogues and characters' actions, how did you manage the "different time scales"?

Appendix C

Let us consider a system of cells, each one with a limit cycle. We may ask if there is a way to couple these limit cycles under a comprehensive limit cycle, in order to keep the ability to compute the evolution.

A limit cycle behavior can be interpreted as a system with an average phase ψ , which moves at constant velocity,

$$\frac{d\psi}{dt} = \omega_0$$

with ω_0 related to the period of limit cycle. This dynamic is given by:

$$\psi(t) = \psi_0 + \omega_0 t$$

Now, I have to consider the effect of the other cycles, the other cells interacting with this cell. Hence, I add to the dynamics a small (ϵ) periodic perturbation

$$\frac{d\psi}{dt} = \omega_0 + \epsilon Q(\psi, t)$$

with $Q(\psi, t)$ that can be expressed via a Fourier expansion,

$$Q(\psi, t) = \sum_{l,k} q_{lk} e^{i(l\psi + kt)}$$

The question now is if it is possible to counter-kill the perturbative effect due to interaction with other cells, in order to preserve the phase-dynamics. To do so I exploit a perturbative approach for $\psi(t)$:

$$\psi' = \psi + \epsilon T(\psi, t)$$

with small perturbation. The requirements to preserve the dynamics reads:

$$\frac{d\psi'}{dt} \omega_0$$

which means

$$\frac{d\psi'}{dt} = \omega_0 + \epsilon Q(\psi, t) + \epsilon \frac{d}{dt} T(\psi, t) = \omega_0 + o(\epsilon^2)$$

Thus, being

$$\frac{d}{dt} T(\psi, t) = \frac{\partial T}{\partial \psi} \frac{\partial \psi}{\partial t} + \frac{\partial T}{\partial t} = \omega_0 \frac{\partial T}{\partial \psi} + \frac{\partial T}{\partial t}$$

the condition becomes:

$$\omega_0 \frac{\partial T}{\partial \psi} + \frac{\partial T}{\partial t} + Q(\psi, t) = 0$$

Decomposing in Fourier and composing again for $T(\psi, t)$

$$T(\psi, t) = \sum_{l,k} t_{lk} e^{i(l\psi + kt)}$$

we end up with

$$i(k + l\omega_0)t_{lk} + q_{lk} = 0$$

$$t_{lk} = \frac{-q_{lk}}{i(l\omega_0 + k)}$$

This means that in order to be $l\omega_0 + k \neq 0$, then ω_0 has to be irrational. The problem is that any irrational number is arbitrarily close to a rational one, with $\omega_0 = \frac{m}{n} + \delta$ ($\delta \ll 1$).

The divergence of the term t_{m-n} prevents in general the phase locking and the phase-dynamics is not preserved.

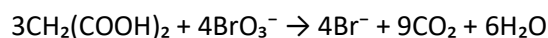
Appendix D

Belousov-Zhabotinsky reaction

The Belousov-Zhabotinsky (BZ) reaction is an exemplary case of non-equilibrium chemical kinetics, showcasing oscillatory behavior due to the oxidation and reduction cycles of metal ions catalyzing the reaction. It takes the name from the first scientist to observe it - Boris Belousov (Belousov, 1959) - and to Anatol Zhabotinsky who a few years later came up with a proper interpretation and mathematical description (Zhabotinsky, 1964).

It involves the bromination and oxidation of an organic substrate in acidic solution. Central to the BZ reaction is the FKN³⁵ mechanism (Field et al., 1972) which involves autocatalytic reactions facilitated by metal ions like Ce_4^+/Ce_3^+ . The reaction displays visible oscillations in color due to the different oxidation states of the metal catalyst.

The whole reaction equation of the FKN model can be expressed as follows:



and involves 10 elementary steps which add up to describe the transformation of malonic acid and bromate ions into bromide ions, carbon dioxide, and water. These steps are cyclic and lead to the periodic changes in concentration observed in the reaction, representing a fundamental aspect of autocatalysis and feedback in chemical systems.

A simplified version of the FKN model, called “Oregonator” (Field & Noyes, 1974) simplifies the BZ reaction dynamics into a manageable system of equations, assuming as constant the concentration of the slowest components to be consumed. The Oregonator, which emphasizes the autocatalytic nature of the process, can be further reduced from three to two equations (Barzykina, 2020)

$$\varepsilon \frac{dx}{d\tau} = x(1-x) + fz \frac{x-q}{x+q} \equiv g(x, z)$$
$$\frac{dz}{d\tau} = x - z \equiv h(x, z)$$

where x , and z represent a-dimensional concentrations of intermediates, while f , q and ε are parameters related to reaction rates. Looking for nullclines and their intersection we can find the equilibrium point, in this case an unstable point. This leads the system, moving along the nullclines, to never reach the equilibrium state hence establishing a periodical behavior described by a limit cycle. Once it enters the periodic regime, the chemical system abruptly exhibits a temporal symmetry breaking passing from the static nature of its initial homogeneous state to the dynamic behavior of its final oscillatory state.

³⁵ From the authors Field, Körös and Noyes.

In our experiment we did a simplified version of a chemical oscillatory reaction similar to the BZ one. In particular, we used a solution of sodium potassium tartrate ($KNaC_4H_4O_6 \cdot 4H_2O$), a copper sulphate solution ($CuSO_4 \cdot 5H_2O$) and 3% hydrogen peroxide solution (H_2O_2).

Practically, 60ml of potassium sodium tartrate solution were mixed with 40ml of hydrogen peroxide in the becher with the stirrer; then the resulting solution was heated to a temperature of $50^\circ C$ and, still with the stirrer running, 1ml of copper sulphate solution was added. The solution assumed a sky-blue color (see Fig. 12). The temperature has been increased then to $80^\circ C$, and an effervescence occurred due to the development of gas, changing the solution colour to an opaque orange-gold (see Fig. 12). If another 40 ml of hydrogen peroxide would have been added, the orange-coloured precipitate would have dissolved and the blue colouring would have appeared again, leading shortly afterwards to return to orange-gold again. The compound is continuously stirred to “simulate” the out-of-equilibrium condition.

This is a simpler version of the BZ reaction, being an oxidation-reaction process, and is not autocatalytic but we can simulate this feature by manually adding precise amounts of hydrogen peroxide.



Figure 12: The colors between which the reaction oscillates, which correspond to two different states (this regime is reached after a transient).



Figure 13: Instruments used in the lab. In particular: bechers, graduated cylinders, graduated pipettes, heatable electromagnetic stirrer, magnetic anchor, thermometer.

Bénard cells

Bénard cells represent a classic example of a self-organizing system in fluid mechanics, where a layer of fluid heated from below forms a pattern of convection cells known as Bénard cells. The phenomenon was first studied by Henri Bénard at the beginning of 20th century (Bénard, 1900). When the fluid medium (a thin layer of spermaceti oil) reaches a certain temperature gradient, hexagonal cells appear as an emergent pattern.

The onset of Bénard convection is marked by the critical Rayleigh number (R_a), which is a dimensionless measure comparing the force of buoyancy to the force of viscosity. The expression for the Rayleigh number is:

$$R_a = \frac{g\alpha\Delta T d^3}{\nu\kappa}$$

where g is the gravity acceleration, α is the coefficient of thermal expansion, ΔT is the temperature difference across the fluid layer, d is the depth of fluid layer, ν is the kinematic viscosity and κ is the thermal diffusivity.

If ΔT is around 0, the system persists in its state of thermodynamic equilibrium which is asymptotically stable. If we slightly increase ΔT , the system transitions into a conductive state, with the temperature becoming no more homogenous in the vertical direction but rather ruled by the equation:

$$T(z) = T_0 - \Delta T z/d$$

where T_0 is the “room” temperature (indeed the top layer is in thermal equilibrium with surrounding environment). If we further increase ΔT we can reach the critical value above which the counterbalancing effect of the thermal diffusion and viscosity can no longer prevent the system to reach a convection state. At this point the fluid displays cells whose diameter is approximately equal to d , with hot fluid going up and cold fluid going down.

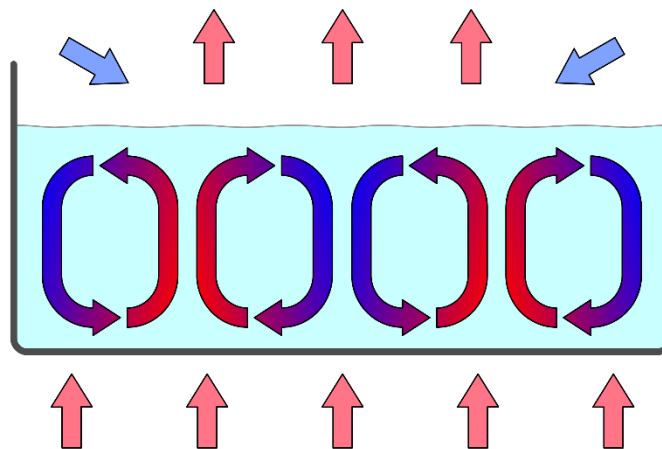


Figure 14: Cells of convection forming in the fluid above the threshold (From: https://en.wikipedia.org/wiki/Rayleigh%E2%80%93B%C3%A9nard_convection).

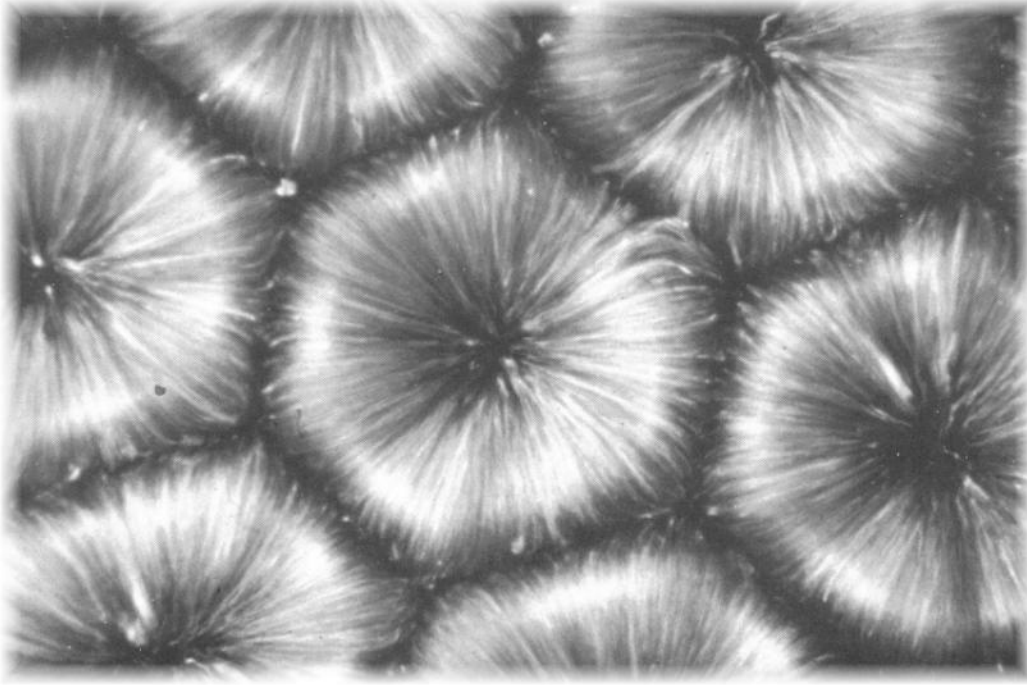


Figure 15: Bénard convection cells (time-lapse) (From: <https://psl.noaa.gov/outreach/education/science/convection/RBCells.html>).

The transition between the state of conduction and that of convection can be described with the equation:

$$\tau \frac{dA}{dt} = rA - gA^3$$

with $r = \frac{\Delta T - \Delta T_c}{\Delta T_c}$, τ is the natural temporal length of the process, g is the gravity acceleration and A is the fluctuation amplitude of a single droplet of the fluid.

Looking for fixed points there's a unique solution holding for $A=0$, if r is close to 0. When r increases, meaning that we are exceeding the ΔT_c , the solution breaks down into two unstable solutions, corresponding to $A = \pm \sqrt{\frac{r}{g}}$.

Then the elementary particles of the fluid start rotating by randomly choosing a left or right-handed direction, according to the two new solutions (see Figure 16).

The study of Bénard cells provides insights into the critical behavior of fluid systems under thermal stress, demonstrating how pattern formation is intimately linked to the fluid's physical properties and the external temperature conditions.

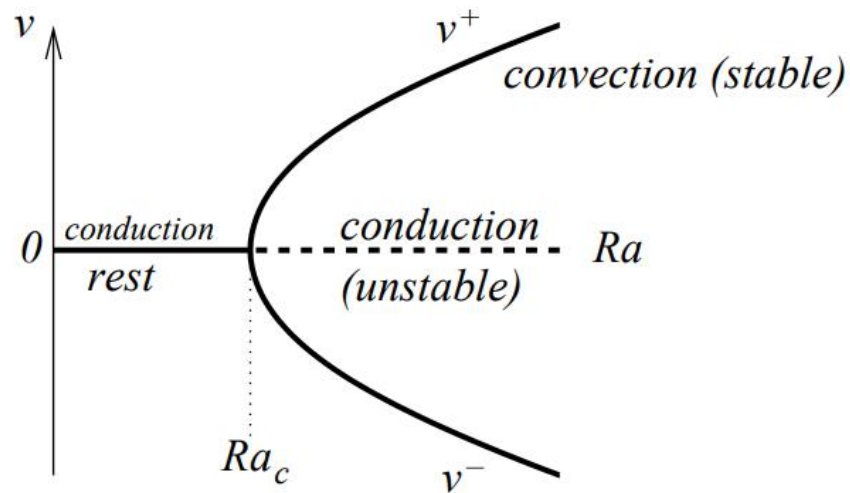


Figure 16: Diagram of molecules' velocities (from Ilari, 2024).

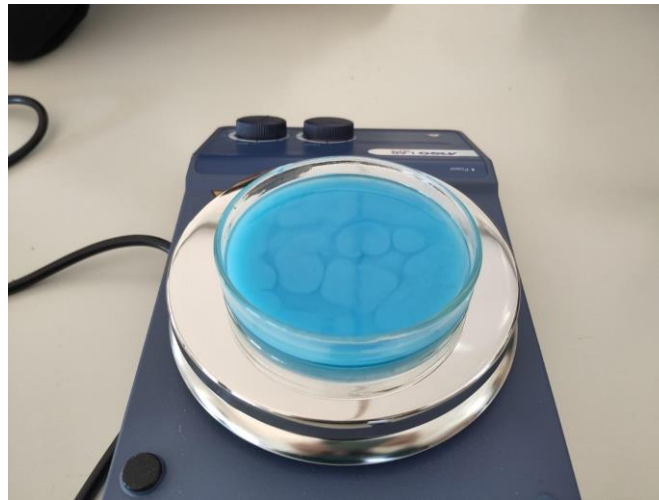


Figure 17: Just one group managed to form some cells (even not that clear) in the fluid, at a temperature of 160°C.

In our case the materials used in classroom were:

- an electric stove
- a mercury thermometer
- a glass or plexiglass saucer

as fluids silicone (with aluminum powder suspended) or olive oil. In general, throughout the experiments, PF, VI, and the other instructors drew parallels between the observed phenomena and broader themes of complexity, such as self-organization, emergent properties, and the interaction between micro and macro levels.

Chapter 5

Introduction

In the previous Chapters it has been introduced the theoretical perspective of *personal-epistemological consonance/dissonance*. To address that, three initial strands have been elaborated and addressed through RQs (I, II, III) answered via two case studies. From Chapter 3, another strand has been added (IIa) with related RQs.

The analysis displayed in Chapter 3 suggested the efficacy of complex systems in triggering personal-epistemological consonances. That result led to the formulation of new Research Questions aiming at inquiring about the role of complexity in general but also specifically of its “temporal structures” in supporting the expression of personal questions.

The analysis made in Chapter 4 confirmed the role of complex systems epistemology in triggering students’ reactions on a personal dimension but also suggested more evidently to what extent design issues were crucial catalysts for such a process (RQ IIa). For what concerns the shift from spatial to temporal structures, time revealed itself to be a critical aspect of students’ lives, confirming the literature in Science Education (Levrini et al., 2021; Ulriksen & Nejrup, 2021).

In this Chapter, I capitalize on these findings in two directions.

- The first one aims to keep inquiring about the potentiality of the 4-layer scheme shown in Section 3.1.3 of Chapter 4.
- The second one concerns the development of the theoretical perspective (*personal-epistemological consonance/dissonance*).

In addition, it will be explicitly addressed the role of epistemic emotions in triggering *consonances/dissonances* (RQ III).

The first part of this Chapter was the core of three presentations done at international Conferences: i) the 4th WCPE Conference, held in Krakow in August 2024 (<https://indico.cern.ch/event/1162407/>); ii) the 110th Italian Physics Society, held in Bologna in September 2024 (<https://2024.congresso.sif.it/>); iii) the 5th Annual Conference in Anticipation, held in Lancaster in September 2024 (<https://www.lancaster.ac.uk/social-futures/events/anticipation-conference-2024/>)³⁶.

Overview of the Chapter

The Chapter is structured as follows.

³⁶ These three presentation have been done respectively by Lorenzo Miani and I (in Krakow), by me (in Bologna) and by Lorenzo Miani (in Lancaster).

In the first Section is introduced the context of the study presented in this Chapter, which was a course for upper secondary students, created as an integral part to reflect about my PhD research and that of Lorenzo Miani (PhD student and co-designer, co-teacher and co-tutor of the course).

In Section 2 the design principles at the basis of the course are described, highlighting their connection with the 4-layer scheme. There is also a discussion about how the two lines of research of Lorenzo Miani and myself informed the course creation. At the end of the Section there is an overview of the contents introduced in class, how they were introduced, the activities done and a general overview of the lectures.

Section 3 is devoted to the description of a game done as the final part of the course, named *FyouTURES*. The game is presented considering its “philosophy” and how it is connected with our research objectives.

Sections 4 and 5 concern data-collection and data-analysis. Specifically, Section 5 is the core of the whole Chapter. I examine step by step what kind of data have been considered at the beginning and how they led to an initial formulation of a local theoretical hypothesis. The data-analysis resembles the typical procedures indicated by Ground Theory literature.

Sections 6 and 7 concern a discussion of the outcomes coming from data analysis and the potentiality of the theoretical hypothesis emerged in highlighting some processes visible during the course experience.

Finally, Section 8 focuses on interpreting the results with respect to the general Research Question of the whole dissertation.

A visual overview of the Chapter’s structure is displayed in the figure below.



Figure 1: An overview of the parts of the Chapter.

1. The Context

The course presented and discussed in this chapter, “Towards new future scenarios: the role of physics to deal with climate change challenges”, has been developed inside the context of the “Piano Lauree Scientifiche” - PLS (“Scientific Degrees Plan”), together with Lorenzo Miani and under the supervision of Prof. Levrini.

The PLS is a STEM-oriented project started in 2004 on the initiative of the Italian Minister for Education, University and Research (MIUR), the Conference of Science and Technology Deans and Confindustria, a national organisation representing companies producing goods and/or services in Italy. PLS is a national intervention plan aimed at addressing six areas of intervention: 1) Enrollment guidance, promoting gender balance; 2) Reducing school drop-out rates; 3) Training, support and monitoring of tutors' activities; 4) Workshops for teaching basic sciences; 5) Teaching self-assessment activities; 6) Teacher training (<https://www.pls.unibo.it/presentazione>).

One of the most common initiatives within the PLS program is to deliver courses for students. These courses aim to provide active opportunities to introduce students to scientific disciplines, using innovative teaching tools and methodologies consistent with the student-centered approach to learning activities. Also, PLS courses aim to carry out self-assessment activities for upper secondary school students to verify their preparation for university access and increase their knowledge awareness to choose an educational pathway.

PLS courses have become a common way to complete the mandatory amount of hours of the Pathways for Transversal Competences and Orientation (PCTO), a national program involving students between grade 10 and 13. PCTO consists of curricular projects which allow students to spend training periods in companies or private and public contracted organisations, but also school laboratories or other environments, as within some PLS courses. At the moment, the amount of hours demanded for PCTO varies according to the type of school (90 hours for grammar schools, 150 for technical institutes, 210 hours for professional schools).

These hours must be accumulated in the last three years of school and do not provide any kind of compensation. Students are free to choose the type of activities they prefer between the different proposals made to them by their school or their teachers, or they can find other options by themselves.

In our research group, PLS courses have been used as an opportunity for designing, carrying out, testing and improving teaching modules. Since the beginning, PLS courses represented a chance to work directly with students, but also with teachers and other collaborators.

Within this framework, PLS courses have been used to collect data to address Research Questions or to inspire new questions, to deepen disciplinary and epistemological aspects of physics topics, to test pedagogical models or educational tools, etc. The main objective of the PLS courses developed by the PER group of the University of Bologna is to introduce concepts both relevant in physics and science in general, but also for society, like for example complex systems (De Zuani et al., 2023), simulations (Barelli, 2022), quantum technologies (Satanassi et al., 2022), artificial intelligence (Barelli et al., 2024) or climate change (Tasquier et al., 2016; Miani et al., 2024).

2. The PLS course “Towards new future scenarios”

This Section introduces the relevant information about the course. Sections 2.1 and 2.2 are devoted to the design of the course, focusing on the boundaries, the objectives, and the expectations; these will be discussed in light of an overview of the lectures. Section 2.3 is dedicated to specifying the logistics of the implementation: the school of participants, the period, the attendance, our roles, etc.

2.1 The module structure

The main goal of the course “*Towards new future scenarios: the role of physics in the challenges of climate change*” (<https://pls.unibo.it/editions/498>) was to serve as an orienting program for 12th and 13th-grade students, helping them to explore potential career paths while gaining insights into how scientists work.

The course was designed upon the multidimensional and interdisciplinary concept of uncertainty, main topic of the PhD of Lorenzo Miani. Another reason of choosing uncertainty was the idea that because of its epistemological richness (as for the complex systems) and its strong connection with present societal challenges such as climate change, sustainability, generative AI, etc., it could activate a resonance with identity aspects.

The structure of the course is grounded upon the 4-layer scheme introduced in the previous Chapter.

Hence, combining uncertainty with the scheme, we came up with a new structure similar to the one presented in Chapter 4:

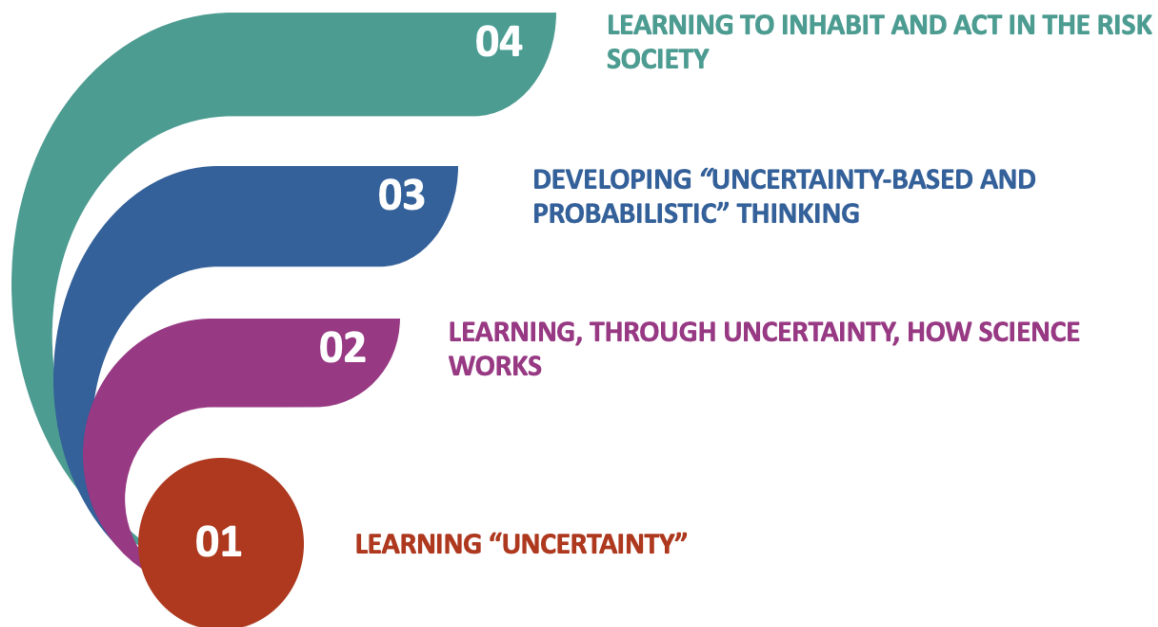


Figure 2: The 4-layer scheme for uncertainty.

The four dimensions entail:

- **Learning uncertainty:** learning the «theory of measurement» in physics (science), statistics and probability concepts and laws, Heisenberg's uncertainty principle (and the distinction between epistemic and ontological uncertainty), the aleatoric uncertainty of complex systems, the climate-related reflexive uncertainty, etc.
- **Learning how science works through uncertainty:** learning how uncertainty makes science advance - how for example uncertainty principle is used in quantum devices (e.g. Kampourakis & McCain, 2019) - or how science deals with uncertainty in its epistemic practices like measuring, modelling, arguing, explaining (Chen et al., 2019; Covitt & Anderson, 2022).
- **Developing uncertainty and probabilistic thinking:** developing a kind of thinking which embraces the different forms of uncertainties as possible epistemic positionings. For example, the Bayesian approach teaches how to take into account new evidence and accommodate it to previous knowledge or consider alternative explanations (Rosenberg et al., 2022). Another example is from the aleatoric uncertainty, which illustrates how being able to reason about unpredictable future scenarios, etc.
- **Learning to inhabit and act in the risk society:** learning to deal with problems where multiple kinds of uncertainties are involved, in out-of-school situations (Fazio, 2023; Pietrocola et al., 2022).

Another choice was to include the theme of the future and scenarios, besides uncertainty.

The course indeed has been designed following also the research of Lorenzo Miani, whose main aim is to explore a different approach for Climate Change Education centred on the concept of uncertainty to develop sustainability competences through the methods of future-oriented science education. The objective is to develop teaching modules that may support sustainability competences development (Bianchi et al., 2022), by framing the multiple forms of uncertainty - epistemic, aleatoric, reflexive (Dessai & Hulme, 2004; Shepherd et al., 2019) - within the framework of future scenarios. In this logic future and uncertainty are instrumental to the competences identified by the GreenComp framework (Bianchi et al., 2022).

Nonetheless, the future-oriented science education approach is also linked to the idea of *personal-epistemological consonance/dissonance*. Educating to imagine the future and to enlarge the span of different futures beyond the probable ones - including also the preferable ones - promotes the activation of personal desires and ambition. In this sense, the research group produced over the last years examples of future-oriented scientific activities for schools (Tasquier & Barelli, 2023), grounded upon future-relevant "focal issues" as they include "(i) *connections to fundamental scientific contents and practices (patterns of reasoning, argumentation, explanation)*; (ii) *future significance, in the sense that they have to represent a societal challenge widely debated also for its implications on the future*" (Levrini et al., 2021). The pillars of these future-oriented activities are scientific topics which involve epistemological aspects such as scientific knowledge, aims, methods, and practices. Hence, exploiting scientific knowledge as a way to orient to the future and support agency in the present resonates with the search for a *consonance* between physics epistemology and students' personal desires, ambitions as well as doubts and questions.

2.2 Intended-learning outcomes and contents

In this section, I present the intended learning outcomes and related topics, following the 4-layer structure depicted in Figure 2. The goal of the course (divided in to seven lectures for a total amount of 20 hours) was to present the different roles of uncertainty and to present its potentiality to open a discussion on the scientific process, to be used as an instrument to reason and its potential role in orienting agency in the society.

The discussion elaborated in this Section already entails the answer to the previous question: *How can the 4-layer scheme be used to develop a course focused on uncertainty?*.

2.2.1 Learning uncertainty

For this first dimension (*“Learning uncertainty”*) we came up with some intended learning outcomes:

- Being able to distinguish the four kinds of uncertainty (epistemic, ontological, aleatoric, reflexive) and enumerate their features.
- Being able to elucidate the main features of climate and climate change, the difference with respect to meteorological variability, the idea of extreme events
- Being able to distinguish between adaptation and mitigation and provide some examples

The objective was to introduce new forms of uncertainty besides the epistemic one, to enlarge the epistemological span of the concept. When we refer to “uncertainty” indeed, we acknowledge that it can be interpreted in different ways, remaining within science and physics. That was one of the reasons at the basis of this choice, as the concept is extremely epistemologically “wide”.

Uncertainty in physics can be divided mainly into three types: i) epistemic uncertainty; ii) ontological uncertainty; iii) aleatoric uncertainty.

Epistemic uncertainty is the uncertainty of classical physics, the error of the measures that must be reduced as much as possible. Within this paradigm, notably recalled by the Laplacian demon, the error exists as a limit of our knowledge (*episteme*), only because of our limited nature as humans; an imaginary demon able to measure with exact precision velocities and positions of all the constituents of the Universe will exactly predict its evolution. With more and more measurements the *epistemic uncertainty* can be reduced. In this sense, such paradigm assumes the ability to develop models able to describe and make visible reality.

Ontological uncertainty is quite different, as exemplified by Heisenberg’s “uncertainty principle”. Within the quantum mechanics paradigm, there are some values (non-commutable) which cannot be simultaneously determined at all with arbitrary precision, not even by an infinitely intelligent³⁷ demon.

³⁷ Here intelligent is used in its Latin sense, *intellego*, something like “being able to see and keep in memory”.

This idea was as simple as revolutionary as it dismantled the paradigm of hypothetical completeness of information affirmed by classical mechanics.

Aleatoric uncertainty is connected to the nature of the system under study and its inner complexity. Many events happenings have a certain degree of randomness, therefore to deal with the inability of making predictions, as for example in the deterministic chaos introduced in Chapter 3, there is the need of a different way of addressing this uncertainty, for example through statistics. There are some systems, such as the Lorenz systems, which display chaotic behaviour even though the equations ruling their dynamics are non-stochastic. Due to the high sensitivity to initial conditions such systems act like aleatoric systems, introducing an intrinsic uncertainty degree to their prediction. Still, aleatoric uncertainty is connected to the complexity of some natural systems, as climate, which strongly question the meaning of creating “explanatory” models. Aleatoric uncertainty adds another layer to determinism and indeterminism, introducing chaos as a component of the systems’ description.

But if we consider specifically climatology, another uncertainty must be considered: reflexive uncertainty (Dessai et al., 2004). Reflexive uncertainty represents the role that humans have in shaping the environment around them and shows the importance of decisions when dealing with our future. As the authors exemplify, humans may actually react to a statement about global warming in two ways: mitigating or adapting to the problem themselves.

“By mitigating (or adapting to) the problem, people are changing the future, which would render the scientist’s original statement incorrect had he or she attached an estimate of likelihood. Thus, within the unknowable knowledge sphere it is appropriate to introduce a new category of reflexive uncertainty, which together with stochastic uncertainty provides a comprehensive picture of unknowable knowledge in the context of climate change” (Dessai et al., 2004; p. 115).

To embrace these differences, in the course, we questioned the univocal vision of uncertainty (epistemic), which is currently developed through science education at secondary school, by presenting the three other forms of uncertainties. This was done mostly in the second and third lectures.

In the second lecture, we recalled the epistemic uncertainty and the determinist paradigm quoting from Laplace, followed by the introduction of both ontological and aleatoric uncertainty. For the first one, we exploited the uncertainty principle to discuss certainty/uncertainty and determinism/indeterminism; for the second one, we used the examples of the Lorenz system and the logistic map to discuss how uncertainty may rise from a deterministic description (deterministic chaos). The “new” uncertainties were discussed also in light of in-group simulations students engaged with, using tools delivered by Phet (<https://phet.colorado.edu/it/>) and Geogebra (<https://www.geogebra.org/>).

In the third lecture, my colleague framed instead the reflexive uncertainty and how that is taken in consideration within climate models.

2.2.2 Learning, through uncertainty, how science works

Related to the second learning outcome, we wanted students to embed the reflection around uncertainties within the climate discourse. Thus, in the first lecture, we invited a climatologist from the

Department of Physics and Astronomy of the University of Bologna, Prof. Paolo Ruggieri, to give a presentation about climate and the history of climatology. His lecture touched on four main points:

- the nature of climate and climatology: a brief excursus on the birth of climatology
- how to make predictions about climate: the first climate models and climate predictions, mentioning also the role of the Charney Report (Charney et al., 1979) in leading to the foundation of the IPCC
- uncertainty and climate: the intrinsic complexity of climate and its chaotic behaviour, the difference between natural variability and climate change, the role of uncertainty in developing SSPs (“shared socioeconomic pathways”)
- the difference between adaptation and mitigation: evidence of climate forcing and examples of mitigation/adaption solutions

Our goal was to exploit the discussion around uncertainties of the first lectures as a proxy to get images about inner science mechanisms. To reach this aim, we decided to explore the functioning and the guidelines expressed by the IPCC, the main scientific reference in terms of climate change, and its functioning from a scientific, decisional and political perspective. Thus, the learning goal we set for this second layer was:

- Being able to illustrate how IPCC works, what kind of reports it delivers and how the multiple uncertainties are considered in the reports

We chose IPCC as an example of how science works as it is a notable image of the collaborative effort of many scientists, but also its report includes a socio-political perspective, becoming a reference for the connection between science and society. The reports produced by IPCC have different targets. In particular, the Summary for Policymakers (SPM) can be seen as a very representative way of integrating complex data from various fields and considering a wide range of uncertainties, as they include the behaviour of climate addressed through specific models but also consider the role of humans. In this sense, aleatoric, epistemic and reflexive uncertainties are examined. One of the different ways in which IPCC addressed these uncertainties is through the development of RCPs (Representative Concentration Pathways) and the Shared Socioeconomic Pathways (SSPs). Since the sixth assessment cycle (2022) RCPs have been integrated into the SSPs.

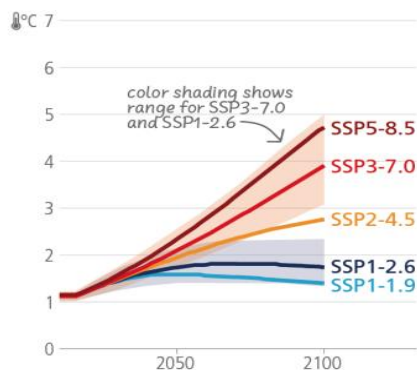


Figure 3: The SSPs with respect to global warming (from <https://apps.ipcc.ch/outreach/documents/707/1687757865.pdf>)

While RCPs focus on potential greenhouse gas concentration scenarios, SSPs describe socioeconomic futures and provide context for these emission pathways (see Section 2.2.3 for more details about SSPs). We chose to insist many times on SSPs as they are also an interesting example of how scientists evaluate uncertainties like the aleatoric and the reflexive ones, while elaborating data-based scenarios.

Related to this, in the third lecture we presented and discussed the concept of “extreme events”, that are those events climate-related that due to different reasons have high impacts and consequences on society. They are marked by high levels of uncertainty, as it is very difficult to predict and prevent them. In the course, we mostly focused on the different strategies that scientists exploit to study them and their connection to climate change. The aim was to highlight the importance and relevance of uncertainty in the scientific process.

The two main approaches used in Detection and Attribution of Extreme Events are the so-called risk-based approach and the storyline approach. The risk-based approach quantifies how climate change affects the likelihood of specific types of extreme events, such as heatwaves or floods, by comparing "factual" and "counterfactual" worlds. This approach is rooted in probability, providing a statistical estimate of the increased risk due to human influence. For example, the risk-based method could be used to calculate how the probability of extreme rainfall might change under different warming scenarios based on historical data (Shepherd, 2016). This method is evidently a legacy of a Bayesian approach to probability and prediction.

In contrast, the storyline approach focuses on explaining the sequence of meteorological events leading to a specific extreme event, offering a more physical narrative. It aims to understand how climate change has influenced the intensity or dynamics of a particular event by analyzing the contributing factors (Shepherd, 2016).

These two methods are not mutually exclusive but serve different purposes. While the risk-based approach excels at providing general probabilistic assessments of climate change’s influence on extreme events, the storyline method offers a detailed examination of specific cases. This nuanced approach allows for a deeper understanding of how certain extreme weather conditions unfold in the context of anthropogenic climate change (Lloyd & Oreskes, 2018).

In the third lecture, we host also an activity with two volcanologists (Prof. Micol Todesco and Dr Barbara Lolli from INGV Bologna), named “Explosive uncertainty”. In the activity consisted in a fake volcano, represented by a toy firework to which it was possible to hang some weights. The firework “explodes” above a sort of tension threshold, which vary from run to run, as these fireworks do not have a standard tension threshold (because of the way they are made). In this activity, the students impersonate politicians and are asked to try diverse runs and note down how many weights were used to reach the explosion for each round. Then, on the “historical data” they get, they have to decide if sending a researcher up to the volcano to gather new data upon which deciding on the evacuation or rather evacuating without further data, with all the difficulties related to a massive evacuation.

The objective of the game was twofold in the logic of the course:

- to illustrate to what extent science must deal with political and societal issues. An evacuation based on specific data collection informs and is informed by political evaluations. This is to

reinforce, again through uncertainty (aleatoric this time), the idea that science contains also political aspects, as evidenced by the IPCC example.

- to highlight how new forms of uncertainties which cannot be solved by more accurate measurements or more data, but only quantified, demand new approaches for decision-making (this aspect are considered in the next section).

2.2.3 Developing an “uncertainty-based and probabilistic thinking”

The third and the fourth dimensions of the 4-layer scheme were considered the “meta-cognitive” layers in the previous Chapter, as we tried to create the conditions for students to reflect on uncertainties and their meanings as instruments beyond the boundaries of physics.

Thus we set two related learning goals:

- Being able to develop new scenarios, recalling from the instruments provided by Future Studies
- Being able to construct a roadmap for future-making

In order to reach these goals, between lecture four and five we presented some tools from the Future Studies as instruments to address the different types of uncertainties. The goal was to engage students in the creation of scenarios, recalling the idea of the FEDORA project about the importance of science education to educate to the future.

Thus, in the fourth lecture, we presented the origins of the field of the Future Studies and its methods, like for example foresight and backcasting, and focused on the future cone presented by Voros (2003).

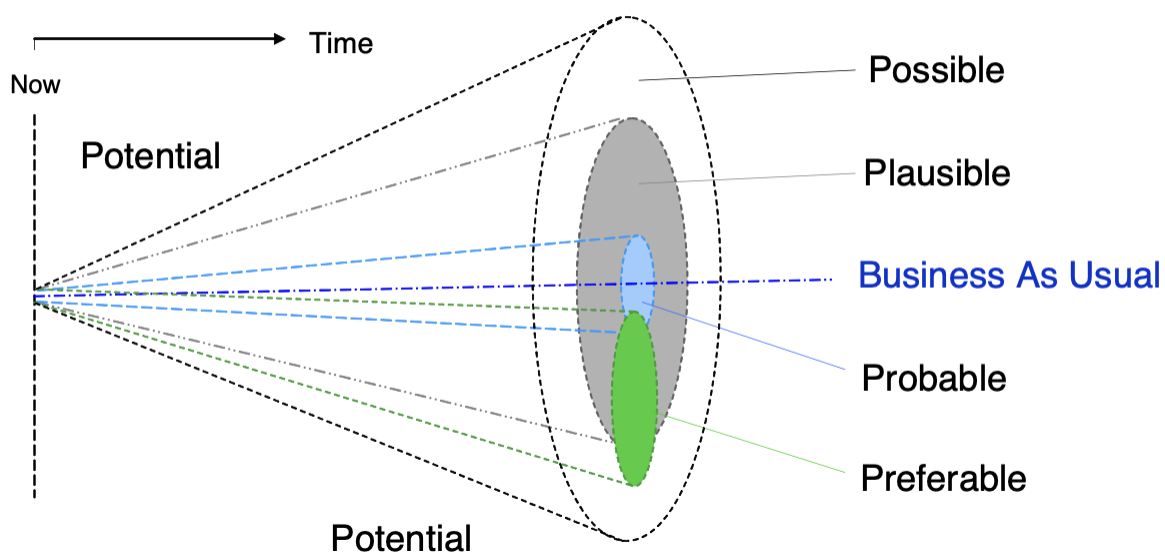


Figure 4: The future cone with different futures and related trajectories (from Voros, 2003; p. 13).

In the future cone, futures are divided into possible futures (what might happen), plausible (what could happen), probable (what is likely to happen) and preferable (what we want to happen). In addition, there are the potential futures (all the types of futures, even those which will not happen) and “business as usual”, hence the future which will occur without changing anything (Voros, 2003).

The introduction of this tool helped us to get students acquainted with the idea that the future is not prescriptive but rather there is space for action and direction (recalling the framework of SSPs).

So, in the fourth lecture, we asked students to describe their idea of what a probable and a preferable future would look like in 25 years, i.e. around year 2050. Then, we asked them to gather into groups and to produce narratives about their ideal futures, combining some values and dreams of the single scenarios. In this part, students used as a support both ChatGPT 3.5 and the Bing image generator.

Overlapped with these activities there was a deepening of the five SSPs (O'Neill et al., 2017) as examples of scenarios from which to take inspiration. Thus, we presented each SSP:

- SSP1: "Taking the Green Road" - Sustainability
- SSP2: "Middle of the Road"
- SSP3: "A Rocky Road" - Regional Rivalry
- SSP4: "A Road Divided" - Inequality
- SSP5: "Taking the Highway" - Fossil-fueled Development

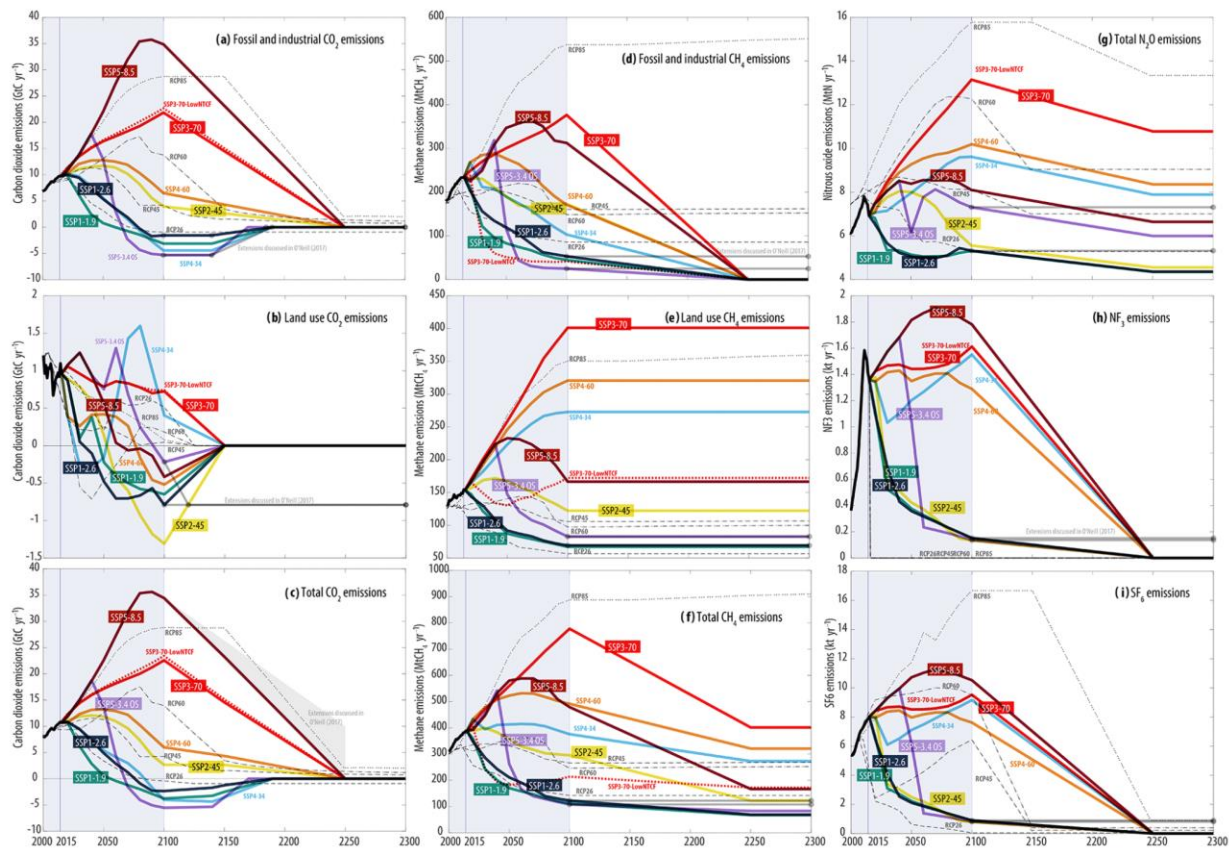


Figure 5: The five SSPs with respect to dependent variables of emissions (from Meinshausen et al., 2020).



Figure 6: The five Shared Socioeconomic Pathways place in a metric confronting adaptation and mitigation (from O'Neill et al., 2017; p.170).

The goal of focusing on the SSPs was to trigger the goal of the third dimension of the 4-layer scheme (Figure 2). The scenarios are indeed based on the evaluation of the diverse sources of uncertainty in the present climate situation (dimension 1), effort of a collaborative effort of modelization (dimension 2). SSPs can be therefore seen as great examples of how scientific concepts, such as uncertainty, can be used to formulate models to look at the world (for instance by policymakers). The possible behaviour of humans (reflexive uncertainty), balancing (or unbalancing) actions of mitigation/adaptation leads to formulating scenarios which become lenses to think about the world, ask questions (*“Do we want to live in a world like SSP4?”*, *“How can we shift from scenario SSP5 to SSP1?”*, *“What values should we promote to reach a scenario like SSP3?”*, etc.) and take decisions.

In this sense, presenting SSPs after having introduced the forms of uncertainties and how they are considered by IPCC, was meant to trigger a “change in perspective” - from linear to complex (Jacobson et al., 2006). This change of perspective can be the first step for the development of uncertainty-based and probabilistic thinking.

Also, the volcano activity of lecture 3 and the final FyouTURES game presented in lessons 5, 6 and 7 pointed to the same direction

2.2.4 Learning to inhabit and act in the risk society

The last layer of the 4-layer scheme is again “meta-cognitive” and strictly connected to the third one. In the course, uncertainty was discussed in a way that could support the understanding of scientific

mechanisms and the development of a kind of thinking more suitable to face non-epistemic uncertainties. The goal was to offer students a disciplinary concept epistemologically rich enough to become a *thinking tool* beyond the physics class; to think about possible futures but also to inhabit and take agency in a society devastated by climate change.

Hence our last learning goal:

- Being able to discuss possible actions to mitigate and adapt to climate change, based on the awareness of the multiple stakeholders involved in sustainability issues;
- Being able to find possible ways to face different kinds of events based on kinds of uncertainty sources.

In order to support a more practical dimension where to put into play the “probabilistic and uncertainty-based thinking” we designed the board game *FyouTURES*, and we engaged students to play it divided into groups. Half of lecture 4 was devoted to explaining the rules, one software used in the game and the co-design of some cards to play with. As it will be clearer later, students were asked to create wildcards representing possible events (climatic, political, social, technological) and related consequences within the game world. Each event should represent one form of uncertainty among the aleatoric, reflexive and epistemic ones. The goal of the co-design was indeed again to support the development of a kind of reasoning informed by disciplinary concepts (uncertainties).

2.3 Lectures’ overview

It is shown here a brief scheme of the six lectures (the 7th was a collective discussion after the board gameplay), mapped with the four dimensions of the educational scheme (see Figure 2).

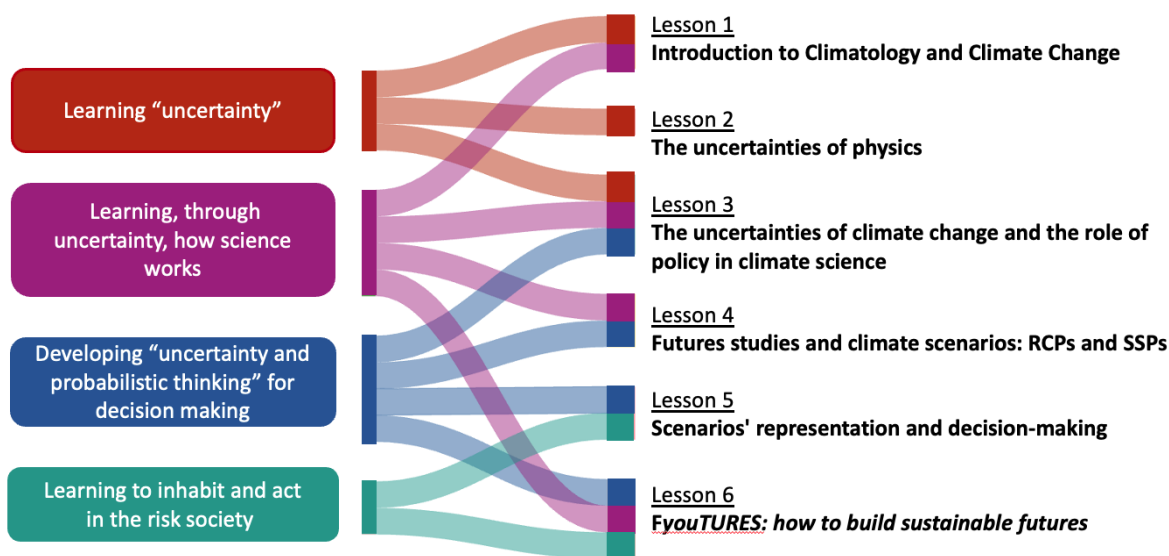


Figure 7: The connection between the four dimensions of the educational scheme about uncertainty and the lessons. As it is shown each lesson was devoted to touching at least one of the dimensions, Furthermore, it is evident an order: the first lectures were meant to lay down the basis (dimension 1), then from the third, we started to address more consistently the second dimension and so on (credits to Lorenzo Miani).

Lecture 1: *“Introduction to Climatology and Climate Change”*

- Introduction to the course by prof. Olivia Levrini: an overview of the topic and the role of physics to orient through uncertainties and scenarios
- Competence questionnaire administration - pre (see Appendix A) (prepared by Lorenzo Miani)
- Introduction to Climatology and Climate Change: a lecture by prof. Prof. Paolo Ruggieri (Climatologist) about climate science, climate models and climate change
- Questions and Discussion

Lecture 2: *“The uncertainties of physics”*

- Epistemic uncertainties and the Laplacian paradigm in Newtonian mechanics
- Ontological uncertainties in Quantum Physics: formal introduction of uncertainty principle, discussion and brief visualisation with a Phet simulation
- Aleatoric uncertainties in Complex Systems: definition of complex systems, examples of deterministic chaos from Lorenz equations and activity with Geogebra about the logistic map

Lecture 3: *“The uncertainties of climate change and the role of policy in climate change”*

- Introduction of reflexive uncertainties as the need for considering the role of human behaviour
- Different approaches to studying extreme events: storyline and risk-based
- How to balance policy-making and science: the role of IPCC
- Decision-making in extreme events: hands-on activity in collaboration with prof. Micol Tedesco and Barbara Lolli from the National Institute for Geophysics and Vulcanology (INGV)

Lecture 4: *“Futures studies and climate scenarios: RCPs and SSPs”*

- Introduction of Futures Studies and their tools
- Futures questionnaire: potential vs desirable
- How to build future scenarios through AI and ChatGPT: group activity starting from questionnaires' futures
- Building hope for the future: using solar punk as a language to express the scenarios (group activity)

Lecture 5: *“Scenarios' representation and decision-making”*

- SSPs and RCPs
- Mapping complexity and representing future: from the speculative maps to the FyouTURES one
- Introduction to the game FyouTURES (rules and participants) and the En-ROADS simulator
- Wildcard creation

Lecture 6: *“FyouTURES: how to build sustainable futures”*

- Game-play of FyouTURES

Lecture 7: Final restitution

- Group presentation of the game reports
- Competence questionnaire (post)

The course consisted of seven lessons, for a total amount of twenty hours, and was held between October and November 2023. Each lesson has been co-designed and co-taught by me and Lorenzo, with the supervision of prof. Levrini. Also, we planned and did a data-collection, included the final semi-structured interviews at the end of the course (see section 4 for details).

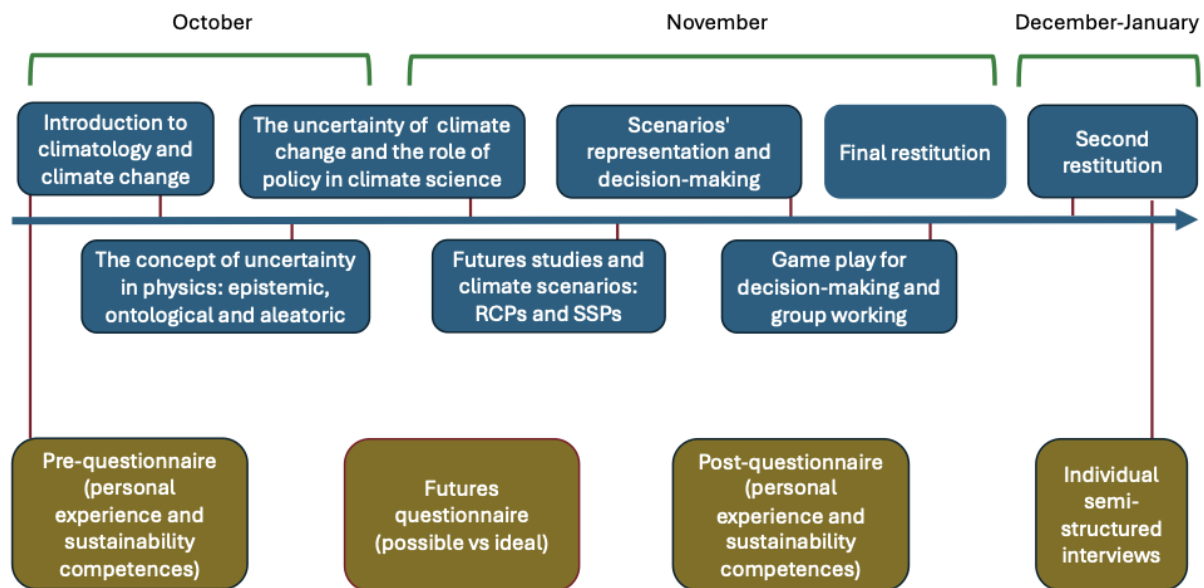


Figure 8: Timeline of the course and related phases.

Thirty-four students participated in the course (some of them were students connected with teachers we contacted, and others were students who saw the course's announcement online). Thirty-one students were from scientific high schools, two from classical high school and one from the humanities high school, with a total number of eight different schools. Some students came from the same class. Twenty-one students were from the fourth grade (12th grade) and thirteen were from the fifth grade (13th grade). Nineteen students identified as females, while fifteen identified as males.

3. FyouTURES

As anticipated before, the final part of the course consisted of a board game we created, named FyouTURES.

Specifically, we aimed to create an extended workshop of scenario-making, aligned with the 4-layer scheme and with specific objectives to pursue:

1. **Center on the contents:** The knowledge and key concepts of the course (uncertainties, complexity, future studies) were placed at the center of the activity.
2. **Illustrate future as open:** The future was framed as an open set of possibilities, and the game was designed to highlight the role of agency in shaping future scenarios, to contrast students' sense of detachment from their future (Angheloiu et al., 2020; Rasa et al., 2022).
3. **Scientifically inform decision-making strategies:** The future-oriented reasoning of the game was grounded in scientific evidence, ensuring a sort of realism for students' decision-making processes.
4. **Highlight sustainability's complexity:** The activity emphasized the intricate nature of sustainability, involving multiple dimensions and stakeholders, requiring students to balance diverse and often conflicting needs and interests. We highlighted indeed that taking decisions with respect to climate change is difficult as the issue is intrinsically complex, because it involves different dimensions (social, political, economical, technological, scientific, etc.), different stakeholders (citizens, policymakers, scientists, NGOs, industries, etc.) and different forms of uncertainties (epistemic, aleatoric, reflexive).

In the section below I report about the genesis of the game.

FyouTURES genesis

One turning point was the inspiration for the representation of scenarios. I came up long time before with a "Speculative Map" exposed at the Milano Triennale exhibition in 2022, named "Unknown unknowns" (<https://triennale.org/eventi/unknown-unknowns>). The map was part of seven kinds of maps created by Frédérique Aït-Touati, Alexandra Arènes and Axelle Gregoire within their book "Terraforma" (Aït-Touati et al., 2022). In the book the authors explore forms of maps which can be used as instruments to explore our world as if it was an unknown world (*terraforming* is indeed the term used to describe the actions of humans to explore and make a new planet suitable for human life). Within the maps, each one presenting a new perspective by which look at the world, there is one named "Space-time" which "seeks to restore a sort of plasticity to space-time by helping us to situate ourselves between the poles of (time) acceleration and deceleration" (Aït-Touati et al., 2022; p. 125). In this model they consider the territory divided into unit-points which then "develops individually between expansion, condensation and retractability" (p.126). The core idea is to conceive the future of a space as something open and not pre-determined. Thus every unit-point becomes a spiral showing its potential evolution, and from a city spatially and temporally normative we pass to a city of "potential times".

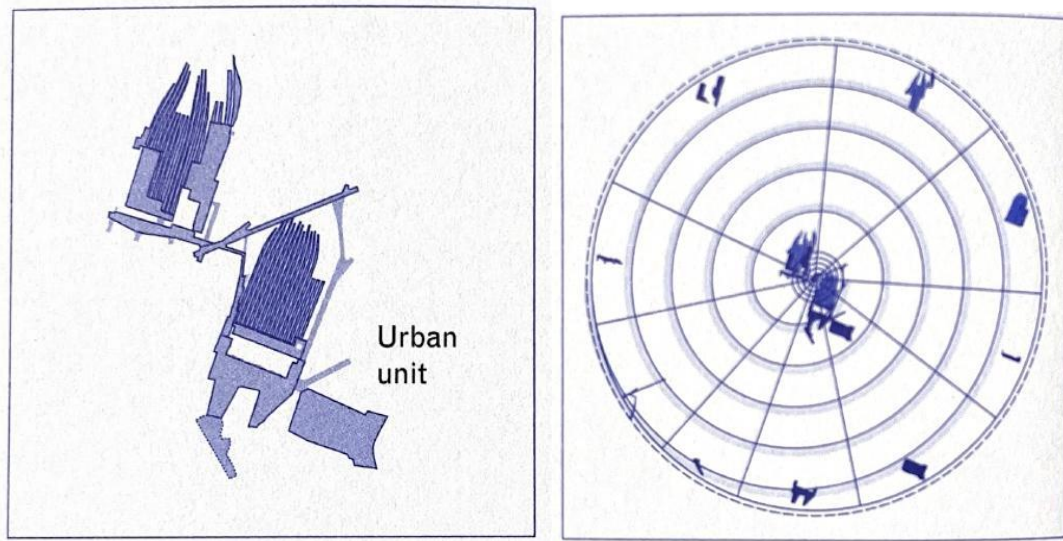


Figure 9: On the left is an example of unit-point: it is an urban unit of a hypothetical town. On the right: each unit-point is divided into sub-units, each one with its future potential development represented by a cone, with the circles of the spiral indicating the seasons, hence time passing (from Terraforma, Aït-Touati et al., 2022; p. 138).

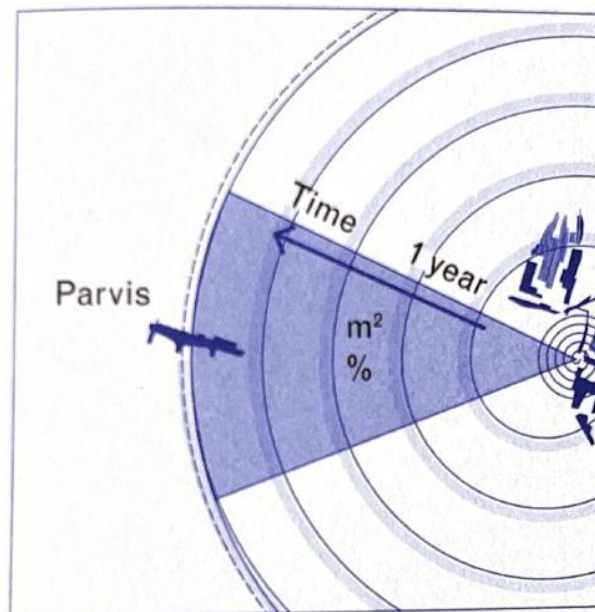


Figure 10: The future cone of one year for a sub-unit (from Terraforma, Aït-Touati et al., 2022; p. 138).

This map was the first turning point and source of inspiration for representing open futures.

A second turning point is represented by the simulator En-ROADS, which Lorenzo recognized as a possible useful instrument to use for grounding the reasoning on scientific evidences and to represent the many dimensions involved in sustainability.

En-ROADS is a simulator developed by Climate Interactive, Ventana Systems, UML Climate Change Initiative, and MIT Sloan and is constantly updated (Siegel et al., 2024). It is a system dynamics model that integrates multiple datasets and differential equations to produce future scenarios up to 2100. Users can adjust sliders representing actions like increasing carbon prices or taxing energy sources which quantitatively display the impact of these actions on global temperature, sea-level rise, and other indicators (see Figures 11, 12 and 13).

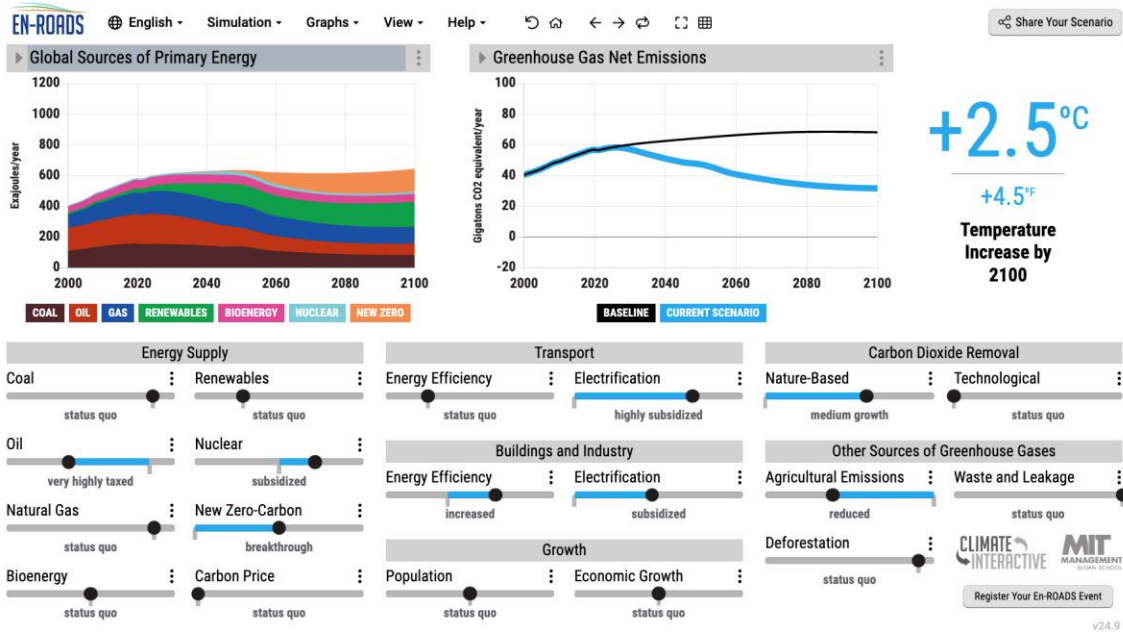


Figure 11: The En-ROADS dashboard. The user can move each slider and immediately see its effect on some dependent climatic variable, for example the temperature increase shown here, but also many other (<https://en-roads.climateinteractive.org/scenario.html?v=24.9.0&p7=48&p30=-0.03&p35=1&p47=2.9&p373=35&p375=23&p60=60&p417=60>).

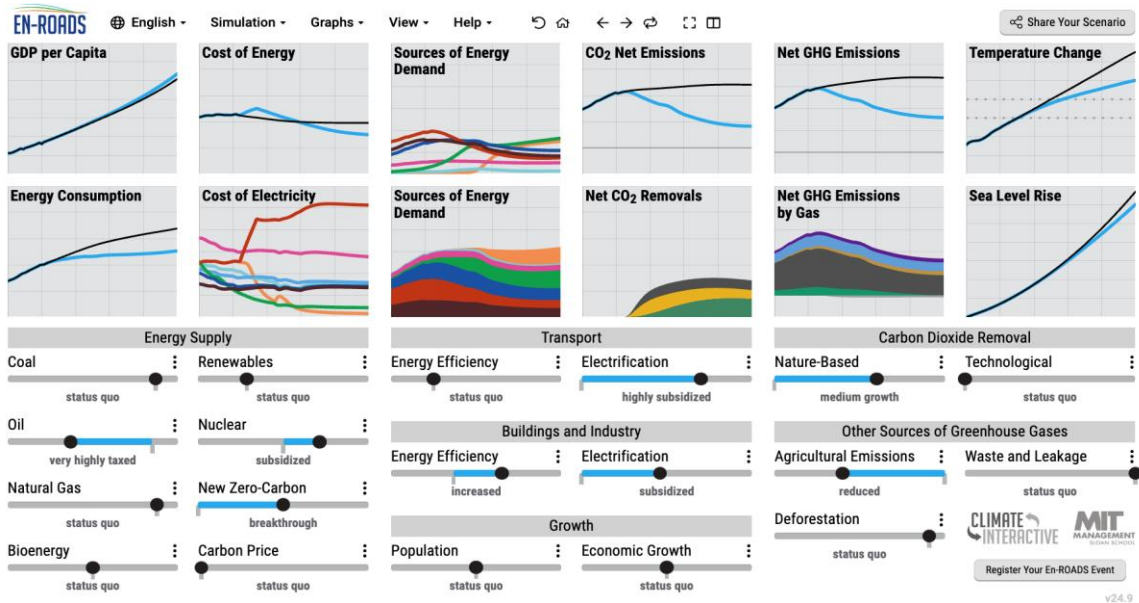


Figure 12: Other dependent variables that can be checked as moving the sliders.

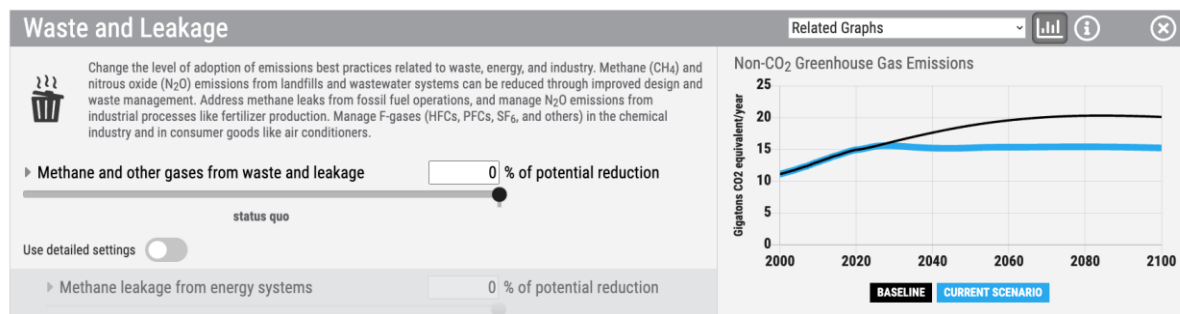


Figure 13: Each slider is explained in detail, and it can also be modified by “detailed settings” options.

The simulator embeds a complex, non-linear causal model (Figure 14) with specific assumptions for usability, and is specifically aimed at “understanding how we can achieve our climate goals through changes in energy, land use, consumption, agriculture, and other policies” (Siegel et al., 2024).

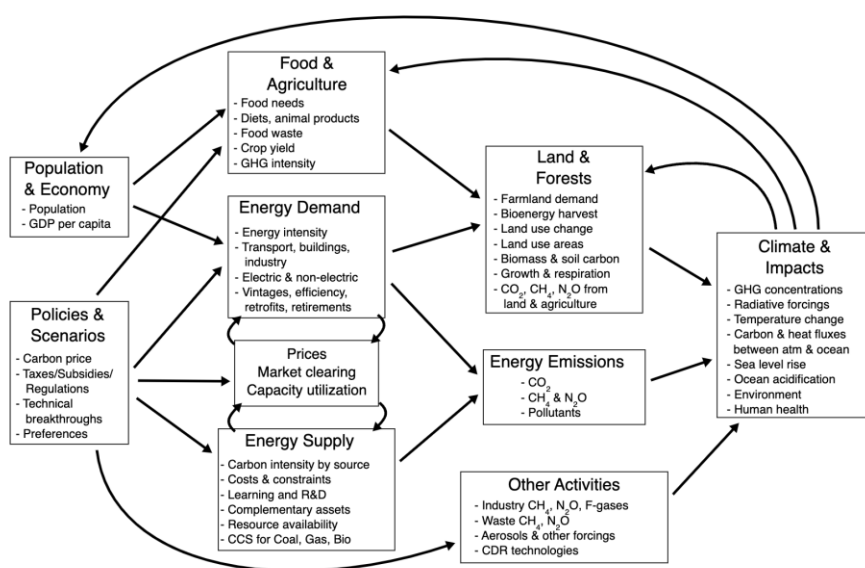


Figure 14: The causal structure of the model (from Siegel et al., 2024). As can be seen is not that easy to identify a primary cause, because of feedback loop mechanisms. The model indeed shows how the energy emissions impact greenhouse gas concentration and are impacted by anthropogenic issues, but also how the climate change resulting from gas concentrations backfires on the human condition, reducing economic growth, conditioning land usage, etc. The model is thus meant to reproduce the complex intertwining of economic, social and environmental dimensions.

En-ROADS was crucial as it provided a scientific basis for creating scenarios. It was possible then to associate a specific decision in the present with future scientifically sound consequences (Figure 12) and thus include realistic information in the scenarios.

The objectives, the map inspiration and the En-ROADs simulator all brought together to the creation of FyouTURES, a board-game where students had to take a role and together with other classmates build their scenario and represent it on the map.

Each player in the group covers an area defined in En-ROADs. The roles were defined upon the kind of sliders (conventional energies, green energies, green areas, emission control, electrification and energy efficiency) and the possible actions to actually develop the future scenario became the movement of the sliders, that we calibrated in terms of costs. To introduce the concepts of uncertainties and force students to find strategies to face them we introduced wildcards, cards that are drawn at each round and are associated with each of the three forms of uncertainties (see Section 3.1.3).

With these choices, we found a way to create a scenario-making activity which includes the complexity of climate change and its forms uncertainties (objective 1), with the aim of developing a future scenario (objective 2) making scientifically informed decisions (objective 3), through accommodating different instances by diverse stakeholders and facing unpredictable forms of uncertainties (objective 4).

In the next section, the rules of the game are explained in detail, how we used the simulator and the wildcards mentioned above.

3.1 Game functioning

FyouTURES (De Zuani, Miani & D’Orto, 2024) is a board game where players are divided into groups of 6 (in this case students choose themselves how to create the groups) and simulate a "government council" with the task of making decisions to develop a future scenario in coherence with some climate-related goals, such as reducing sea-level rise and limiting global warming by 2100. The kind of scenario we aimed to convey is a multidimensional possible image of the future, presented as a coherent narrative explaining how different components evolved from present trends (Börjeson et al., 2006). According to Börjeson and colleagues, scenarios may belong to three different categories: predictive (What will happen?), explorative (What can happen?) and normative (How can a specific target be achieved?). In our case, the objective of the game was to create a scenario in which global warming and the sea level rise were contained below specific thresholds, which was then a normative one.

3.1.1 Glossary

Here are reported the terms used in the rules with specific meaning.

- **Areas of intervention:** the areas of intervention are macro sectors identified on the EnRoads simulator and each contains several sliders from those available and represents general themes (e.g. «green energies»).
- **Actions:** they represent sectors in the gameboard, and they are EN-Roads simulator sliders. They are grouped into ‘Areas of intervention’ accordingly to the related theme. The coins can be spent or earned in the actions, with specific distinctions (see later).
- **Coins:** they represent the budget through which the group can take actions hence moving the sliders in EN-Roads. They can be spent or earned in the actions with the following rule: every

notch in the sliders is equal to 1 coin. Taxation usually makes earn coins whereas subsidization usually makes spend coins.

- **Notches:** notches are marks on the game board that keep track of the decisions made for the actions and allow to develop the future line. They correspond to the unit of measure of the shifts for the sliders in EN-Roads, and each equals 1 coin.
- **Budget:** this is the number of coins that can be spent per turn. It consists of a fixed component and a variable component which can be gained with taxation.

Further materials

- **Wildcards:** these are unexpected cards that are drawn at each turn and represent favourable or unfavourable events that the group must face. They are inspired by the three forms of uncertainty related to the climate issue: epistemic uncertainty, aleatoric uncertainty and reflexive uncertainty.
- **Character cards:** character cards indicate the role each player will play. Each player will be responsible for one area of intervention, meaning that he/she has to suggest to the group how to use the budget for the sectors («actions») of each area. The characters can be personalised if needed.

3.1.2 Game Rules

Each player is responsible for a specific area: green areas, emission control, green energies, conventional energies, energy efficiency, and electrification, and suggests possible actions to do in their sector. The game is structured into three rounds, corresponding to the present (in which they plan the scenario for 2030), 2030 (planning for 2050) and 2050 (planning for 2100).

In each turn it is possible to spend or earn coins in one or more actions. The actions depend on the areas of intervention and correspond to the sectors of each area. For instance, the conventional energy area corresponds to the actions: coal, oil, natural gas and bioenergy (see legend top left in Figure 15).

At the beginning of each turn, each group must draw 3 wildcards.

How to spend and earn coins?

The meaning of spending and earning coins is to subsidize (and thus spend) or tax (and thus earn) in the different actions of the intervention areas. On a practical level, if it is decided to spend or earn one coin for an action, it will correspond to a shift of the corresponding slider in the EnRoads simulator (to find out how much shift corresponds to a single coin for each slider, please see the Calibration Table in Appendix A).

In the first round, players have a budget of 10 coins which they can spend in the different sectors; in the next two rounds, the budget will be increased by 5 more coins each. In addition to the 'fixed' budget, players can build up a 'taxation budget' (the extensions of the budget visible in the game board) by taxing

and thus earning coins in the sectors that allow that (namely those with positive notches on the gameboard).

At most then the coins given by the sum of the 'fixed' and 'variable' budgets can be spent each turn.

The coins spent or earned in the first turn, for each action, are investment or taxation plans that must be confirmed throughout the turns. Therefore, in the second round, the group has to start from the budget situation reached at the end of the first round.

The decision of where and how to spend the coins is agreed upon by the group (members can decide whether by majority vote or by unanimity).

How to move around the board?

Depending on the group decisions, members will have to draw a 'future line' representing the decisions to spend/gain coins.

On the game board (Figure 15) for each action (coloured sectors) there are markers with a corresponding sign: the markers with a plus sign indicate the number of coins gained while those with a minus sign the number of coins spent on that action reached in that turn. The white line represents the 'zero' (referred to in the sliders as the 'status quo') and indicates a zero balance of spending on that action, for that turn.

On the first turn, all spending decisions made will be represented with lines starting at the centre and ending in the notch corresponding to the amount of coins spent or earned for that specific action.

An example: if in the first round for the 'Green Energies' sector the decision is to tax the 'Nuclear' action by 3 coins and de-tax the 'Renewables' action by two coins, the group must draw a line for the first action (starting from the centre and ending at the +3 notch, and a line for the second action starting from the centre and ending at the -2 notch. If in the second turn the group confirms the choices for these actions the two lines will start from the notches reached in the first turn and end on the same notches for the second round. If, on the other hand, the group decides to change the spending, the lines will start from the notches reached in the first round and end on the new notches for the second circle.

Also note that the number of attainable notches (and thus the number of coins that can be spent and earned per turn) increases over the course of the three turns (see calibration table in Appendix B).

At the end of the third turn, the group will have three lines for each action, corresponding to the lines drawn for each turn: these constitute a final picture of the future scenario created.

End-of-rounds activity

This game is an exercise in creating possible future scenarios, where the scenarios are made by the endpoints of each action for each turn and are the result of the group's discussion and decision (hence the name of the game). At each circle (i.e. each turn), the group has to complete a budget (see bottom left in Figure 15) by colouring in the notches according to how the budget has been spent. At the end of each round players are finally asked to produce a brief narrative description of the scenario reached, imagining what kind of world they created.

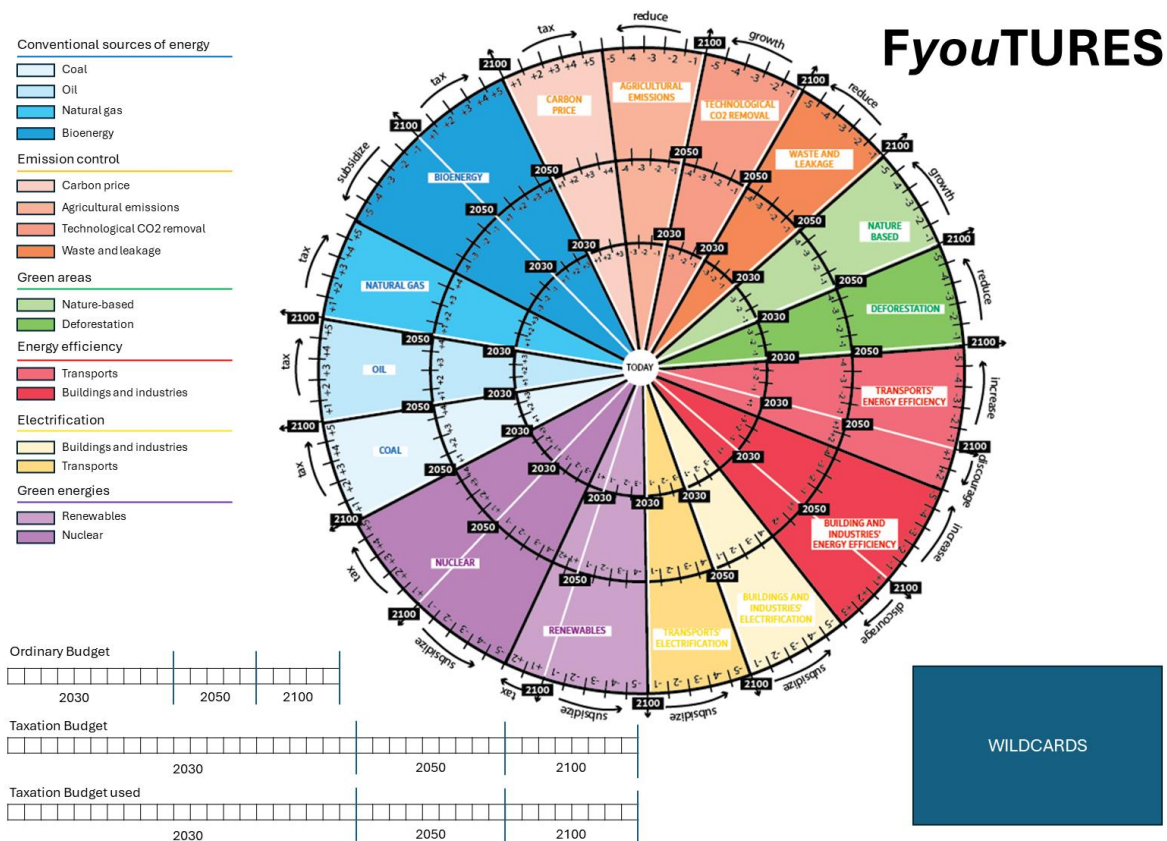


Figure 15: The game board of FyouTURES (this is a second updated version, different from the one students played with). It is recognizable the inspiration from the “Space-Time” map by Terraforma, with the cones of futures for each area, spanning over three time horizons. On the top left the six specific areas each one containing one or more sectors corresponding to the En-ROADS sliders, which are reported with the equivalent number of notches in the round at the centre. On the bottom left is indicated the budget for each turn, with a cell for each coin available. On the bottom right the card of “Economic De-growth” chosen by the group. In the circle are visible the black lines indicating the coins spent/earned. For example, in the Renewable sector (yellow) it can be seen that in the first round they invested one coin, confirmed in the second round and then increased to 5 coins in the last round. The white lines indicate the status quo, meaning no movements of the slider.

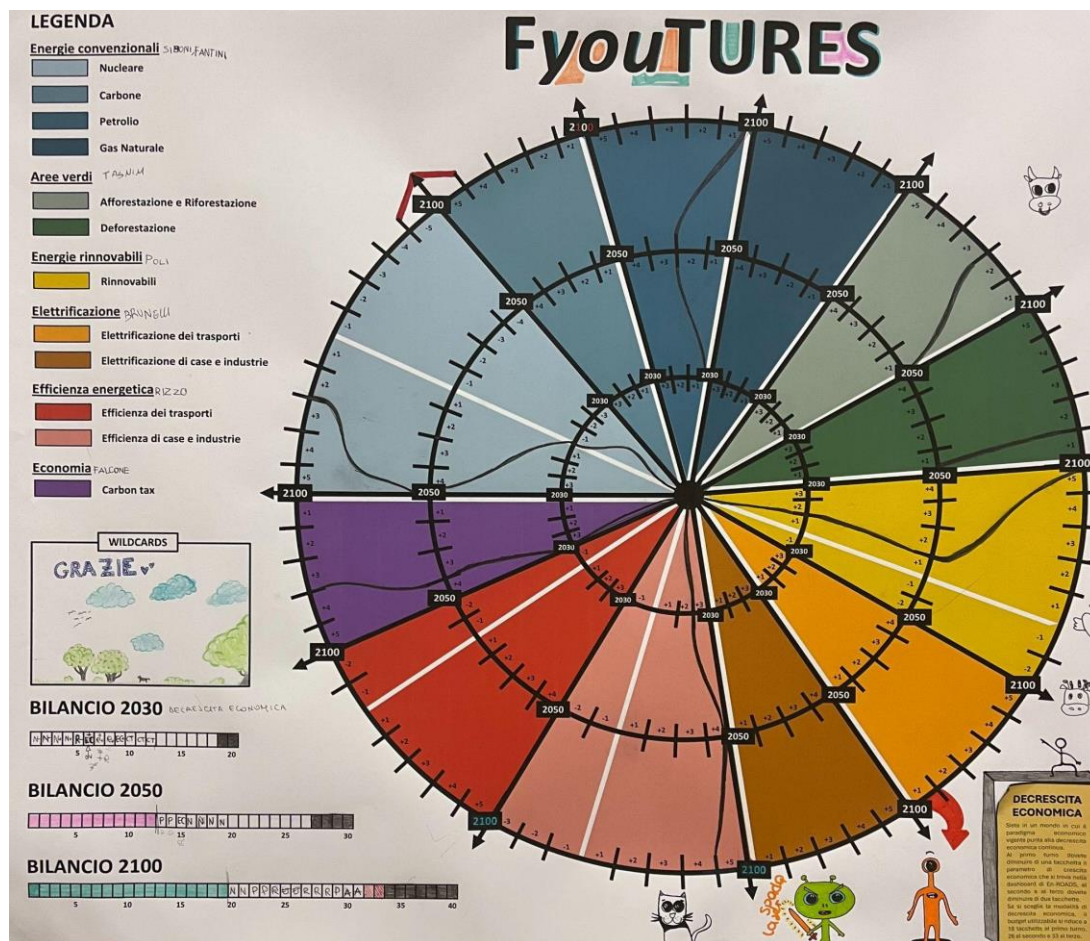


Figure 16: The game board of FyouTURES as filled by Group 1. This was the first version of the game board.

3.1.3 Wildcards

The table below reports the wildcards used in the first version of the game. Some of them have been created by me and Lorenzo Miani, the others were created by the groups in Lesson 5 and then voted by the rest of the class. Only some of them have been included in the final list. They are divided according to the kind of uncertainty they represent.

TO THE ARMS	NO COAL	WELCOME
A war breaks out. The cost of energy goes up, much is invested in the military industry and rearmament and little in sustainable technological development. Effect: You are obliged to subsidize fossil fuels to meet the strong need for energy. You must incentivise the area of conventional energies by a	Following a strike by the miners' union over their working conditions, a social movement succeeded in raising awareness against the use of coal-fired power stations. Effect: You have to tax coal-based energy production by two coins, and invest them in renewable energy production.	Exponential increase in migration due to the effects of climate change. Effect: Effective integration policies are introduced, leading to technological development. The new zero carbon slider is increased by one notch.

total of 3 coins. For this round, you cannot tax conventional energies.		
GO VEGAN	FLOOD	BACK TO THE PAST
There is widespread awareness of the need for a different diet: there are fewer farms, and crops are converted. Effect: Spend two coins to reduce Agricultural Emissions by 20%.	An unprecedented large flood hit many populated areas, requiring emergency spending to restore and secure the affected areas. Effect: Your ordinary budget decreases by 5 coins.	Prolonged torrential rains led to the collapse of a major dam used to produce hydroelectric power. Effect: You are forced to reinvest in non-renewable energy sources. You spend three coins in your choice for subsidizing non-conventional energy sources (oil, coal, natural gas, bioenergy). For this round, you cannot tax conventional energies.
YOU, AGAIN?	NUCLEAR ALERT	FIRE! FIRE!
A pandemic leads people into forced isolation, with a consequent effect on the economy. Effect: Decrease economic growth by 4 notches. Effect: Change the use of oil, coal and natural gas in the sub-variables by 10%. Effect: Deforestation decreases by one notch for free.	An earthquake causes problems in the cooling system of a nuclear power plant, stopping its operation and causing a leakage of radioactive materials. Effect: Spend two coins in the waste and leakage sector.	A fire of unprecedented proportions devastates the Amazon rainforest, burning more than half of it. Effect: The costs of actions in the 'Nature based' area triple throughout the game. However, the new space is being converted and used to build solar parks. Effect: Subsidize a coin in transport energy efficiency for free.
TWIST	CiaO2	FAKE PLASTIC
A new technology related to the study of materials leads to a decrease in the cost of batteries and makes them biodegradable. Effect: You have one free coin to subsidize in the renewables sector, and 2 coins in the transport electrification sector. At the next turn, it turns out that these batteries are short-lived and non-biodegradable. Effect: You are obliged to subsidize 2 coins in the 'Waste and Leakage' sector.	After much effort, an efficient CO2 removal technology can be developed, whose cost-benefit balance is positive. Effect: Increase the 'technological' slider in the carbon dioxide removal field by two notches (free).	A new technology has been developed that produces a synthetic material with the same characteristics as plastic but much less polluting. Effect: Decrease oil utilisation. Decrease oil use by 35%. Increase the energy efficiency of buildings and industries by 1 notch for free.
EUREKA!	INTERNET FOR EVERYONE	I-HELP
Cold nuclear fusion is finally carried out: the cost of energy is greatly reduced, and technological development accelerates. Effect: Energy efficiency actions, whether for transport, buildings or industry, can be done at half the cost (two notches cost one coin). Effect: The new zero carbon slider is increased by one notch.	The development of new technologies for high-speed Internet connection allows people all over the world to study and work remotely globally. Effect: Decrease population growth by two notches	The use of algorithms based on artificial intelligence makes it possible to optimise production processes. Trade increases and the prices of many goods lowers. Effect: The ordinary budget increases by 5 coins. Effect: Subsidize a coin in transport energy efficiency for free.

Table 1: The set of wildcards. They are related to the three forms of uncertainty embedded in the climate change discourse: aleatoric uncertainty (red), reflexive uncertainty (blue), and epistemic uncertainty (green).

4. Data collection

4.1 Data preparation

During the course we collected different kinds of data, aiming to be used for different research objectives and needs.

Specifically, we used the following strategy. First, we formulated Research Questions interesting for both the PhDs works before the beginning of the course and then we tried to think about the kind of data which might have been useful for each question.

Thus, for the first Research Question of Lorenzo Miani's research ("To what extent can an 'uncertainty-centred' course on climate change develop Greencomp sustainability competencies?") he designed a pre-post questionnaire, aimed at inquiring about the self-perception of sustainability competencies.

The questionnaire asked participants to think and write about an event which they personally relate to the impact of climate change on their daily life. Then they were asked to answer some close-ended questions about the story they have described (10-point Likert scale), such as

"Regarding your story, can you identify the reasons behind the problems you face? No, I have the feeling that I do not understand the reasons behind the problems I have around me = 0. Yes, I can clearly discern and understand the whys of the problems around me = 10"

or

"To address the problem described in your story, how much do you think your individual actions can contribute? Not at all = 0. Very much = 10".

The questions aimed to map all the 12 sustainability competences suggested by the GreenComp (Bianchi et al., 2022). These competences are divided into four main areas: "embodying sustainability values", "embracing complexity in sustainability", "envisioning sustainable futures" and "acting for sustainability" (Bianchi et al., 2022). The final questionnaire can be found in Appendix A.

We also delivered another questionnaire, in the fourth Lecture, around futures studies and scenarios. In that occasion we asked students to think about their image of future 25 years from now and the image of their *ideal* future 25 years from now. They were asked to think about these two (potentially) different futures after the introduction of futures studies and especially the Future Cone by Voros (Voros, 2003), so they were already aware of the multiple kinds of future available.

In this questionnaire students were also asked to think about what decisions, choices and actions would have led to their ideal future and to share an emotion felt during this reflection, choosing among the following options:

- **Strengthening**; I can make things happen
- **Optimism**; there is work to be done, but things are starting to move
- **Cynicism**; there are too many forces opposing sustainability or any real change
- **Motivation**; the changes I make together with others can have an impact

- **Anger**; all this could have been avoided or addressed long ago
- **Commitment**; I want to work with others and act now
- **Desperation**; no one is taking the issue seriously
- **Injustice**; those most responsible must act
- **Overpowering**; the situation is so big and out of my control and influence
- **Impatience**; visible changes are too slow
- **Actually**, I have other things on my mind
- **None of the above**
- **Other**

Two other questions were considered while designing the data collection, related to my PhD research objective:

“What kind of teaching practices used in the course are most likely to activate episodes of epistemological-personal consonance/dissonance?”

“To what extent can physics uncertainties activate epistemological-personal consonance episodes?”

Concerning these questions, we thought the only way we could have tried to answer them was by collecting the words emerging both in the lectures (as a comment) and in the in-group activities (as a discussion). Hence, we decided to record all the lectures and two focal in-group moments: the writing of wildcards and the playgames. The recordings have been done through iPads placed close to the speakers, so they were audio-only. Students have been informed of the data collection and gave the consent to be recorded.

Still, already before listening to the recordings, we knew that it was necessary to design deep interview sessions, to trigger reflections not spontaneously emerging in the course or to examine interesting discussions happened during the lectures.

4.1 Interview design

The aim of the interviews was to inquire the personal relationship with science before and during the course and how they perceived the disciplinary contents presented in the course. Furthermore, we were interested in evaluating students' learning of the forms of uncertainties, the key concepts of complexity and the difference between climate change and weather variation, and their position with respect to the sustainability competences embedded in the GreenComp.

As a first step then, we tried to address these aspects by listening the recordings and writing down some notes when students were expressing something interesting, especially in the final discussion and during the in-group moments. For what concerns my research focus, I took note of all the moments when students were showing engagement with cognitive-epistemic elements, and started to reason why these happened in that specific moment during that specific activity. Then we triangulated these first impressions among the three of us (Lorenzo Miani, Olivia Levrini and me).

This was the starting point for the design of the interview protocol, which ended up divided into 5 parts. The first part was made for breaking the ice and enter in the details of aspects interesting to my research:

motivation behind the choice of the course and expectations; previous personal episodes concerning studying science and physics and first impressions about the contents addressed in the course. The second, third and fourth parts were more related to Lorenzo's research, addressing the results of the questionnaires, aspect related to climate science and future studies and some impressions of the scenarios developed in the game. In this phase, Lorenzo passed through the questionnaires that students filled during the course (sustainability competences and future scenarios), asking to comment their answers. As for the sustainability questionnaire, the decision was to focus on the items where the gap between initial and final answers (Likert-scale, 10 points) were higher or equal than 3 (we decided for this threshold to be a potential indicator of something interesting happened in the course).

The last part was again more related to my research. Specifically, the first part was about episodes when students' sense of themselves were enhanced or questioned during learning science experiences. Also, students were asked about contents of the course they felt more close or distant to them, to their tastes and identities. Then, when it was possible, we presented them with a brief excerpt from the recordings where the interviewee was discussing with some classmates or with us, showing a specific kind of engagement with some epistemic elements introduced in the course. They were asked to comment on this and then to come back to the previous question and evaluate their previous answer. The aim of this zoom-in and zoom-out was to trigger a stronger involvement of the interviewee by asking to comment her own words, and to avoid generic and not personal answers. Also, that might have served as the chance to confirm or revise the previous more general answer. The protocol ended with two final questions about their perception of the course and the existence of roles that students must adopt in class, and if they change according to the subject (see Appendix C for an example of a full protocol)³⁸.

Research Questions

Given the context described above, three general Research Questions have been elaborated, to address in the data analysis. Two of them are linked to the development of strand IIa (how contents can be dealt with), introduced in Chapter 3. The other one aims to further explore strand II (what kind of contents).

RQ IIa.1: How can the 4-layer scheme be used to develop a course focused on uncertainty?

RQ IIa.2: In the PLS course, what does emerge concerning the potentiality of the 4-layer scheme in supporting identity development?

RQ II.3: To what extent can the forms of uncertainty trigger epistemological-personal consonance?

As displayed by the figure 17, they expand the structure of the scheme recalled in Chapters 3 and 4. In the next Section is presented the data analysis, related to the objective of the thesis. Given my research objectives and questions, the only useful data were the recordings and (mainly) the interviews. Thus, in the next Sections are discussed those data, whereas is skipped all the analysis of the questionnaires and the answers to the questions more related to Lorenzo's research. Nonetheless, the analysis of those materials has been done together and led to the production of two papers (see Section 8 for a very brief overview).

³⁸ In the protocols there are questions which ask to examine previous answers or recordings, so they are all different in terms of the data included (the appendix shows the case of MD, one of the 9 interviewees).

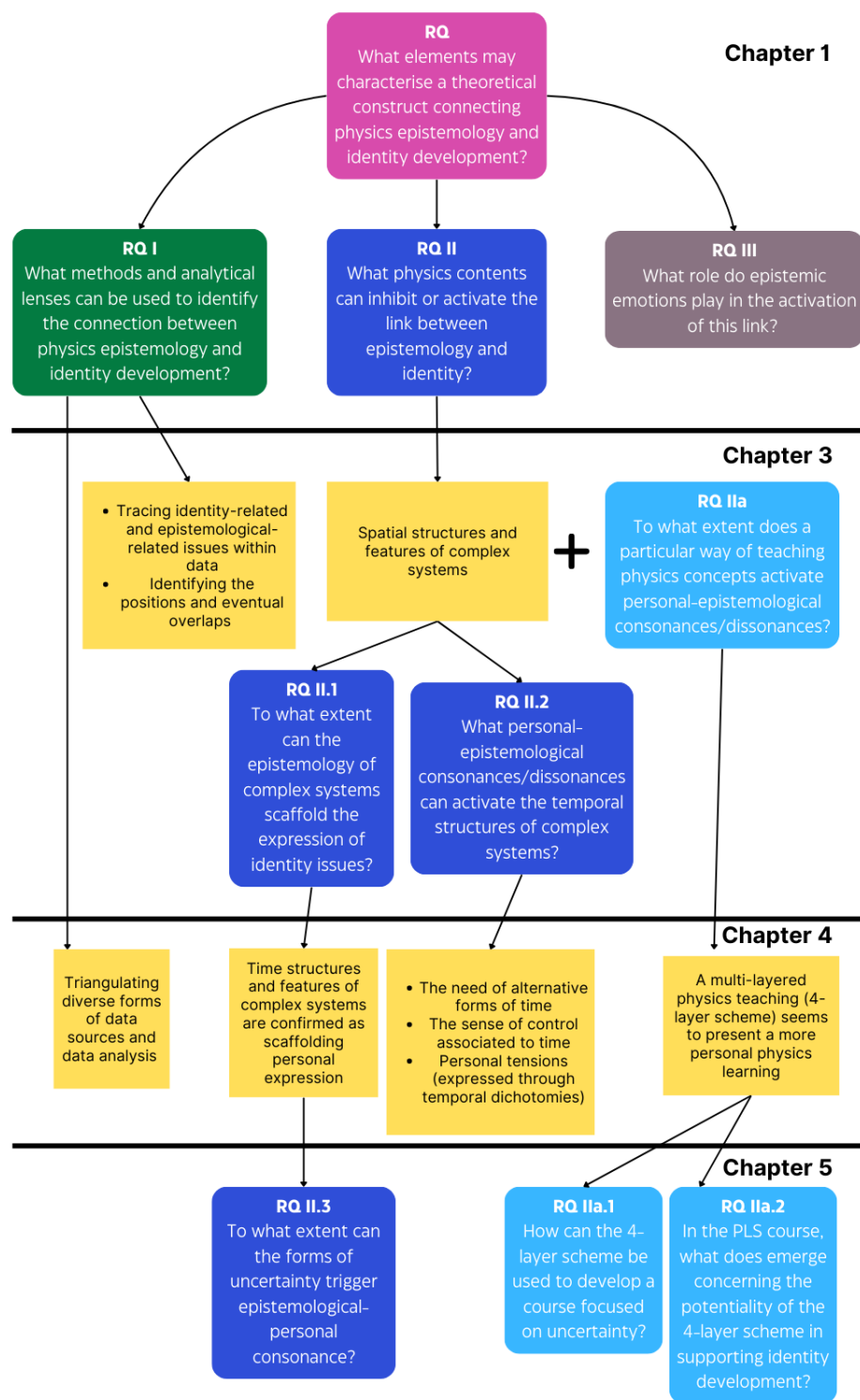


Figure 17: The evolution of the scheme of the Research Questions and outcomes shown in the previous Chapters. The context and the objectives of the course discussed above led to formulate three new Research Questions: RQ II.3 linked to strand II and RQ IIa.1 and RQ IIa.2 linked to strand IIa.

Timeline of the analytical steps

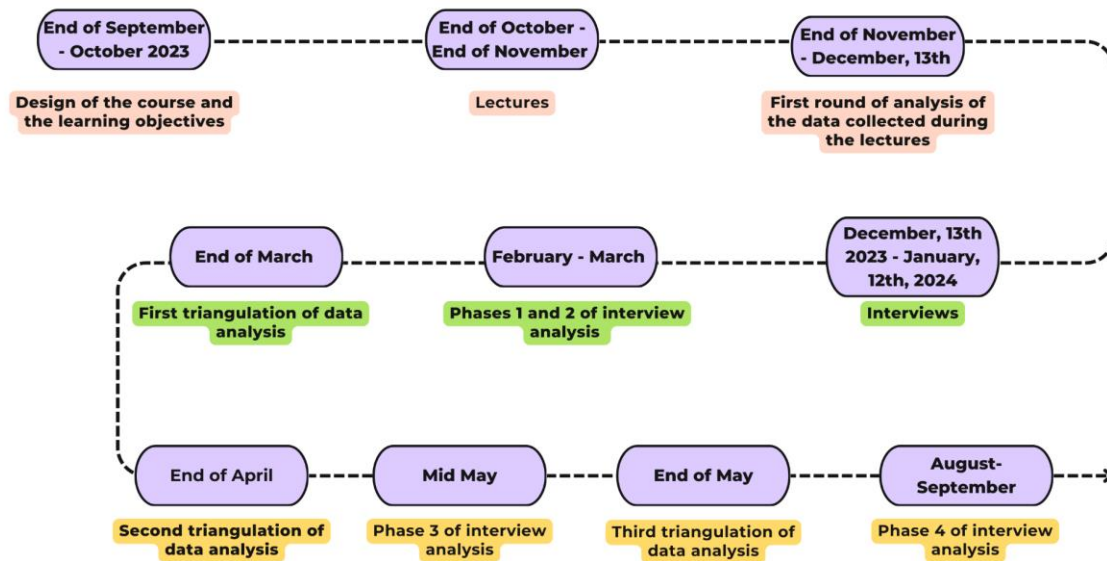


Figure 18: Timeline of the project. Between October and November we collected all the “in-field” data. In the time between the last lecture and the first interview, we did a preliminary analysis of the data. Hence, we discussed together the most interesting aspects emerging both on a general and individual level and then developed the interview protocol. Then, just after each interview the three of us discussed our impressions and noted down some general issues that have emerged from the interviewee. Five interviews have been done in presence whereas the other four online, due to logistics reasons.

5. Data analysis

At the beginning of the interview analysis, I noticed a case of personal re-positioning towards science, due to the course and the game, with also the presence of a strong emotional reaction to the contents. I also came across a contrastive case, of no-repositioning towards science. These two profiles captured my attention even because of their explicitness, and I started thinking if and how a shift (or no shift) in the positioning towards science is related to identity development.

Thus, I first had to understand the initial positionings, then see what kind of evolution happened (if happened), how the game and the course activated and supported such evolution and finally how this can contribute to the *personal-epistemological consonance/dissonance* construct.

To do so, I unpacked the research objective into three specific questions to address with the data:

- *What were the students' initial personal epistemic positioning at the beginning of the course?*
- *Were there any evolutions of these personal epistemic positionings?*
- *How did the course and the game enable and support this evolution? Is it possible to develop an explanation or a local theoretical hypothesis?*

These questions will be addressed in the next subsections, structured as follows. In Section 5.1 I present and discuss the initial personal epistemic positionings of the two interesting profiles mentioned above. These are two students among those interviewed at the end of the course. I discuss the profiles by using the four dimensions of the FRA framework (Erduran & Dagher, 2014) and argue my interpretation by reporting excerpts from the interviews and the lecture recordings. These two “case studies” are the basis upon which I will develop a theoretical hypothesis of what happened in the course. The profiles of the other 7 students will be considered as further data to test and refine the theoretical hypothesis, on the legacy of Grounded Theory (Glaser & Strauss, 1967).

Thus, in Section 5.2 I present the first step of analysis done through the lens of epistemic emotions, discussing the rationale behind this tool and the outcomes emerging from its use. Also, in this section, I start to develop an argument for how certain epistemic elements provoked different emotional reactions in the students, by recalling the specificities of their initial personal-epistemic positionings.

In Section 5.3 I enrich the thickness of the emerging theoretical hypothesis by comparing its inner mechanisms with external inputs from both literature and brainstorming with other researchers³⁹.

In Section 5.4 I check the structure of the theoretical hypothesis against the other profiles to develop a more reliable and valid version (a process named “theoretical sampling”).

In Section 6 I conclude by formulating the final version of the theoretical hypothesis and a discussion in light of qualitative assessment criteria.

³⁹ This step in particular is the outcome of a deep discussions about the emerging local theoretical hypothesis conducted both within the Physics Education Research Group at the University of Bologna and the University Pedagogy Research Group at the University of Copenhagen, where I was hosted as a visiting student for four months.

5.1 Phase one: Initial personal epistemic positionings

The idea behind these personal-epistemic positionings was due to the need to trace diversities that students showed in the course and in particular during the interviews. The focus is to map their diverse approaches to the cognitive-epistemic core of science and physics.

For personal epistemic positioning I mean the students' relationship with the discipline in an epistemological sense (I will therefore not be concerned with their experiences with teachers, peers, etc., in science lessons, as much as rather how they view contents, methodologies, values, etc.). In other words, each student manifested a peculiar opinion about the aims, values, methods, practices and the kind of knowledge science produces, which I was able to retrieve from their words (mostly in the interview since we triggered specific reasoning about their image of science, but also in some comments spread in the course).

I argue that students' specific opinions about aims, values, practices and knowledge of science can be read as self-positioning with respect to it. I am borrowing here what Harré and Langenhove define as "deliberate self-positioning": the expression of personal identity by stressing personal agency and referring to one's unique point of view (Harré & Langenhove, 1991). As the authors suggest, self-positioning is a "dynamic alternative to the more static concept of role" (p.1) which assumes a reference upon which the position is developed. As Ofek-Geva and Fortus (2024) show, the external reference can be also science.

Operationally, I chose to develop narratives, in which selected excerpts from the data are reported and rephrased to convey a general picture of the students' self-positioning with respect to science. Narratives indeed are particularly effective to introduce an external reader into a context but also in creating a picture of the thoughts and ideas of an individual. In fact, "Narrative inquiry has become common in education research [...] and serves as a tool for revealing and understanding people's personal experiences, and through them their positions" (Ofek-Geva & Fortus, 2024; p. 241).

In the present case then, for each student, I read several times the interview and the "after-interview reports" that we did by triangulating the interviewers' notes, with the aim to get a sense of the characteristic epistemic self-positioning. Then I tried to return this sense by summing it up into a sentence, inspired by the "signature idea" marker proposed by Levrini and colleagues in their model of appropriation (Levrini et al., 2015). Each "signature self-positioning" is supported by excerpts that have the role of making as transparent as possible the interpretative work done. In doing so I was inspired by what Polkinghorne calls "narrative smoothing" (Polkinghorne, 1995), in the sense that I selected only the words in which students were reporting their signature positioning (both explicitly and implicitly) and on the other hand I got rid of all the excerpts non-related to that. Of course, while doing this I constantly checked if the sentences I was eliminating were not at odds with the signature self-positioning, hence including them as additional issues in the opposite case, for the sake of fairness. Indeed, *"Narrative smoothing is an action in which elements which do not contradict the plot [here the personal epistemic positioning] but which are not pertinent to its development, do not become part of the research result, the storied narrative"* (Polkinghorne, 1995, p. 16).

In the following subsection are presented the narratives of the two cases which initially got my attention and which guided the initial development of a theoretical hypothesis. I also produced narratives for the

other seven students, but left them apart for a second step to check the emerging structure. The narratives are mostly based on the individual interviews.

It is important to remind that each student (minor or adult) has been informed about data collection and signed a consent form authorizing the use of data for scientific purposes. The data have also been anonymized.

5.1.1 Individual self-positionings

The self-positioning narratives are reported using a code of two letters together with the gender students recognized themselves with. The narratives included are based on original excerpts (mostly from the interviews).

SB (female)

SB's initial personal positioning with respect to science could be summarized by the phrase, "science gives a sense of security." This is because it is a discipline inherently made up of laws that are universal and invariant. Science therefore gives a sense of security because it is based on things that add up; it is structured in laws that are valid everywhere, and this is reassuring.

FDZ ⁴⁰	07:33	<i>But instead, how do you usually relate to science? With physics?</i>
SB	07:39	<i>But like in school? Or I don't know...?</i>
FDZ	07:41	<i>In general. I mean not with, we're not asking you "are you doing good or are you doing bad" in school, no. What kind of relationship, well now this thing here (aleatoric uncertainty) made you feel small however it fascinated you, demoralized you. Instead in general usually what kind of feelings do you have, what kind of relationship do you have with science?</i>
SB	08:10	<i>well, it's a little bit... Um, it's a little bit of security, well, in the sense that, that maybe, well is certain, I don't know how to say. That maybe it's more the math, well, that it's all accurate and everything has to add up. And when it all adds up then you know it's true, well what you're, you're doing or reading, so yeah, security. It gives me security.</i>

In the following excerpt, she brings up another example, related to science, to justify her feeling of security, which for her is a human and common feeling.

SB	09:06	<i>[...] well actually like even when now... I mean when they⁴¹ thought the earth revolved around, well no the sun revolving around the earth, mm, and then instead, well for them that was the safety. So actually, well, I don't know we're not 100% sure that then... well it all adds up however maybe there are errors, I don't know, well in the conception.</i>

⁴⁰ FDZ is me, LM is my colleague Lorenzo Miani and OL is prof. Olivia Levrini who joined most of the interviews.

⁴¹ Scientist before the Copernican revolution.

In this excerpt, SB points out that it is normal to lean on scientific certainties, even though these may later turn out to be wrong, because perhaps "there are errors in the conception." Asked to comment on this feeling of security, she goes on to argue it consciously.

FDZ	22:30	<i>But on the contrary, did you instead have topics that you saw in science and physics that instead gave you an opposite feeling?</i>
SB	22:44	<i>What (sense)... about security?</i>
FDZ	22:45	<i>Yes</i>
SB	22:48	<i>So, I'm thinking about what we saw, what we did...</i>
FDZ	22:55	<i>But also in books, uhm in whatever you want, in general.</i>
SB	22:58	<i>In life or was I just thinking in the lab?</i>
FDZ	23:00	<i>Your relationship in general to science.</i>
SB	23:07	<i>Um, well like certain laws that are true throughout the universe, those give me confidence. Then, as I also said before, well math that is in just one way...</i>
FDZ	23:27	<i>Why do laws that always apply give you security?</i>
SB	23:32	<i>Well, I'm... well let's say I go to the other side of the univers- was it stuck?</i>
LM	23:47	<i>Yes - say you go to the other side of the universe?</i>
SB	23:51	<i>Well, I already have a basis here, I know that that law applies.</i>
FDZ	23:56	<i>You have something to start with.</i>
SB	23:59	<i>Yes, exactly. As like a, no I can't make an adequate comparison.</i>

A sense of security emerges strongly, due to the fact that the laws are universal and always valid. SB sticks very much to a view of science as consisting of blocks of laws; for her, science has the form of law.

The idea of the importance of "making things add up" is repeated by referring to a book SB has read before. It begins with this exchange, right after the example of the men who were sure that the Sun revolved around the Earth.

FDZ	10:05	<i>Well this you say historically there was that moment of insecurity, I mean first it was secure then later it became... You were saying it in that sense. And instead you, well, in the sense at this moment in the course you found, but were there other times previously when you had the same feeling of insecurity, with respect to science?</i>
SB	10:45	<i>Well. I don't know, I didn't understand the question</i>
FDZ	10:50	<i>Did you not understand the question?</i>
SB	10:55	<i>Um, I don't know. How would you respond, well, give me an example of an appropriate response</i>

The two interviewers responded with two examples, at which point SB got unstuck and brought up this example.

SB	14:38	<i>Well, but like, maybe I don't know if it's an adapt example. But I read this book that you may have read too, the one about Fermat's theorem.</i>
FDZ	14:54	<i>And what is the book?</i>
SB	14:55	<i>Fermat's Last Theorem.</i>
FDZ	14:58	<i>Mh mh.</i>
LM	14:58	<i>No, I have not read it</i>
SB	15:02	<i>Mmm in this book um, there is this Fermat, well he, well all of his, the theorems that he had, had, ehmmm, exposed had been solved. Only remains, well only remained this one here that remained for over that... for so many centuries remained this problem to be solved and, eh, and, and well, um, and then they solved it though they didn't make it well, they solved it using some, some, some methods that at the time he had, had expounded this theorem didn't exist yet so well we don't know how he had it, well no one else after him was able to prove it here in the way he had then proved it, well they solved it centuries later in, well in another way so... And then they couldn't give it for, for, for true, well unless they proved it. Well, I don't know if.</i>

The thing that bothers SB about Fermat's last theorem is that it was solved centuries later with tools that were not available in Fermat's time. So, in a sense, there was something at that time that could not be made to add back, namely the solution of the theorem. SB expresses through this example her idea that sometimes making things add up is not easy and so at that point, one has to "accept" the uncertainty, and start making assumptions. But it is an attitude that is not easy to handle emotionally for her, who is instead very anchored in a sense of security.

FDZ	16:29	<i>And so you point to this as an example of?</i>
SB	16:34	<i>Of what, not of uncertainty...</i>
FDZ	16:44	<i>That is, this made you feel how? We ask this question maybe.</i>
SB	16:55	<i>It made me feel that making everything add up is difficult [laughs].</i>
FDZ	17:07	<i>And so you have to stay with things even when they don't add up.</i>
SB	17:16	<i>Well, no.</i>
FDZ	17:17	<i>Oh no? So how do we do that?</i>
SB	17:20	<i>So, well, so much effort.</i>
FDZ	17:24	<i>But if things don't add up, well, until we make them add up, what happens?</i>
SB	17:32	<i>Well...the assumptions, I don't know. Well, yeah, assumptions, hypothesis. Uhm and that's the part a little bit that, yeah well that's uncertain...</i>

If we interpret the nature of science by adopting the FRA model (Erduran & Dagher, 2014), SB seems to be positively stuck to the value of “universalism” and “predictability” that a certain kind of science (e.g. classical mechanics) has. She finds security in having laws which are universally valid and let add things up all the time. Even though she insists on laws and models (which are practices more than values) she does so by highlighting the associated value of universalism and absolute efficacy.

TL (male)

TL's initial personal positioning with respect to science could be summarized by the phrase, "*the pragmatic approach of science is what brings me closer to the objective explanation of how the world works*".

There is a solid and repeatedly held belief that there is a way things work and that science, more in its pragmatic sense than in its ideological sense, can make it clear what that way is. TL has a strong positivist sentiment, which he also expresses unconsciously by the repeated use of words such as "objective," "surely," "explanation," and "description," signs of a conviction that science can sooner or later surely find an objective explanation of the way things are.

In the following excerpt, for example, TL answers to the question that asked if there was anything in physics in particular that he felt close to him as a person.

TL	01:34:44	<i>That's what it would come down to for me to say. The point is...then for each person it's different... I just like the fact of general physics, but not a specific topic, every topic of it because in the end physics is the description of how our universe works, but also stupid things, for example how a refrigerator works. After really understanding how a refrigerator works, I see it in a different light. Because I say "AH but you see why? This takes TOT energy and then by consuming that work it creates a colder environment inside and a warmer environment (outside). It's amazing stuff..." And I see this a little bit in everything, the point is this is what makes me curious about physics, the fact that I know how the mechanics of the universe works.</i>
FDZ	01:35:37	<i>So it is how it works, however on any topic... there is no particular one?</i>
TL	01:35:45	<i>No. But of course, there are topics that fascinate me more than others.</i>

Emerges an image of physics as the description of how the world works objectively. And this for TL applies in general, from the refrigerator to the laws of the universe. What is interesting in TL and therefore defines his positioning is the ability to see the mechanism of the world, underlying a vision centred around “mechanicism”. TL, commenting on his decision to tell in one of the course activities about the time he had found out that we succeeded in reducing the hole in the ozone layer, reports that the choice was to give an example of a positive story in which one succeeded in solving a problem.

TL	27:48	<i>[...] The second one is more positive in that sense and the fact that we are ... although we had a big problem, we were able to solve it and this surely is possible with other problems.</i>

In the expression "this surely is possible with other problems," and especially in the term "surely," we still see TL's characteristic positivist attitude and confidence that science will solve all problems. TL's attitude

is pro-active, he is driven by curiosity to learn about new mechanisms and is not frightened by open questions, precisely because his approach is grounded toward always finding new explanations for new phenomena. If there were no more mechanisms for him to know, the essence of his relationship with science would be lost.

- FDZ 09:45 *That is, how do you relate (to science), do you relate from near, from far, do you relate with fear, with curiosity, with expectations?*
- TL 09:57 *I personally with a lot of curiosity, but also a little bit the excitement. I have often had it, for me we feel -- we are a people always on the frontier in the science of the knowable. A lot of people when we talk, I've had a lot of discussions, they don't like the fact that the more we search the more we increase this bubble of things that we don't know. Honestly, for me it's the most exciting thing just the fact that the amount of things we don't know grows, because it seems boring to get to a point where we won't have anything more to know.*

TL is fascinated by being able to find explanations, and also to be able to arrive at progressively more refined and deeper explanations.

- FDZ 01:35:49 *You are always fascinated by (physics topics in general) because of the mechanism behind them, right?*
- TL 01:35:54 *Yes! Which then in the end, thinking about it, they all devolve -- you have a harder and harder explanation, don't you? For example (takes the same cup of before). Cup: if I drop it, it breaks, simple explanation. "Ah well it fell because of gravity, because of the force of gravity." But what is the force of gravity? "Ah yes it is a force that applies to every object that is on the earth, but it is actually applied according to the mass of the earth." Et cetera, et cetera, et cetera. It starts from an explanation that then starts from classical physics, first a pure observational question - the cup falls - why does it fall? It falls but it has a weight. But what is weight? What is mass? Why does it fall? What is the direction in which it falls? What is the value with which it falls? What is the most precise explanation for why it falls? And so we go from simple observation to Newton's classical physics, then we go to Einstein's relativity. And so on and so on and so on with more and more fascinating questions, more and more at the frontiers of us. And it's ultimately a little bit what's most fascinating, what's at the frontiers, what we already don't know. Which is then looking at what we don't know of not knowing.*

TL enjoys looking for the "ever more precise explanation" of why things work one way or another. Also, TL shares a vision where scientific knowledge becomes a useful tool for dealing with life's issues, from the biggest to the simplest.

- FDZ 01:37:25 *And when you understand the mechanism no? So you ask the question and you give the answer, that thing there you like it... but then you use it for other things outside of physics? You use it as let's say a tool to do other things, to do other reasoning? ... or decisions?*
- TL 01:37:59 *Many times yes! [...] You know the scene where Sheldon and Leonard (Big Bang Theory) are taking the closet up to Penny's saying "ah put the closet like this, at 30 degrees, because then some of the weight is distributed down and so we have to use less force to push it up." Which then really happened to me, because I had to carry*

something with my father upstairs to our house and he was carrying it like this at right angles to the ground. And I said, "Tilt it up it gets easier later." And he said, "Ah you're right about that." But yes, this is an example of the application of what I study, it fascinates me and then I bring it into real life. In the end being physics, how the Universe works, and knowing how things work later helps you in your daily life.

Finally, it is also interesting to note that TL is aware of how science is linked to and also determined by political aspects.

LM	40:47	<i>Politics in general. How much do you see the link between science and politics?</i>
TL	40:51	<i>Talking about how I see the world a little bit with respect to what I said earlier about wars I would say that for me the political view also influences the view of how to do science, which then in the end is all about movement, of human social evolution. Because, let's say, people how conceived not only science, but the world 200 years ago is completely different from how we conceive it now. Now we could say we are in a postmodernist view, whereas 200 years ago we were in a positivist view that is completely different. It changes the way of doing things, it changes how people think, which then also changes the way of doing politics and consequently the way of doing science.</i>

So, for example, he chose this PLS because he wanted to try to explore somewhat more social issues as well, but which he nonetheless already sees as connected to scientific discourse.

TL	07:06	<i>Because the topic is a little different from the others, usually in physics PLSs you have a technical topic, in fact now the one I will be doing in February is photons and electromagnetism, it was purely a technical topic. This one has more of a social angle.</i>
FDZ	07:21	<i>And so this was of interest to you this fact of having a social dimension?</i>
TL	07:26	<i>Yes, I was a little piqued in the interest by this, yes.</i>

Reading again through the FRA model, TL seems to span over different dimensions. He is attracted by the practical functioning of things like a refrigerator (knowledge dimension) but shows also an interest in the multiple levels of descriptions that science can provide about what for instance a cup is. This, together with his acknowledgement of the connection between science and politics reflects an attention to the practices of science. Still, as for SB, in TL it is dominant the discourse around science values. To TL, science is powerful because it can *explain objectively* the *mechanism* behind the phenomena. These three words witness a kind of science dominated by a mechanistic and a positivist footprint.

5.2 Phase two: personal epistemic positionings' evolution

The feeling that some students have been questioned in their initial epistemic positioning by the course experience was shared by the three of us (FDZ, LM and OL). In particular, I got stuck with the case of SB,

probably because she was more explicit than others in sharing her sense of re-positioning. The problem was that I did not know how to verbalize the inner sensation that I had as an internal observer and which tools to adopt to make clear for an external reader the phenomena I was “seeing”.

The first strategy adopted was inspired by SB herself. In the interview, she told us that she felt at odds with some of the new concepts that we presented in the course. In particular, the typical feelings that she associated with doing science and thinking about science were contrasting with these new feelings that the uncertainties (aleatoric, reflexive, ontological) provoked in her. Nonetheless, she also said, and this is the crucial point, that she eventually managed to deal with such emotions by re-considering her image of what science is and what it means to do science. Thus, SB was displaying an evolution on a cognitive level (her conceptualization of science) but made evident through an emotional level. Hence, the idea to report the evolution for her case, but also for the others, was to try to follow the emotions provoked by the concepts presented in the course.

To do so, the natural choice was to use the lens of epistemic emotions, for the reasons indicated in the first chapter.

5.2.1 Mapping epistemic emotions

In this Section, I report how I used epistemic emotions - emotions related to the operation of knowledge construction (Davidson et al., 2020; Sansone 2009) - and the results emerging from the mapping step.

The rationale for looking for epistemic emotions is that they are defined by the experience of both encountering new knowledge and facing it (Muis et al., 2015). They can be likely assumed, considering also the case of SB, as the affective dimension activated during the personal epistemic re-positioning.

Given the intention to map epistemic emotions displayed by students with respect to the contents addressed, a question arises as to which emotions can be used as labels.

Recalling the literature and trying to refer mostly to the epistemic emotions upon which there is enough consensus, I considered as possible labels: frustration, confusion, boredom (D’Mello & Graesser, 2012), curiosity (Silvia, 2010), joy, anxiety (Muis et al., 2015), surprise (Foster & Keane, 2015), trust, interest, difficulty (Arango-Muñoz & Michaelian, 2014), fascination (Morton, 2009) and confidence (Nerantzaki et al., 2021).

Once defined the set of epistemic emotions, they have been used as follows.

First, I mapped all the epistemic emotions visible in the narratives of “initial personal-epistemic positionings”. These emotions have been highlighted in green and assigned to the label with the corresponding kind of epistemic emotion, for example, “interest”, “trust”, “confidence”, etc. The excerpts are mainly taken from the responses to the questions in the first part of the interview protocol, which was aimed precisely at probing the students' initial personal positioning with respect to science.

Secondly, I focused on the excerpts related to what happened in the course experience and looked for the epistemic emotions expressed there. These excerpts come mainly from the responses to the questions in the last part of the protocol, which was aimed instead at going on to probe the effect of the course

content. Students also expressed epistemic emotions related to the course in their responses to questions in the middle sections of the protocol, which were about the experience of the course and the game.

The epistemic emotions in this second set of excerpts are highlighted in orange and light blue. Orange for epistemic emotions that signal an emotional gap, and light blue for emotions that signal emotional continuity. I considered an “emotional gap” whenever I saw new epistemic emotions with respect to the “initial” epistemic emotions, which do question the typical feelings associated with the epistemic positioning. On the opposite I claimed “emotional continuity” to be represented by whatever epistemic emotions expressed not questioning the emotions in the initial “epistemic positioning” or even overlapping with those (see below for examples).

My idea was to look for emotional continuity or gaps as pieces of evidence of a potential "epistemic evolution".

I present this second mapping now for the two profiles presented before. There will be a repetition of some excerpts to show the epistemic emotions of the initial epistemic positionings and then I will introduce the new excerpts and related epistemic emotions to discuss how the two students reacted to the contents of the course.

SB

SB's positioning showed a strong sense of security due to features such as universalism and positivism. In this sense, there are many expressions unveiling epistemic emotions of trust, based on the feelings of security.

FDZ 07:41 *Instead in general usually what is your feeling, what is your relationship with science?*

SB 08:10 *well, it's a little bit... Um, it's a little bit of security, well, in the sense that, that maybe, well is certain, I don't know how to say. That maybe it's more the math, well, that it's all accurate and everything has to add up. And when it all adds up then you know it's true, well what you're, you're doing or reading, so yeah, security. It gives me confidence.*

[...]

SB 23:07 *Um, well like certain laws that are true throughout the universe, those give me security. Then, as I also said before, well math that that well is in a unique way...*

Then, in the course experience, she saw new concepts such as the three types of uncertainties. In reference to the new concept of ontological uncertainty, we see an epistemic emotion of confidence, which does not express an emotional gap.

SB 01:05:12 *So yeah, in my opinion that one is more related just to the actions of humans so it's not like you can control it. Um, the ontological one, whatever is a limitation just of our knowledge, so that one didn't upset me too much, well...*

LM 01:05:43 *Okay. well, you take it as a limitation so it doesn't bother you in quotes?*

SB 01:05:49 well, we can't know it anyway, so there's not, there's not even the problem, well.

A few lines after sha again refers in this way:

SB 01:08:26 No, well, they are different. That, like the ontological one... well is a given limit, not not not a limit of man that he cannot know, just a limit that existed before.

LM 01:08:48 Okay. But getting to that limit gives you a sense of... well, okay. We understood that from here.

SB 01:08:57 Well, yes

LM 01:08:57 We can't do anything

SB 01:08:58 Well, yes... *it didn't upset me.*

LM 01:09:06 Ok. Interesting

SB 01:09:12 Like another law, I don't know how to say, always one thing, well if I can't have it is enough...

With respect to the operation of the FyouTURES game, there is an epistemic emotion of confidence and comfort, which still does not express an emotional gap. The operations of the game gave her a sense of certainty, in continuity with her initial epistemic positioning.

FDZ 27:21 Uhm, so, let's say, coming back a little bit on the course. Well, we tried to give an image of science that for example made you feel insecure no? However, how did you perceive it - if you had to say it - how did you perceive the image of science that we tried to give compared to your vision of science? The way physics is treated compared to how physics is usually treated?

[...]

SB 28:48 And then the, mmh, well also when we did the game that we were changing upstream, yes that how is it that you say, underneath we were changing and afterwards there were still established consequences. *Well, not everything made me feel insecure, like these things calmed me.*

LM 29:23 Okay, I mean, what you're saying is the ability, for example in this case, of the platform that we used to make the game, to create predictions based on today's choices, that is, the fact that there were then graphs let's say that changed the shape.

SB 29:42 Can you repeat it?

LM 29:44 Everything that happens on the platform, so the fact that you based on

SB 29:48 Yes, yes.

LM 29:49 To the type of slider that you go to modify you have the ability to predict

SB 29:50 *That*

LM 29:51 *That gave you confidence?*

SB 29:54 *Yes*

Compared with aleatoric uncertainty, on the other hand, we have an epistemic emotion of frustration, confusion and difficulty. These emotions instead, mark an "emotional gap."

FDZ	05:33	<i>On the other hand, compared to the one of the volcanologists, why did that one (an activity about phenomena which are unpredictable as volcanic explosions) hit you instead?</i>
SB	05:39	<i>well that in the sense that struck me in the sense that, well, it kind of stuck with me that anyway well, we can try to study all we want, but in the end it's all going to be kind of random, well. So also impressed in the sense a little bit, I don't know... not sorry, a little bit like that.</i>
LM	06:09	<i>Like what?</i>
SB	06:09	<i>Sorry... what?</i>
LM	06:13	<i>Like what? Not sorry but?</i>
SB	06:17	<i>Well, a little demoralized, I don't know</i>
FDZ	06:20	<i>Why? Demoralized because she cannot predict? Why?</i>
SB	06:26	<i>well, well, I don't know it demoralizes me that, well then what's the point of studying if it doesn't lead to anything anyway?</i>

In another following excerpt:

SB	01:06:10	<i>Well, that one, well, well that one I didn't understand if- well that one also not, well that one theoretically could be predicted however in practice not, it's impossible, right? (she refers to aleatoric uncertainty) uhm that one is the one that struck me the most here, because even compared to the speeches I made before, well that is very difficult here. Now I say a lot of times here. Well, it's very difficult, it seems to me, it gives me a feeling of fatigue.</i>
FDZ	01:06:49	<i>a feeling of fatigue?</i>
SB	01:06:51	<i>Yes</i>
FDZ	01:06:52	<i>Why?</i>
SB	01:06:54	<i>Because so many things, so many, well so many variables yes, intersecting, well like a tangle to unravel.</i>
LM	01:07:18	<i>Which, however, can never be fully dissolved.</i>
SB	01:07:22	<i>Yes, exactly, which is impossible to dissolve.</i>

Below aleatoric uncertainty is again associated with an epistemic emotion of anxiety and discomfort.

SB⁴²: *The aleatoric uncertainty that we have seen gives me a sense of insecurity, like anything that cannot be controlled and predicted, it causes me a kind of anxiety, which I also have in the moment when I don't know the outcome of a test or examination.*

However, this was the first impact with new content such as uncertainty, which over time started instead to be associated with new epistemic emotions. We see emerging epistemic emotions of surprise (not necessarily negative), trust, interest, and curiosity.

SB: *Instead, after the course however, I realized that the idea of physics that I have- that I had was a little bit limited and instead the world is much more complex, there are many more variables to consider and there is also uncertainty, which however not necessarily in a negative sense here.*

[...]

To manage that insecurity and maybe even find in it a new feeling of security I think we can accept it by letting go of the need to control everything and with the knowledge that the future is knowable the moment we experience it. Thinking about it, I think it is also nice that we are not one hundred per cent certain about every future event, whether it is a scientific prediction or even an everyday life event.

However, the uncertainty and anxiety it can cause can be converted into curiosity, and hope, sometimes followed by disappointment.

SB has evolved from her initial state. In particular, first instability and insecurity caused by new topics such as uncertainty, especially aleatoric uncertainty, seemed to emerge. In fact, the view of science as a set of laws that gave her security was challenged, and this caused her to feel anxious and demoralized.

However, SB shows that she has managed this initial sense of insecurity and developed a new vision of science. In particular, the sense of insecurity has been converted into curiosity and hope: this is because her image of science is broader, and there is also room for uncertainty, which is therefore no longer seen as something disturbing.

TL

From the previous narrative, it was emerging emotions of curiosity and excitement with respect to scientific knowledge creation.

FDZ 09:45 *That is, how do you relate, do you relate from near, from far, do you relate with fear, with curiosity, with expectations?*

TL 09:57 *I personally (relate) with a lot of curiosity, but also a little bit of excitement. I have often had it, for me we feel -- we are a people always on the frontier in the science of the knowable. A lot of people when we talk, I've had a lot of discussions, they don't like the fact that the more we search the more we increase this bubble of things that we don't know. Honestly, for me it's the most exciting thing just the fact that the*

⁴² This excerpt and the following two are reported in a different template (without time indications) since it was an annex of the interview. We lost the connection and we were not able to finish the interview so we asked SB to send us the answers to the final questions via e-mail. Following excerpts formatted like this are part of the answers received via e-mail.

amount of things we don't know grows, because it seems boring to get to a point where we won't have anything more to know.

Evidences of epistemic emotions of curiosity, interest, and fascination, related to physics.

- FDZ 14:35 *I try to formulate the second question, however, by declining what you said: you had started with theoretical physics why? And then I ask why did you change your mind instead? What topics, what experiences made you say that what maybe you felt it was more personal, maybe it was a practical dimension?*
- TL 15:00 *In the beginning, especially for the theoretical physics question, it was the fascination, the fascination of physics. I've always liked physics, even when I was a kid I liked to see ... I always inquired about different topics than normal. Quantum mechanics, for example, I used to watch videos or tutorials when I was in middle school just because of pure curiosity, while the journey to get to this idea of being more engineering... One because frankly, I wouldn't see myself in academia, I would see myself at most up to the master's degree, a PhD I don't see myself as a PhD, I don't see myself as a researcher... it's not really an area that ... I'm curious about it, yes, but I don't see myself as a person to be here like you are, researching, finding other topics.*

Here for instance is evident an emotion of interest.

- TL 06:24 *Personally, because I am really interested in physics but especially in PLSs.*

Here again emotions of interest, curiosity, and satisfaction.

- TL 01:34:44 *That's what it would come down to for me to say. The point is... then for each person it's different... I just like the fact of general physics, but not a specific topic, every topic of it because in the end physics is the description of how our universe works, but also stupid things, for example how a refrigerator works. After I really understand how a refrigerator works, I see it in a different light. Because I say "AH but you see why? This takes tot energy and then by consuming that work it creates a colder environment inside and a warmer environment. It's amazing stuff..." And I see this a little bit in everything, the point is this is what makes me curious about physics, the fact that I know how the mechanics of the universe works.*
- FDZ 01:35:37 *So it is how it works, however on any topic there is no particular one?*
- TL 01:35:45 *No. But of course, there are topics that fascinate me more than others...*

In this case instead an emotion of joy (of his physics teacher but which he also projects upon himself).

- TL 01:48:32 *[...] my prof. The point is that he many times does a little bit like me, especially on some exciting topics, especially in physics, sometimes you can just see the joy inside his eyes while he's explaining things. For example, just in the third grade, I think we were talking about rotational motions and we had the example that he took the student and he put it on a disk that you could move and he gave him the wheel in his hand and he spun it around and he said, "You guys look how amazing this is because if you hold it like this the momentum goes in this direction because looking at it..." Just with the joy on his face, very beautiful...*

The case of TL is quite different with respect to that of SB as the new topics and the course in general did not provoke an emotional gap. In fact, no different epistemic emotions are noticed from those already present in TL's initial positioning.

Specifically, reflexive uncertainty does not cause him to react negatively, but rather he is confident in the humans.

TL 00:04 *Scared not particularly, I presume--as I said I'm quite optimistic about these things. I assume that the human soul is pragmatic enough not to blow us all up...*

Again, TL in general does not see a discontinuity from his initial epistemic positioning.

FDZ 17:00 *Okay, last question of this part. You came into this course with a certain idea of physics and science at the beginning and compared to that, what you found, that is, the image of physics that we tried to present, how did it position itself compared to your image of physics? The way of doing physics no? i.e. also involving Professor Ruggeri and the two volcanologists, all this....*

TL 17:44 *Basically, they didn't have a practical application but for a lot of topics we can say they won't have it for now a practical application...honestly compared to how I see physics it wasn't very far away, compared to the way I do it typically. So I don't know I couldn't say a position but if I really have to say broadly it wasn't very far from how I see it. If, on the other hand, you mean how it changed for me the way I see science, it didn't change it greatly. In the end, the way I see things around me remains the same, only certainly in the field of climate change I have some more information that has helped me and made me curious.*

5.2.2 Activators and connections

In the previous step I coloured the epistemic emotions related to the initial epistemic positioning and those that emerged in the course due to the new contents, divided into “emotional gap” and “emotional continuity”.

Then, I proceeded as follows in the data analysis.

I identified the elements of knowledge (contents addressed in the course) that activated the "orange" and the “light blue” epistemic emotions, and I named them respectively “tension activator” and “confirmation activator”.

Afterwards, I started to inquire why the activators created an “emotional gap” or a "confirmation". For instance, behind a confirmation there may be many reasons: some problems related to learning the concepts which thus leave one indifferent, an understanding of them (even a deep understanding), a resonance of the content with an initial epistemic positioning, etc. These reasons are anyway dependent on personal epistemic positioning. The activators indeed create tensions or confirmations in light of their

relationship with an initial epistemic positioning. Thus, to understand the nature of confirmation or tensions it is necessary to consider “what the activator confirmed and why” or “with what the activator clashes and why” with respect to the initial epistemic positioning.

In this section are then presented the activators and are discussed the connections for the two case studies examined so far.

SB

Tension activator

Recalling the epistemic emotions color codification of the previous section, it is possible to recognize that the element of knowledge (activator) that produces an emotional gap is the aleatoric uncertainty. The emotional gap takes the form of frustration, discomfort, helplessness, and demoralization precisely because SB can no longer regain the sense of security and satisfaction she had toward science. She is presented with a type of science that no longer gives her a feeling of certainty.

There is a sense of perceived fatigue in front of complex systems, where there are so many variables "crisscrossing like a tangle to be untangled," and yet "it is impossible to untangle", as she says. SB perceived the depth of the message brought by aleatoric uncertainty, how revolutionary it is and to what extent it involves a mental shift, and this is what causes her sense of fatigue. The fatigue is accompanied by anxiety, which she compares to that she feels when facing the unknown grade of an exam.

Confirmation activator

From the emotions codification, it emerges that ontological uncertainty produces emotional continuity. This is because the example of ontological uncertainty presented in class (i.e. the uncertainty principle), unlike other examples connected to the other uncertainties, has a form of law, and this is totally consistent with SB's view of physics being made of laws. It is just adding one more law stating that one cannot know at the same instant position and velocity, but this does not require a revision of the initial epistemic positioning.

Similarly, even having sliders in the game and knowing apriori how the scenarios would change by moving each slider does not create emotional tension in SB as it is consistent with her image of calming science which provides certainties in its predictions. As SB reports, there were "established consequences" (in the functioning of the sliders) and this gave her a sense of quietness because there was consistency with her view of what science can give (ability to determine).

TL

Tension activator

In TL's case, no epistemic emotions were found to signal an emotional gap.

Confirmation activator

TL shows several epistemic emotions witnessing forms of emotional continuity. In particular:

- 1) The way of treating physics and showing how it is connected to the political and social world activated a confirmation with some visions of his initial epistemic positioning.

- 2) Also, the aleatoric and reflexive uncertainties activated epistemic emotions in continuity with the initial positioning. However, in this case, these concepts were not properly appropriated (Levrini et al., 2015) but were rather overwhelmed by the epistemic uncertainty that was dominant in TL's vision, which may be the reason for the absence of an emotional gap⁴³.

FDZ	17:00	<i>Okay, last question of this part. You came into this course with a certain idea of physics and science at the beginning and compared to that, what you found, that is, the image of physics that we tried to present, how did it position itself compared to your image of physics? The way of doing physics no? i.e. also involving Professor Ruggieri and the two volcanologists, all this....</i>
TL	17:44	<i>Basically, they didn't have a practical application but for a lot of topics we can say they won't have it for now a practical application...honestly compared to how I see physics it wasn't very far away, compared to the way I do it typically. So I don't know I couldn't say a position but if I really have to go broadly it wasn't very far from how I see it. If, on the other hand, you mean how it changed for me the way I see science, it didn't change it greatly. In the end, the way I see things around me remains the same, only certainly in the field of climate change I have some more information that has helped me and made me curious.</i>

The topics have interested him. What he feels is that he has more information than before on which to ground his epistemic positioning.

The fact that TL says that the two images of physics (the one he had and the one he saw in the course) are partly similar is true because, for example, the multidimensional character of science and its connection to political, social and other issues was something that already belonged to TL as shown in his initial profile.

Also, the idea of using the concepts of science as tools to look at reality (strongly emphasized over the lectures - see layer 3 in Figure 2) was something that was already rooted in TL, creating thus a sense of confirmation and continuity:

FDZ	18:44	<i>I'm just asking a question because you said something that I'm interested in that is when you know things, so those you just see as extra knowledge, not as something that changes your perspective in general? Or does that happen as well?</i>
TL	19:04	<i>It depends on the situation: an extra knowledge many times can change even so much the method of doing, a typical "Ah, but why don't I do that too! Much better!".</i>
FDZ	19:16	<i>Did it happen with physics?</i>
TL	19:20	<i>Lots of times</i>
FDZ	19:20	<i>For example?</i>
TL	19:20	<i>Now giving examples I don't know. But the way of looking at things i.e. one of my comrades for example might have said to me "Ah why don't you see ... vectors why</i>

⁴³ This of course is a claim that has to be tested in the further steps of the analysis.

don't you look at this instead of that!" And that could completely change the way of doing

FDZ	19:39	<i>The way to do what? The exercises?</i>
TL	19:44	<i>But also apply to the way of seeing things.</i>
FDZ	19:44	<i>Out of physics, you say?</i>
TL	19:46	<i>Yes! Extra knowledge could completely change the way you see something. For example, if I see... (picks up a cup)... From the outside, I say as an introduction, "Ah it's a cup...it's white! It has writings on it..." Okay however if then someone tells me that this cup I don't know, is made of strings that vibrate, I could see it in a different way, I could see many things around me in a different way, in a way that I didn't conceive before because I didn't know that this could be made of strings....</i>

With respect to this, the course confirmed and reinforced this view, as noted in a comment by TL during one of the lectures:

TL: I am especially intrigued by the fact that in our everyday behaviour we can consider it a chaotic system, literally all existence can be considered a chaotic system. The point is that saying "Wait I do one thing differently," we could never know what would have happened if I didn't know five years ago, instead of the red coffee cup I took the blue coffee cup... now what would have happened? Now I could be who knows where...

In this excerpt, TL shows that he is doing, with new topics such as complex systems and deterministic chaos, the same process he used to do. Hence the course has given some extra information, it served to build a somewhat richer and “more suitable” framework, in accordance with his necessity to build an explanation closer and closer to the objective mechanism of how things work.

TL	31:05	<i>After all the lectures yes I felt a need to approach as you say the problem from a more general view because I noticed a more general view and a description more suitable for the situation we have now with Climate Change.</i>

It served to give more precise names, for example, to concepts he already knew.

FDZ	07:57	<i>I mean in the sense my question is, specifically what kind of physics did you expect?</i>
TL	08:12	<i>I expected classical physics, at most I already knew about the intervention of chaos theory with Lorenz's calculations, and especially for uncertainty, I didn't know it was called aleatoric uncertainty, but I knew that the movement of clouds was a chaotic movement. I was already expecting this, and for that matter pure classical physics about the movement of the atmosphere... honestly, my expectation was this.</i>

For what concerns aleatoric and reflexive uncertainty, it is evident that they are often placed in the same “sense frame” of epistemic uncertainty.

For example, in the following excerpt related to aleatoric uncertainty TL makes the epistemic uncertainty (we cannot follow each particle because of a limit to our ability) overlap with the aleatoric uncertainty. In this way, he struggles to see the element of rupture that aleatoric uncertainty brings:

TL	01:01:02	<i>[...] On the fact of how the ontological, as much as we can find ourselves, we cannot know, resolve this uncertainty. The aleatoric, if I took a cup of water--generally, if</i>

you look at the system at the macroscopic level it's an aleatoric uncertainty, we can't predict every movement of every molecule at a very statistically tiny level. But if you monitor each molecule, molecule by molecule in each of its data, so mass, kinetic energy and direction of motion, we can also predict where it would collide, and how it would resolve. Instead, if you only look at the system at the macroscopic level we won't be able to know because the uncertainty is aleatoric, right?

There is as anticipated a strong presence of an epistemic principle of knowability: with more and more accurate knowledge applied to more and more efficient models, certainty can be approached. In reference to future predictability and what resulted from the game, TL for example commented:

TL	01:14:13	<i>“Wild cards” will always exist, but if you study well, if you study well what the sociopolitical situations of each nation are like, eventually you could make even a good estimate of what might evolve in five years...</i>
LM	01:15:00	<i>So for you, in general, it is always knowledge, that is, knowing something very well....</i>
TL	01:15:05	<i>It could lead to estimate...</i>
LM	01:15:08	<i>It is knowledge for you that is at the heart of it, that is, the more you know, the more effectively you achieve ... a kind of truth ...</i>
TL	01:15:17	<i>The fact remains that 100% certainty does not exist. However, much easier to estimate something that could happen tomorrow than something that could happen 10 years from now. Then, as I always say, nothing is 100%, now I could say I wake up tomorrow, that is almost certain, but who knows?</i>

It is difficult for TL to really get into the discourse of reflexive uncertainty, as is evident in several passages. For example, referring to the human being:

TL	00:04	<i>[...] as I said I'm quite optimistic about these things. I assume that the human soul is pragmatic enough not to blow us all up...</i>

For him, humans and the things they do are understandable within a mathematical model. Therefore, there is no way to consider human behaviour as a non-predictable variable, in accordance with the epistemic core of reflexive uncertainty (Dessai & Hulme, 2004).

5.2.3 Positioning and re-positioning

So far I described the initial epistemic positionings with respect to science of two specific cases, trying to consider the diverse nuances as depicted in the FRA model (Erduran & Dagher, 2014). Then I looked for the epistemic emotions both within the initial epistemic positioning and specifically concerning the course's contents. The epistemic emotions related to the new contents addressed in the lectures were divided into those showing “emotional continuity” and those showing “emotional gap”. For each emotion of these two groups I looked for the activator: indeed, to be epistemic emotions they must be linked to an epistemic element (in this case most of the time the activators were the new forms of uncertainties presented). Once found the “tension activators” and the “confirmation activators” for each profile, I examined those with respect to the initial epistemic positionings, considered antecedents of such emotions (Muis et al., 2015).

The discussion around both kinds of activators led me then to consider the consequences of both confirmation or tension experiences and evaluate potential positionings' confirmations or re-positionings.

The following lines describe the mechanisms of positioning/re-positioning for the two case studies considered so far.

SB

Re-positioning

The re-positioning that is seen in SB is a broadening of the idea of science and the elements that constitute science. There are laws but also uncertainties of different kinds and unpredictable phenomena. This broadening is a consequence of how SB handled the emotional tension that arose from having crossed concepts that did not fit into her initial epistemic positioning.

For example, the course brought her to realize that an image of science made up of perfect laws and models is somewhat limited.

SB 01:18:30 *My image of physics. Well is a little bit more, a little bit broader view, a little bit more.... well if before it was just the physical laws, without, even now we in school do, anyway like we talk about ideal gases, about, mmm, without like maybe not considering air friction, well it's all, it's all perfect though, it's so, well it's very small, instead. Instead after the course however I realized that the idea of physics that I have- that I had was a little bit limited and instead the world is much more complex, there are many more variables to consider and there is also uncertainty, which however not necessarily in a negative sense here.*

In the "new image of science" there is also room for uncertainty, which no longer has a negative connotation. It is no longer seen as the "enemy" of science, preventing things from "adding up" but now finds its own meaning and place.

SB: To manage that insecurity and maybe even find in it a new feeling of security I think we can accept it by letting go of the need to control everything and with the knowledge that the future is knowable the moment we experience it. Thinking about it I think it is also nice that we are not one hundred percent certain about every future event, whether it is a scientific prediction or even an everyday life event.

SB shows to be well aware of her transition and that she has reevaluated the concept of uncertainty, which initially caused her anxiety, insecurity and fatigue. She also reports that is possible to manage the sense of insecurity and indeed find new security in it.

This witnesses the broadening of the image of science: the sense of security concerning laws is preserved as it was initially, but now she can find a sense of security in the very thing that used to create the sense of discomfort.

SB: However, the uncertainty and anxiety it can cause can be converted into curiosity, and hope, sometimes followed by disappointment

This maturation of scientific vision is not something accidental that emerges from the interview, but it proves to be something more general that is also reflected in how SB thinks about her own life, about her own future.

- SB 52:34 *uhm in my opinion yes. Uhm the thing that I liked and interested me the most was when we did the, the spectrum of futures, the cone of light that goes to illuminate the possible futures with all the, um, possible, probable drawbacks. That very interesting one and also it, it also pushed me to think about my future in general not just the future of the planet, well just about my own personal.*
- LM 53:10 *ok and how?*
- SB 53:12 *I mean like I thought like how do I see myself? I mean how will I see myself in the future, what also what do I want to do? Well what, well just concrete things. I don't know if I want to have a family, when I want to study, what job I want to do. Then maybe well I gave myself various answers that are, they correspond to the various scenarios, so...*
- LM 53:47 *Okay, and this thing here, well you have it, what was the last one let's say, okay the cone of futures that anyway also serves to give a kind of dictionary to explain no? A little bit the differences... [between futures] but was there a particular moment in the course where you realized, "Okay, now can I build these scenarios?"*
- SB 54:10 *Well....*
- LM 54:12 *Or was it the course in general?*
- SB 54:17 *um, well after we dealt in the first part with uncertainty, afterwards, when we started to talk just about future scenarios, well there I thought about it anyway, in general, yes, during -- well in general, not in one particular lesson.*
- LM 54:31 *Okay, so, did this thing of reasoning about your futures happened in class while we were in the course or maybe at home at a specific moment?*
- SB 54:43 *No, well not only, even later at home.*
- LM 54:48 *Okay, okay. And how, well before you didn't think about these things or you thought about them differently?*
- SB 54:58 *well, now I take this, I take an example, like, anyway well I thought about it, like, I was already thinking about it, however though it has, it has me. Well, I don't know I thought about it in a different way after we talked about the future scenarios. In a different way in the sense, well, more, it gave me more options here, well before I was thinking what do I want to do when I grow up? Then I used to think one thing and that was it. Whereas now, after we talked about the future scenarios, I was thinking "What do I want to do?" and then I was thinking about more things and how to get to each thing, what actions I have to take first to be able to get to that, to get that result?*

In this excerpt, SB says that the future cone tool, but in general the whole course, pushed her to think about her personal future in a different way. And this reflection was triggered - as she reports - not only incidentally in the course but later when she was at home.

The interesting aspect is that before she says that when she was thinking about the future she was thinking about "one thing and that's it", whereas now she is thinking about "several things". This broadening

mechanism is extremely similar to the mechanism of "broadening the vision of science" that she reports several times. Before, science gave one answer and that was comforting; likewise, she looked at her future in one way. Now, science sometimes gives more answers or none at all and she looks at her future in more than one way. Thus, it seems that new contents, which find their place in an expanded image of science, become tools for thinking about one's identity trajectory.

Confirmation of positioning

In Section 5.2.2 I considered how and why ontological uncertainty provoked epistemic emotions in continuity with the initial epistemic positioning for SB. Looking at how SB was able to accommodate it in her epistemic positioning shows us that SB did not abandon her initial positioning completely, but rather she expanded it. It is clear that physics is still made of laws, and ontological uncertainty resembles a law for SB, so to accommodate it, space for laws must be maintained in the new and broader image of science.

This also perhaps demonstrates a maturity of SB in that she does not necessarily question everything, but seeks to add new perspectives that allow her to "accommodate" new concepts in her view of what science is.

TL

Re-positioning

There were neither epistemic emotions linked to an "emotional gap", nor repositioning.

Confirmation of positioning

TL's epistemic positioning, which was not challenged by the course, also positioned him socially, for example in the way he related to his classmates during the board game. TL had in his and everyone's view a leader attitude because at that moment he was taking charge of achieving in the game the "common good," which for him was objectively the environmental sustainability.

During a discussion about the meaning of the common good TL shows how for him the common good is something objective, and this influenced the way he posed himself in the game (pushing his teammates to follow the line toward the common good). In the discussion, however, it is brought out that he regarded the objective common good as only the environmental salvation and this has resulted in a final scenario with dystopic consequences at the social level (see Section 8).

FDZ	01:25:07	<i>In your game, according to you, you played it by putting the achievement of the common good as the basis, right?</i>
TL	01:25:14	<i>Yes</i>
FDZ	01:25:14	<i>In your play, the common good, who decided what it was? it was you?</i>
TL	01:25:21	<i>yes it was us</i>
FDZ	01:25:23	<i>So was it subjective or objective?</i>

TL	01:25:26	<i>The common good we achieved and established with respect to what we were told, which was that the goal, the "good" would be a maximum climate change expectation at 2.1 (degrees) and an economically stable situation at the end of the game, and we achieved that thing.</i>
FDZ	01:25:46	<i>We did not say that was the common good, we said "This is the goal of the game."</i>
TL	01:25:50	<i>And we took it as the common good</i>
FDZ	01:25:51	<i>You have taken it as the common good. That is interesting, however, it is not taken for granted. I specify one thing we did not say, there was no judgment on that achievement, it was a task and then everyone chooses how to do it.</i>
TL	01:26:08	<i>And the point is that honestly, this is my subjective view, the fact that we achieved that goal is good because you discounted so much pain afterwards because then eventually after even 2100 it's not like the climate situation or even the social situation grows exponentially again and goes back to the levels it was before, it would still have remained low, it would still have remained at the levels optimized in 2100 if not growing even more. Much easier economic growth in 2100 with a sacrifice now, I personally think other members of my group as well, have considered it preferable to a "Let's be well now and also be decently well later." So yes, this decision toward the common good included a sacrifice.</i>

In this excerpt, TL says at one point that the common good was influenced by his (and his teammates') subjective opinion, which, however, he earlier reported as an "objectively better strategy":

TL	01:20:20	<i>[...] from an objective point of view, taking into action those policies that were taken during the game, our game, would objectively have led to a better future.</i>

I think this is again an indication of how even subjective issues are overwhelmed by a paradigm of knowability where an objectively right explanation can be (always) formulated.

As he reports again at the end of the interview, TL has a view of science very much anchored in the idea of determinism. The following excerpt discussed whether or not one may be afraid to answer questions during class.

FDZ	01:54:34	<i>But does that change according to you depending on the subjects? Does the type of fear change?</i>
TL	01:54:41	<i>It depends. It could change; in more humanistic subjects like in Italian for example, which I see almost nothing deterministic in it, even a little bit similar to what was said before, that even physics subjects now are very often indeterministic however at least as long as it's classical physics, you don't have indeterminism you just have determinism. When you have a mathematical subject you know you have a definite answer, if I don't know or I'm uncertain, there's no point in answering because it's probably wrong anyway. Whereas in a humanities subject usually when you have questions I often hear more answers because it's more personal very often or at least if I say something personal, because in the end poetry is pure interpretation, I'm a little bit more confident in answering that fact rather than a math subject where I'm uncertain. Here uncertainty to answer in a humanities subject creates less fear than uncertainty to answer in a mathematical way.</i>

LM	01:56:01	<i>Why do you say there is a sense of truth in the scientific part while the rest is more...</i>
TL	01:56:01	<i>Open to interpretation, especially philosophy.</i>

Although he reports that physics also has degrees of uncertainty and indeterminism, it is possible to see how anchored he is in the idea of mathematics having only one precise answer and physics being deterministic.

5.2.4 An emerging theoretical hypothesis

The analytical steps fulfilled so far were pointing to developing a local and humble theoretical hypothesis to make sense of the data emerging from the interview. Hence, I decided to consider two opposite cases to better structure such hypothesis. In this sense, it seems helpful to recall and reinterpret the steps as the steps of a Grounded Theory development (Glaser & Strauss, 2010).

As Vollstedt and Rezat (2019) summarize, *“Grounded theory further provides a particular set of systematic methods, which support abstraction from the data in order to develop a theory that is grounded in the empirical data. These methods include different coding procedures, which are based on the method of constant comparison”* (p. 83).

Hence, Grounded Theory is a local theory grounded on data with the aim to explain and report as clearly as possible what the researcher sees emerging from the data. One interesting feature of Grounded Theory is that it is iterative: ideally, new data are collected as the *theorization* proceeds, to test and direct the theory evolution itself. This keeps going on until a saturation threshold is reached, thus when new data do not add anything new to the theory.

It is structured in sets of coding operations.

The first one is named “open coding”. In this phase, *“data are broken up into smaller parts and then, these smaller analytical parts are compared with respect to similarities and differences”* (Strauss & Corbin, 1998). This first phase is the most creative one when the researcher has to activate a strong sensibility to detect the presence of interesting issues or patterns. As Glaser and Strauss comment, *“The primary source of any meaningful theorisation is the sensitising intuitions of the observer himself”* (Glaser & Strauss, 1967).

The “open coding” in my case consisted of noticing the centrality of epistemic emotions as indicators of reactions to the course. From that initial intuition, I first looked for the elements connected to initial epistemic positioning and “read” them according to the FRA dimensions of the nature of science. Then I shifted to code all the epistemic emotions, both related to initial positioning and the course experience (see Figure 19).

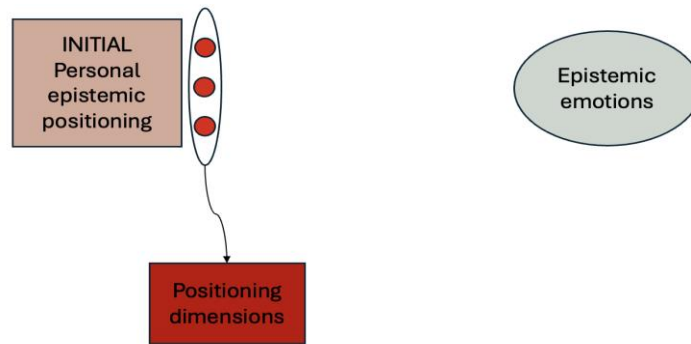


Figure 19: The “open coding” phase of the present study. The red dots are “symbolically” representing that an epistemic positioning is composed of multiple dimensions (discussed in light of the FRA model).

The second step of Grounded Theory is called “axial coding”. In this phase, the researcher has to investigate “the relationships between concepts and categories that have been developed in the open coding process” (Strauss & Corbin, 1998).

In my case, the “axial coding” consisted of the following. As long as I was passing through the epistemic emotion codes for the two case studies, I gathered the codes into two broader categories – emotions displaying an emotional gap or an emotional continuity with respect to the epistemic emotions populating the initial epistemic positioning. Thereafter, I identified the specific activators for each epistemic emotion of both the categories and I connected each specific confirmation/tension activator to a characteristic of the initial personal-epistemic positioning of the individual, to display why that specific activator was producing a tension or a confirmation.

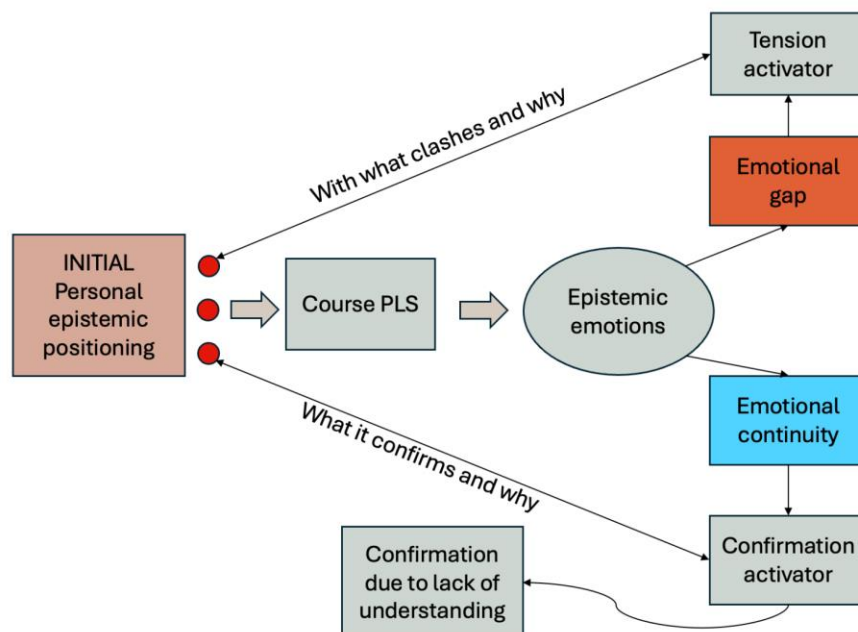


Figure 20: The “axial coding” phase of the present study. Initial codes in the epistemic positioning and the epistemic emotions mapping have been connected, letting emerge a more detailed structure. The arrows between “Initial Personal epistemic positioning”, “Course PLS” and “Epistemic emotions” do not mean implications, but rather that the course created a context for facing new epistemic elements (knowledge) and thus made emerge epistemic emotions.

The outcome of this process made evident a meaningful and data-driven connection between the categories of epistemic emotions, epistemic activators and the initial personal-epistemic positioning.

Then in Section 5.2.3, I started discussing both the cases of positioning confirmation and re-positioning for the two profiles studied. This brought me to formulate the first version of an empirical argument discussing why TL did not shift his positioning and what kind of re-positioning instead was displaced by SB.

This last step made me connect the tension/confirmation activators with also the final positionings of the students, expanding the structure of the theoretical hypothesis.

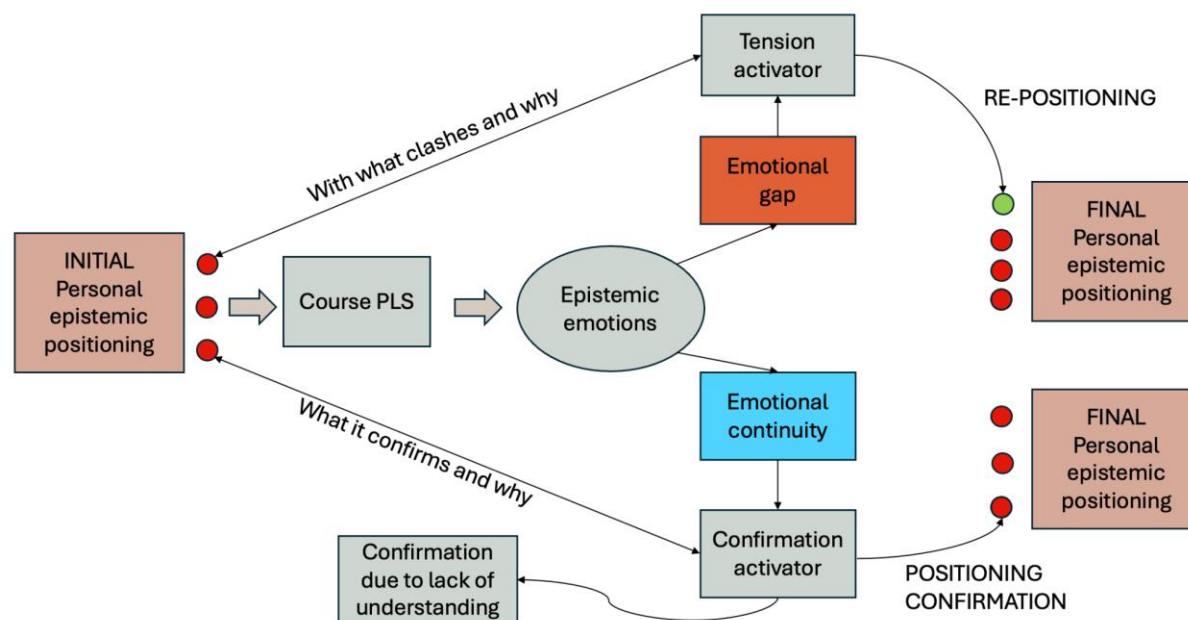


Figure 21: The second part of the “axial coding”. The final positioning can be a confirmation of the initial one (bottom right) or a development of it - here repositioning. From the data, it seemed to emerge these two options. The green dot represents a new element which is included in the epistemic positioning. As the case of SB shows, the re-positioning does not mean a complete questioning of the initial perspective but is more a reconsideration of some local aspects and the inclusion of new knowledge and new awareness.

In the next Section, I discuss how I dealt with the third step of Grounded Theory: the “selective coding”.

5.3 Phase three: selective coding

The objective of selective coding is to refine and integrate in a more cohesive way the structures developed through the axial process. Usually, in the selective coding, the researcher tests the emerging theory against outcomes from the literature and triangulates them with external researchers.

Also, selective coding involves “theoretical sampling”. This sampling means collecting new data, chosen according to their potential contribution to the further development and refinement of the local theory.

In my case, the new data “sampled” consists of the narratives (see Section 5.3.5 for details) of the other seven students interviewed.

In the next Sections then, I will articulate how I proceeded with the refinement of the theoretical structure through the “selective coding” and the “theoretical sampling.”

5.3.1 Triangulation with literature

While studying the emergent theoretical hypothesis presented so far, I started to look in the literature to expand the perspectives about the connection between epistemic positioning and epistemic emotions. I found then a close similarity with other theories studying the role of what they name “epistemic beliefs” have concerning epistemic emotions, and vice-versa (Hofer & Pintrich, 1997; Mansfield & Clinchy, 2002; Muis et al., 2015). Such theories are mostly framed within the learning sciences and conceptual change.

Epistemic beliefs, as introduced by Hofer and Pintrich, are individuals’ beliefs about knowledge and knowing (Hofer & Pintrich, 1997). They are distinguished by purely cognitive issues as they focus on how individuals conceptualize knowledge and examine its justification. In particular, the authors suggested a model made of four “spectra”: 1) certainty of knowledge: the belief in whether knowledge is fixed and certain or fluid and evolving; (2) simplicity of knowledge: the belief in whether knowledge is made of isolated facts or is highly interrelated; (3) the source of knowledge: the belief in a knowledge handed down by authority (e.g., passively acquired) or in a knowledge actively constructed; (4) the justification of knowledge: this refers to how individuals validate their knowledge, from an external authority or through systematic critical process (Hofer & Pintrich, 1997; Muis et al., 2015). The first two are related to the nature of knowledge whereas the last two are related to the nature of knowing.

For a long time research in developmental psychology has been focusing on the link between epistemic belief and cognitive strategies (Strømsø & Bråten, 2010), self-regulation (Muis et al., 2018), motivation (Nussbaum et al., 2008), academic performances (Schommer et al., 1992), etc.

Also within the science education community, the role of epistemic beliefs has been investigated. For instance, Nussbaum and Bendixen (2003) showed how students with an epistemic belief rooted in a vision of knowledge as simple, certain, and unchanging tended to avoid practices of argumentation. On the opposite, diverse studies disclosed a positive correlation between a vision of science as dynamic and constantly changing and more complex and integrated forms of scientific argumentation (Baytelman et al., 2020; Bell & Linn, 2000). An example in this sense is the study by Cheng and colleagues in which the authors found out that “epistemic beliefs in the unambiguous, certain nature of scientific knowledge had a direct positive relationship with beliefs in justification by school-based authority” (Cheng et al., 2021; p. 981). As a consequence, these forms of epistemic beliefs do not provide much space for argumentative and critical thinking skills development. Nonetheless, some studies examined the potential of some activities in supporting more naive epistemic beliefs to evolve. For instance, Kalman and colleagues demonstrated that a combination of pre-class reading with metacognitive reflection, and in-class active learning producing cognitive dissonance supported an epistemological growth for physics (Kalman et al., 2015).

An interesting aspect of this last study is the focus on cognitive dissonance as a way to trigger what Nussbaum and colleagues (2008) call “conceptual shift”: *“By conceptual shifts, we mean nascent revisions of knowledge that can serve as precursors to more substantial knowledge restructuring or conceptual change”* (p. 1980). I stress here the proximity between the idea of conceptual shift and what I have so far addressed in the empirical study as “epistemic re-positioning”.

Thus a first outcome from navigating the literature is the use of more precise and connotated words to describe the elements of the emerging theoretical hypothesis. Instead of “personal-epistemic positioning” I will from now on use “epistemic belief”.

I mentioned also above how theories considering the mutual relation between epistemic beliefs and epistemic emotions have informed this analytical phase. Given their proximity to claims raised through a triangulation with colleagues, they are examined and discussed in the next Section.

5.3.2 Peer debriefing

During a moment of triangulation about the theoretical structure as shown in Figure 21, two doubts emerged:

- Can we interpret TL’s predominance of epistemic uncertainty over aleatoric and reflexive uncertainties as a form of “cognitive dissonance”?
- Is the emotional gap necessary for understanding? (in other words, “Is there any difference between this theoretical hypothesis and a traditional constructivist theory?”)

I start by discussing how I dealt with the first one.

Cognitive forms of disequilibrium in learning have been investigated since the ‘50s (Festinger, 1957) together with the emotions provoked by them (Muis et al., 2018).

For example, when individuals’ epistemic beliefs align with the epistemic nature of the learning task or the epistemic structure of the content, cognitive congruity will occur. Conversely, when individuals’ epistemic beliefs do not align with the epistemic nature of the learning task or the epistemic structure of the content, cognitive incongruity (cognitive dissonance) occurs (Kalman et al., 2015; Muis et al., 2018). As Kalman and colleagues (2015) exemplify, this is often the case in science learning environments: *“Students have been experimenting since they were very young and their understanding of nature clashes with the Newtonian synthesis presented in the classroom and in their textbook. At the same time, they have strong beliefs that knowledge is conveyed by authorities (instructor and textbook). This results in cognitive dissonance. [...] Likewise, if a student comes in thinking that physics consists of a bunch of equations to be memorized, and the instructor focuses more on concepts, there is conflict”* (p. 2).

In general, both episodes of cognitive congruity/incongruity may provoke definite emotions, which are not general emotions but rather *epistemic* emotions, as they are due to a cognitive process of constructing and accommodating knowledge.

According to Muis for instance, cognitive incongruity may predict confusion, anxiety, frustration and boredom (Muis et al., 2018). Despite the potential negative emotions which may arise related to cognitive incongruity, which depend on many factors, many scholars have highlighted epistemic dissonance as a “driving force” for a change of the epistemic belief (Bendixen & Rule, 2004; Kalman et al., 2015; Muis et al., 2015).

If we recall the two cases presented previously, TL exemplifies a sort of cognitive congruity whereas SB shows cognitive incongruity. Nonetheless, as suggested during a triangulation session, there seem to be traces also of a *possible* incongruity for TL. In that case, what I indeed so far referred to as a “saturation of epistemic uncertainty” over the other uncertainties, may be also due to a form of cognitive incongruity not expressed in the interviews (or even implicit). It can happen sometimes that incongruity drives individuals to ignore the “conflicting information and maintain their beliefs” (Muis et al., 2015; p. 181).

Therefore, the terms “cognitive congruity” and “cognitive incongruity” are now used to sum up the expressions “with what clashes and why” and “what it confirms and why” (see Figure 21).

In light of what has been said so far, the theoretical hypothesis of Figure 21 becomes as follows.

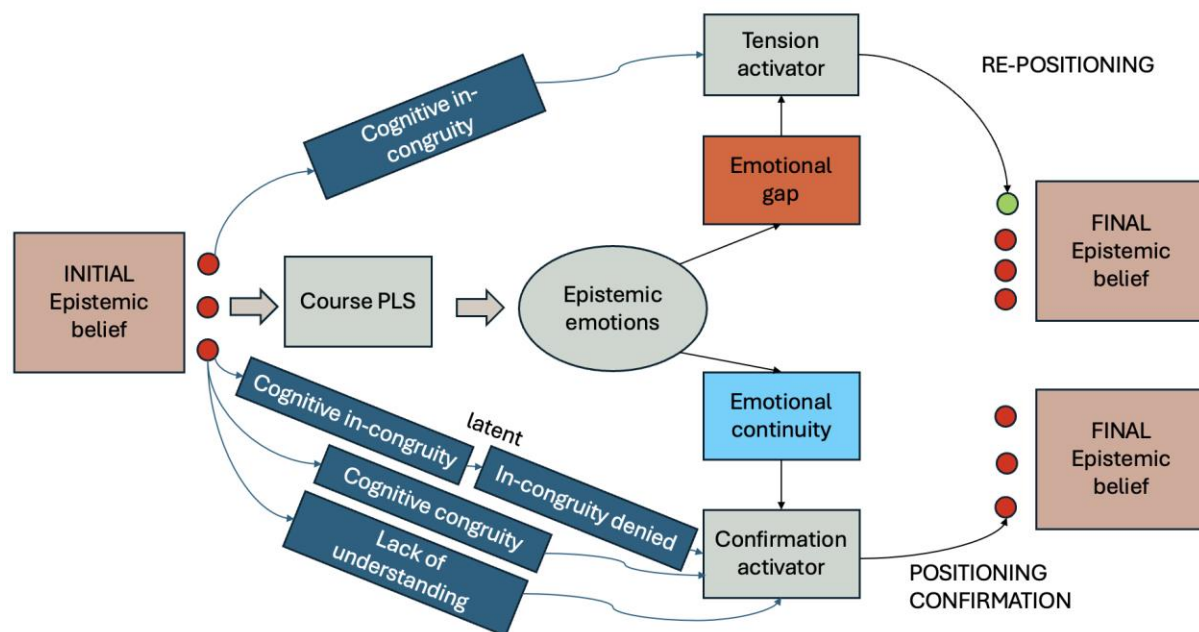


Figure 22: A first evolution of the theoretical hypothesis according to the third analytical phase. The term “personal-epistemic positioning” has been changed with the more connotated term “epistemic belief”. The link between tension activator and initial epistemic belief is expressed by “cognitive in-congruity” whereas the link between confirmation activator and initial epistemic belief has been split into three possible paths: i) a latent cognitive incongruity then denied; ii) cognitive congruity; iii) lack of understanding.

If we focus on the bottom left part of the figure as it is now, we notice the presence of three possible options leading to confirmation. In the previous version (Figure 21), I ended up with two options (based on the case of TL): an emotional continuity happens when no epistemic belief is questioned by the new

knowledge or when the new knowledge is not fully appropriated in its ontological or epistemological aspects, thus no cognitive incongruity occurs (“lack of learning”).

As introduced above, there may be a third option: the new knowledge is understood in depth but is too demanding to deal with, as it questions too strongly the epistemic belief. Then, the individual may decide (implicitly or explicitly) to ignore or underestimate the new knowledge to avoid revisioning the epistemic belief.

In the present case, this represents a hypothesis that must be checked against the case of TL and other cases included, by the theoretical sampling (Glaser and Strauss, 1967, 2010).

In the next Section I exploit the work by Muis and colleagues (2018) to help me out with the examination of congruities/incongruities. The aim is to better grasp “what kind of congruity/incongruity happened”, how the related epistemic emotions have been managed and how that had consequences on learning aspects as well as re-positioning of the epistemic beliefs.

This step has the objective of developing the theoretical hypothesis to address also the second bullet point (“Is the emotional gap necessary for understanding?”).

In Section 5.4 instead, I describe the theoretical sampling process.

5.3.3 The intermediary role of epistemic emotions

Muis and colleagues, in their studies, have corroborated their hypotheses that epistemic beliefs are antecedents of specific epistemic emotions (Muis et al., 2015). They examined students’ reactions to conflicting information about climate change, revealing that multiplistic and evaluatist epistemic beliefs (Serrano et al., 2023) - hence individuals who believe that the justification of knowledge requires critical evaluation of multiple sources - experienced higher levels of joy and curiosity and lower levels of boredom. A belief in the complexity and irreducible forms of uncertainty of knowledge about climate change was linked to lower levels of confusion, anxiety, frustration and boredom (Muis et al., 2015).

In a following work, they deepened the role of epistemic belief and epistemic emotions to study their effect on learning strategies (Muis et al., 2018). Specifically, they studied antecedents and consequences of epistemic emotions, proposing a model to study self-regulating learning. In particular, they recalled the epistemic cognition literature studying the emergence of curiosity and confusion as a consequence of the surprise carried by new information to deal with (Chevrier et al., 2015; D’Mello & Graesser, 2011). Typically, the level of surprise determines the emergence of subsequent emotions: if the surprise is low because the novelty level is low nothing in particular happens. Nonetheless, if the level of surprise is high two distinct emotions may arise: curiosity or confusion according to the evaluation of complexity (respectively high and low). Recalling D’Mello & Graesser (2011), if confusion is not solved, it may shift to frustration and then boredom (disengagement with the knowledge). Besides complexity, the congruity/incongruity between the new information and the epistemic belief has been shown to correlate with epistemic emotions of curiosity and confusion (Chevrier et al., 2015). Building on these results, they suggested a model for the emergence of epistemic emotions considering four interacting dimensions: novelty of information, complexity of information, capacity to understand (i.e., ability based on prior knowledge and skills), and value of information (Muis et al., 2018; p.9).

In the logic of the model, several cases can occur:

- 1) If complexity and novelty are both high and the capacity to understand is **higher** than the complexity of the information, curiosity follows the initial surprise.
- 2) If complexity and novelty are both high and the capacity to understand is **lower** than the complexity of the information, confusion follows the initial surprise, if the perceived value is high.
 - a) If confusion is not solved it may lead to frustration and finally boredom
 - b) If confusion is solved it may lead to joy
- 3) If complexity and novelty are both high and the capacity to understand is higher than the complexity of the information, but the information is perceived as unvaluable, curiosity may not occur.
- 4) If complexity and novelty are both low as well as capacity, boredom may emerge.

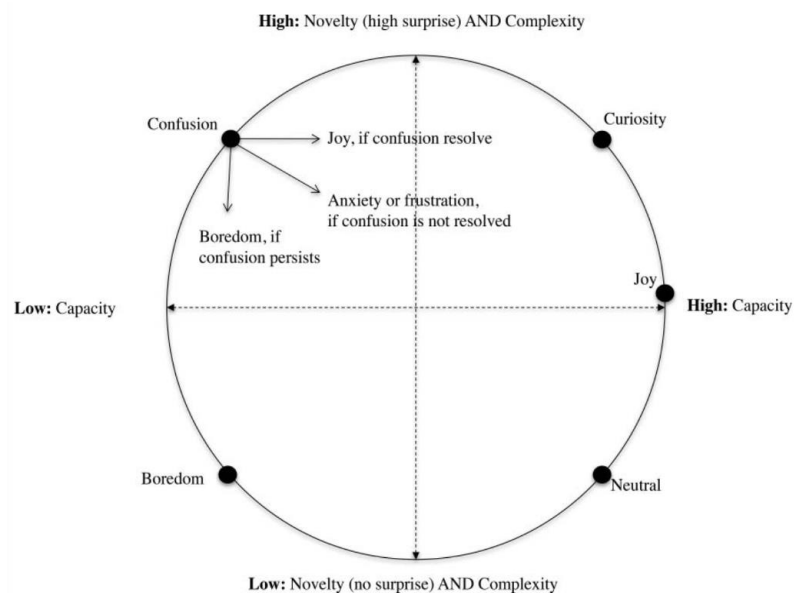


Figure 23: The model suggested to predict the rise of confusion, curiosity, boredom or neutral reaction (from Muis et al., 2018; p.10). On the y-axis the combination of novelty and complexity of the information whereas on the x-axis the capacity to manage the new information.

This figure represents the affective part of a theory they suggest, to describe the phase of self-regulating-learning: *“In the first step, new information is appraised in terms of novelty with prior information and [epistemic] beliefs. If novelty is sufficiently high, then this will trigger surprise. In the second step following surprise, the information is appraised in terms of complexity, capacity, and value, which will determine whether surprise transitions into curiosity or confusion. At the third step, the epistemic emotions that are triggered in the second step will signal to the learner something about their rate of progress toward meeting their epistemic aim”* (Muis et al., 2018; p. 9).

The epistemic aim mentioned is crucial in the study of epistemic emotions. The evaluation of the achievement of an epistemic aim, such as being able to explain or illustrate new knowledge, heavily determines the kind of epistemic emotions which may occur. Again D’Mello & Graesser (2012) suggest that individuals may end up in states of “confusion and frustration” or “flows”, depending on whether

their epistemic goals are blocked or not. Hence epistemic emotions may emerge also due to metacognitive evaluations and become antecedents of individuals' learning strategies. In fact, the authors suggest five possible dimensions informed by epistemic emotions: a) planning and goal setting; b) motivation; c) cognitive and metacognitive strategies; (d) learning outcomes; and (e) revisions to control, value, and epistemic beliefs.

Again anchoring on results from epistemic cognition literature, the authors describe how confusion and anxiety can lead to a downgrade of epistemic aims whereas curiosity and joy may lead to an upgrade in the learning standards. Confusion, combined with the need for definitive knowledge may support the "need for closure" (Kruglanski, 1989), a "state to reduce experiences of discomfort that are generated by uncertainty and the desire for definitive knowledge" (Muis et al., 2018; p.12). The need for closure is the counterpart of the "need for cognition", the feeling that individuals may perceive in front of challenging tasks which are faced with curiosity and joy. The need for closure can end in people ignoring new knowledge as too contradictory with respect to epistemic beliefs.

Also, epistemic emotions are recognized as triggers for cognitive and meta-cognitive strategies which in turn impact learning outcomes (Chevrier et al., 2015; Muis et al., 2015, 2018). For instance, the surprise may lead to curiosity and the activation of extra cognitive strategies if the perceived control is high. According to Muis and colleagues (2015), confusion and curiosity are both positively related to the activation of metacognition self-regulation which in turn negatively correlates with learning outcomes; on the other hand, curiosity and anxiety positively correlate with skills as critical thinking strategies which in turn positively correlate with learning outcomes. A possible reason could be that metacognitive self-regulations occupy part of the cognitive capacity (Ellis & Ashbrook, 1988) preventing full focus on the content, whereas emotions such as curiosity and anxiety drive individuals to increase attention, for the sake of learning outcomes.

Finally, according to the authors, epistemic emotions "may play a role in changes to learners' perceptions of control and value for learning, and in changes to their epistemic beliefs" (Muis et al., 2018; p. 15).

5.3.4 Theoretical hypothesis development

The studies and the model of Muis and colleagues (2018), as well as results from supporting literature, have been considered to revise and extend the theoretical hypothesis presented in Figure 22, leading to a new version (Figure 24 below). They also allowed me to elaborate on the tensions and confirmations and modify them into "high surprise" and "low surprise".

Epistemic cognition literature indeed converges on the specific role of surprise as a variable which may trigger or not an epistemic emotional reaction. The term "surprise" is argued to be more neutral than tension and confirmation, which can be perceived as connotated. Tension for instance may lead to thinking about something negative which stresses the individual, because of incongruity between new knowledge and the epistemic belief. Instead, as the literature suggests, this is not always the case, as it could be the case of people surprised by new *conflicting* knowledge but reacting with curiosity because of perceived capacity, etc. On the other hand, confirmation can be still modelled with a low surprise carried by the new information, as it fits with the original epistemic belief. Hence, I adopted the terms "high surprise" and "low surprise".

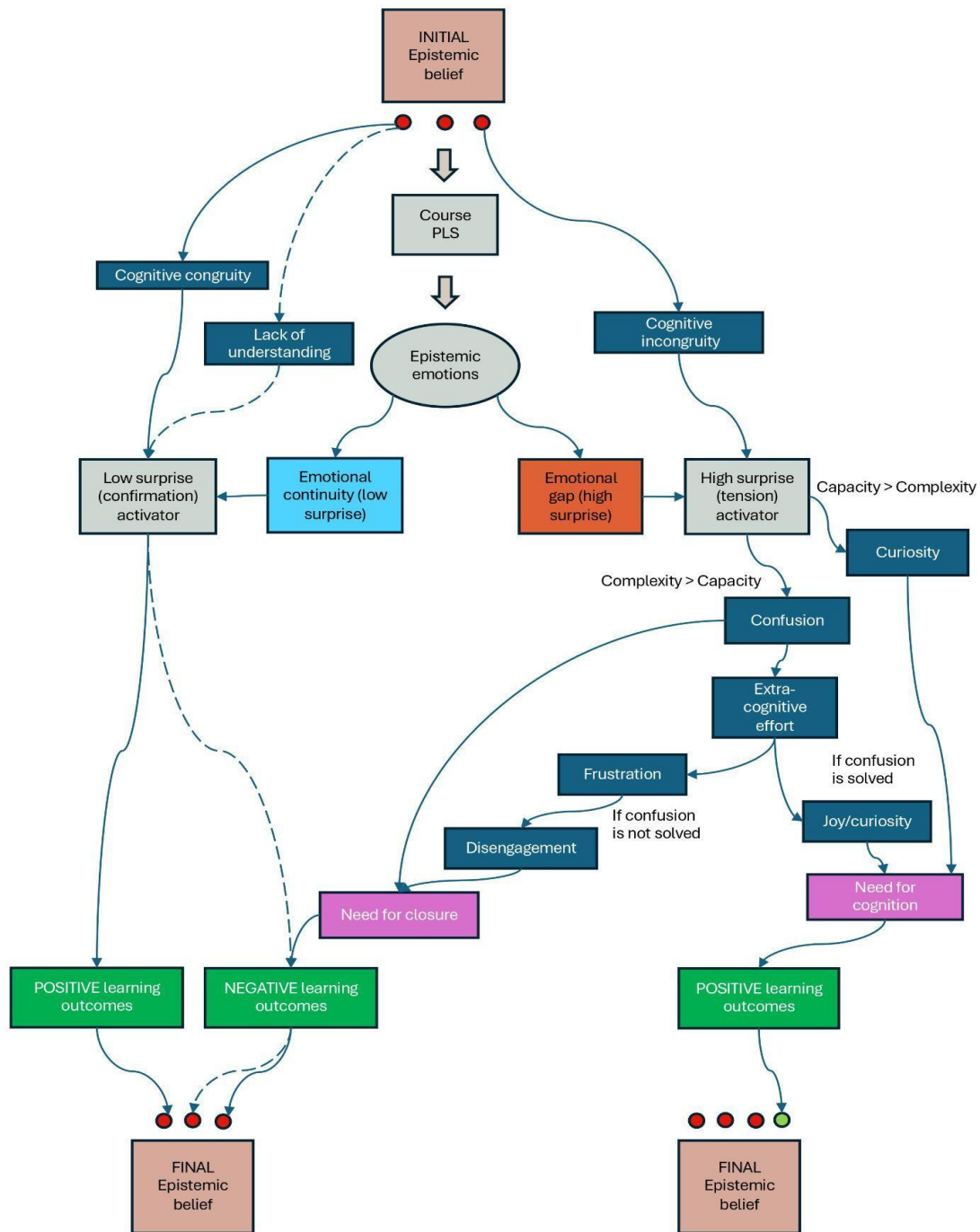


Figure 24: Revised structure of the theoretical hypothesis considering the “selective coding”. Tension and confirmation activators have been changed into “High surprise” and “Low surprise” activators. Also, the dynamics of the epistemic emotions suggested by the literature have been included to reach two possible conditions: the need for closure and the need for cognition. A further layer considering learning the new knowledge has been included before the final epistemic beliefs.

Therefore, the case of high surprise has been expanded by exploiting literature findings. Specifically, the balance between complexity of the new information (previously called also “epistemic element”, namely the activators of Section 5.2.2) and the perceived capacity to deal with that, determines the kind of emotions following the initial surprise. If capacity overcomes complexity, then an individual is likely to perceive curiosity, otherwise confusion arises (D’Mello & Graesser, 2011; Muis et al., 2018). Confusion can provoke different reactions. On the one hand, it activates a stronger cognitive effort to face the new information, which brings to joy and curiosity if the confusion is solved or to frustration and disengagement if the confusion keeps being unsolved. On the other hand, confusion may directly lead to underestimating the meaning of the knowledge, and also forms of misinterpretation and avoidance. These represent a “need for closure” displayed by individuals, which can be also the result of disengagement (Kruglanski, 2013).

If confusion may result in the need for closure, opposite to that is the “need for cognition” stimulated by epistemic emotions of joy and curiosity. As defined by Cacioppo and colleagues (1996), the need for cognition is the tendency of individuals to engage in and enjoy effortful cognitive activities, which is a stable trait that can also be stimulated by specific tasks and contexts.

Then need for cognition is positively associated to positive learning outcomes, which means an effective learning of the knowledge encountered. In this case, the knowledge provoked high levels of surprise because of cognitive incongruity, which has been addressed and solved leading to a revision of the epistemic belief in order to create space for the conflicting knowledge.

Alternatively, two possible situations can lead to the confirmation of the initial epistemic belief. On the one hand a low surprise due to either an initial lack of understanding or a cognitive congruity which correlates respectively with positive and negative learning outcomes⁴⁴. With this respect, I answer to question suggested at the beginning of Section 5.3.2. If the question is “Is the emotional gap necessary for understanding?”, the answer is that it depends on the epistemic belief and how the new content to be learnt is positioned with respect to it. Then in general, the emotional gap does not seem to be a necessary condition.

On the other hand, need for closure as a reaction to confusion due to high surprise, correlates with negative learning outcomes. Both the cases do not question the epistemic belief which is then left as it was initially.

For instance, SB seems to retrace the path on the right. An initial surprise concerning aleatoric uncertainty, due to cognitive incongruity. This surprise initially leads to confusion which is then solved provoking curiosity and satisfaction. She is then also triggered in a sort of need for cognition, with respect to other eventual topics and she seems to having deeply understood the meaning of aleatoric uncertainty, ending with a revision of her epistemic belief. It is also interesting to notice her reflections about what values within science.

⁴⁴ In the previous Figure there was also “Latent cognitive incongruity” as one of the options for the emotional continuity. The hypothesis of latent incongruity has been unpacked into the path: “emotional gap” -> “high surprise” -> “confusion” -> “extra cognitive effort” -> “frustration” -> “disengagement” -> “need for closure”.

TL instead seems to be positioned on the left side of the Figure, as it is confirmed in some aspect of his epistemic belief. Nonetheless, it remains still open the interpretation of possible reasons behind his misunderstanding of aleatoric and reflexive uncertainties.

The resulting theoretical hypothesis is then hybrid, data-driven (as it was developed in its backbone starting from the analysis of two case studies) and theory-driven (extended through literature). The aim of the present hypothesis is to be able to help interpret the two cases analysed but also the other seven profiles left out as “further data” (theoretical sampling). It is important to highlight the role of the theoretical hypothesis, which is not to explain how learning works in general but rather to *locally* contribute to interpreting some interesting aspects related to how students reacted to the knowledge presented in the course. In this respect, the hypothesis is a suggestion that must be checked and - if necessary - revised against new data. Thus, the next Section tests the narratives developed for the other profiles against the theoretical hypothesis presented in Figure 24 and discuss the related outcomes.

5.4 Phase four: Theoretical sampling

5.4.1 Empirical elaboration on the process of epistemic revision

To test the revised theoretical hypothesis, I dived into the other students’ narratives and I found three interesting profiles which display a similarity to the example of SB and contribute to validating that part of the theoretical hypothesis shown in Figure 24.

The first example is that of LA, which is interesting as it shows quite clear traces of epistemic belief revision.

Despite LA’s image of science is quite classic and close to the vision of classical mechanics, her epistemic belief appears to be “evaluatist” (Nussbaum et al., 2008), as she believes in the individual critical construction of knowledge. Her tendency is to create her own connections between topics as a way to make sense of scientific knowledge. She is used to setting this as a sort of challenge to herself that stimulates her while attending lectures.

Furthermore, she likes science as she feels a resonance between her succinct way of communicating with others and the scientific construction of concise, self-consistent explanations:

LA 01:15:07 *Yes, in general, yes, I feel that science subjects are a bit more mine because they are easy to understand, they are summarised because they don't need too many explanations, too many words and as soon as you see them you can understand them and usually when I speak or even how I express myself, it's quite concise and so let's say that I can understand them a bit more, in that sense.*

By actively creating connections and elaborating the contents, LA developed a sort of confidence and custom in dealing with knowledge, which resulted in a proactive attitude:

LA 01:30:09 [...] And new things don't discourage me, or ... (long hesitation). No, maybe they lead me slightly to think more and ...(long hesitation) and to interface more, expose myself more, just because I want to understand how something new works.

This is remarkably testified by the way she dealt with reflexive uncertainty. Reasoning in terms of epistemic emotions, her reaction is connotated by surprise and then confusion, because of a cognitive incongruity with her image of science.

LA 51:30 [the aleatoric uncertainty] Yes, *it seemed to me a bit further* from the path you were taking...

LM 51:42 But scientists are people in the end, and politicians are people in the end...

LA 51:45 yes, I know!

OL 51:48 And the behaviour of certain people in the face of certain.... as in the face of the pandemic the behaviour of people was a very important factor in the evolution of this virus. So even how people behave at Campi Flegrei⁴⁵ depends a lot on how one can adapt or mitigate... how one can adapt when faced with a situation of uncertainty...

LA 52:17 *Yes! I found it more distant from the idea of... physics, of science I had*

OL 52:37 Interesting...

LA 52:53 Yes because it seems more related to psychology, sociology but actually all fields of knowledge are related...

Still, in the course we often highlighted how scientific discourse is intertwined with political, social, economic and ethical issues, through the concept of reflexive uncertainty, the activity with volcanologists, but also studying IPCC, SSPs, etc.

Despite the initial confusion provoked by reflexive uncertainty, the course seems to also have created the conditions for LA to reconsider her image of science, and address the incongruity that emerged through that form of uncertainty:

FDZ 01:26:13 Two questions and then we're done. So it comes out a pretty clear idea of physics that you have, of discipline. And this course, in the light of everything, that is, how does it position... that is, how does it affect your image of physics? Does it question it? Does it leave it indifferent?

LA 01:26:45 Yes, it changes it, but perhaps for the better compared to what I thought before. Because it's not just doing calculations to see how something is going to develop, but it's also more related to more factors, including people. And so, yes, it changed my

⁴⁵ This is a large volcanic area in the Naples suburbs. It has been used for the fictional setting of the volcano activity in the third Lecture.

view of physics and I found it generally more interesting than the physics they make us study at school...

Her tendency was to connect aspects of science as a way to make sense of knowledge. Then reflexive uncertainty introduced humans and that felt a bit strange for LA, as she was not expecting to include humans in her “sense-making networks”. Still, the surprise was overcome due to her natural tendency to avoid closures but rather “*to think more and ...and to interface more, expose myself more*”. Hence, curiosity and interest (“*and I found it generally more interesting than the physics they make us study at school...*”) followed surprise, resulting in a more mature conception of science:

FDZ 08:37 *OK, so we kind of understood that you were expecting a few things, but not necessarily the things you saw.*

LA 08:46 *But they didn't penalise, because they were different things, so it wasn't for the worse but maybe it was even for the better. Because then I realised that the physics is not just what they show us, but it's also more?*

In this case, there are no elements underpinning the step “need for cognition” shown in Figure 24 (we will discuss later other cases with pieces of evidence of “need for cognition”).

In this sense, the course ‘opened the eyes’ and allowed LA to create connections between aspects that she could not connect before because for her they seemed to belong to two disconnected worlds:

FDZ 01:06:59 *And in light of all the course, of the game we've been playing etc. have you started to think a little bit about climate change or related aspects in a different way than before?*

LA 01:07:17 *Yes, slightly yes, for example, if I came across articles about climate change, I used to keep scrolling to look at other things, and now I dwell on it a bit more, because it's opened my eyes a bit more to this course anyway, and when you start to learn about something, to see other things that connect, it interests me... and so it's been useful.*

Overall, her epistemic belief is revised as her span of what science can entail is broader, hence she is able to make greater and more sophisticated connections (for instance activating links with sociological and political aspects which were initially inhibited).

The relevance of her epistemic belief revision is supported by her choice to share with her classmates some concepts she learnt in the course:

LA 01:09:14 *Our physics teacher just proposed that we do some research and the main points were engines, diesel engines, because we just did thermodynamics and he also added the*

point about climate change. And AC⁴⁶ and I immediately thought of doing it because we thought this course was very good, in general, and so informing and involving our classmates also seemed important to us. And even without this project proposal at school, I would still have liked to present what we did a little bit, because it can help to open up the vision a little bit more than (the) physics (taught) in the classroom.

LA appears to recognize the importance of her personal epistemic belief revision and she wants to share her experience with her classmates, with the hope that what happened to her might inspire also them. I argue with this that it vividly emerges here the consequence of the course experience, and specifically its epistemic part, on the identity dimension (this aspects are discussed in Section 7).

Also the cases of FC and CS show evolutions similar to SB and LA, indicating more clearly also traces of “need for cognition”.

CS's vision of scientific knowledge was similar to a world within which it is beautiful and stimulating to navigate and look for the solutions. It is comfortable and stimulating because sooner or later (even by dutifully following the teachers' instructions) one will always find the solution to the problem at hand, as the solution therefore always exists. In this sense she has a positivist view.

She is curious about new things even when they are difficult, as far as she feels able to deal with them and they fit with her idea of science knowledge.

However, when CS encountered the ontological uncertainty in the course, surprise emerged, followed by frustration:

CS	01:03:39	<i>[...] (the ontological uncertainty is) probably the one that surprised me the most. I think that time there, when you asked 'How do you feel?', I gave an answer, I said that it made me feel a bit powerless, the fact that... that is, that you can't know, but not because we can't, but because you just can't, and so. That had struck me very much, because it's something a bit strange, I mean usually, at least I wasn't very used to thinking about science, about these things, understood in this way. A slightly different way of...</i>
LM	01:04:31	<i>And how do you understand science instead?</i>
CS	01:04:32	<i>In the sense that at the level of uncertainty what comes to mind, in my opinion, is epistemic uncertainty, that is, you can't know because you have to measure but you don't know... and in that sense. And not instead that you just can't because you can't, that it's not a question of instruments. And no instead that aleatoric also struck me a lot there is the discourse that there is of the pinball or the fact, it was what you had done the thing of the pendulum.</i>
LM	01:05:08	<i>The double pendulum simulation...</i>
CS	01:05:09	<i>Yes the double pendulum.... and that even moving it a little bit then you get a completely different result, it's something that at first when one sees it can seem a bit</i>

⁴⁶ AC also joined the course but did not propose for the the interviews.

absurd, I mean it's hard to think about in my opinion. But yeah, so I would say those two are the ones that surprised me the most. So yeah.

Nonetheless, it emerges crucially the balance between complexity and capacity as a factor for transforming frustration into curiosity.

FDZ 01:05:30 *But once you feel powerless, the emotion afterwards is what?*

CS 01:05:35 *Mh perhaps even more curiosity, that is, wanting to understand better how it works.*

Although the two uncertainties do not fit with the initial epistemic belief, CS is stimulated by the challenge to face them and solve the tension, as she feels that she has the ability to do it. This is demonstrated also by the fact that she takes this challenge lightly and she is able to joke about the cognitive difficulty. Curiosity, in this case, seems to have led to an explicit “need for cognition” (“wanting to understand better how it works”), in the sense that now she recognizes that depending on the phenomenon to study, the thinking tools and reflections to activate can be different.

CS 01:07:20 *(the image of science) It's changed a little bit because there are still these two... these various aspects because anyway if one deals with phenomena like climate or things like that, we said that... or climate change, one has to take into account certain types of uncertainty rather than those that one takes into account when one talks about quantum physics, which is not the same thing as using a certain instrument to measure something. It is more different ways to approach different ... [...]. And instead, others like for example the climate that works like a pinball machine, like something that if you change even a little at the beginning then at the end you completely upset the result. So I don't know, depending on the subject, depending on the field, you reason a little differently...*

In this long excerpt, CS reflects on the image of science at the beginning of the course and what she defined as a new vision of science, where there is space for new uncertainties that require different reasoning strategies.

In the following dialogue, CS shows how the curiosity and the need for cognition ended up by revising the initial image of science, from “unique” to “varied”.

FDZ 01:09:24 *OK. Let's do an exercise... so your image you said has changed. Let's try giving one word for the image you had before and one word for the image of science you have now, shall we?*

CS 01:09:58 *Yeah, maybe it was a bit, like, unique before [...] And now a bit more maybe... a bit more varied, a bit more varied [...]*

FDZ 01:10:44 *And of a unique science that, let's say, doesn't leave you powerless, what do you do with it? How do you use a unique science that doesn't leave you powerless?*

CS	01:10:58	<i>No, I mean, in the sense that... it doesn't mean that you know everything but that you can go on knowing more and more.</i>
FDZ	01:11:10	<i>So let's say you haven't yet known this thing, uncertainty. You have an image of science, you need science for something, don't you? How do you use it? How do you use a science that has that image there?</i>
CS	01:11:32	<i>No, even just an idea of science that is related precisely to knowing aspects of our reality, discovering new things and then maybe making inventions, so something that always progresses like that and not that you get to a point where you say 'there's something wrong, there's something that we'll never be able to understand but because that's how it is', so...</i>
FDZ	01:12:11	<i>And then it turns out that science is different. At that point you as a person what do you do with that science there which is different?</i>
CS	01:12:17	<i>Mh... however you reach a point where even to know more you can no longer do it in the same way as before, but you have to go through this other way as well [...] So we can't ignore it, because otherwise we couldn't go on anyway. There would be many mysteries that would remain unsolved, but perhaps many things remain that are not known but could not be investigated without these, that is, without these new paths.</i>

The new paths mentioned at the end of the excerpt are the new strategies mentioned before that need to be used when facing new forms of uncertainty, such as the aleatoric and ontological ones. CS shares her intention to understand better these paths (need for cognition), displaying an enlargement of her initial epistemic belief (there are problems for which is not possible to find a solution).

FC's narrative also shows indications of a "need for cognition" activated by the forms of uncertainties. She started with a sort of "absolutist" epistemic belief, showing her fascination for the Universalism of physics laws. She also is very confident with Physics (she intends to enrol in that Bachelor's program in two years).

When she encounters aleatoric uncertainty she feels curiosity, as it questions her initial belief,

FC	08:33	<i>Let's say, however, that also the fact that there are all these things that we actually think we know but we don't [...] makes me a bit curious, and so that's what I think is the fact that all these uncertainties are a bit like that... They call into question what is being studied.</i>
FDZ	09:09	<i>That is?</i>
FC	09:11	<i>That is to say, everything we study at school, I said earlier that we take things very standardised and we take everything for granted, in inverted commas, even the teachers always tell us 'you don't understand this, but you take it for granted'. And instead we have seen that it is not always the case, that something is just so... but we have seen that the climate being a complex system, it can be one way or another. And so that made me a bit curious.</i>

Curiosity drives the desire to learn more about ("need for cognition"):

OL 01:06:13 *Any other moments where you felt particularly comfortable? Where you've said 'Here are really, there are really moments where I've had the feeling where you say "I feel, I feel myself in these things, I mean it's touching me on some deep chords".'*

FC 01:06:35 *In the second lesson, when we talked about the various uncertainties, even though I might not have understood everything. However they were things that I was curious about, and I liked them. And so they almost excited me a bit, I wanted to find out more about these things.*

also due to a great self-perception of the capacity to understand scientific subjects in general,

FC 01:07:19 *When it comes to subjects that I don't care about, like art history, even if I know something, it's not like anything moves in me. On the other hand, when it comes to subjects like physics or biology, it's just the fact of learning new topics that I like as a thing to do. [...] For me, more than anything else, it makes me curious, that is, trying to actually understand what is going on, even if you may not come to a real conclusion in the end. [...] it makes you want to know more. That is, maybe even try to discover new methods. That is, something that we, for example I don't know the atom comes to mind, that was thought to be indivisible. Instead of thinking that it is, trying to find out more about that subject, and then maybe even being able to contradict something that you thought up until then.*

FC is well aware of her “need for cognition” and that it could lead her to revise what she used to think, as it happened in the course:

FDZ 01:14:04 *OK. And, in conclusion, compared to the course and precisely to your image of science, of physics, how does it come out?*

FC 01:14:31 *Maybe a little bit changed, because at school we never really dealt with uncertainty much, so I thought it was all very, you know, it's just the way it is, and that's it, it's already established, but doing the course I found out that not everything is just one way, but there are various ways of looking at it and of being, in quotes.*

5.4.2 Empirical elaboration on the process of epistemic confirmation

I suggested above the intention to test an eventual “need for closure” within TL’s narrative.

Despite the lack of elements to inquire about the presence of “need for closure”, one argument can be used to support such interpretation.

In the following excerpt, TL reports a perfect explanation of the difference between aleatoric and ontological uncertainties, when first asked about:

TL	58:09	<i>[...] Then the aleatoric uncertainty where the agent of chaos acts, that is, if we take two situations A, but the second situation A, which now becomes situation B, we change it slightly, even minimally the initial situation, it can lead to completely different consequences given a certain period of time. For example, if now instead of walking out this door, if instead of staying here and talking to you, I walked out this door and ran away, who knows in fifty years maybe aliens will come... I don't know something like that. But it would describe the big difference in the distance of time, based on simple choices made now, which could also be stupid choices such as 'Today I'll have tea, and tomorrow I won't!' While the third, ontological uncertainty, I like to describe it as the universe telling us 'No, you can't know this, sorry'. Above all, we talked about the Heisenberg uncertainty, about how you can't know... I always remember it in English, "the momentum and the position of the same object at the same time", because if you know the momentum or the velocity of an object automatically you don't know the position, you can't know both at the same time, firmly the Universe doesn't allow you to.</i>

It is striking to see such a detailed description of two uncertainties, recalling also the uncertainty principles, followed a few lines below by these words,

TL	01:02:06	<i>... I see the aleatoric uncertainty, whereas in the name it is an uncertainty based on chance and then in the end it is also represented of the cup of water in a certain sense, but it is still a statistically based uncertainty. The aleatoric uncertainty, the water cup, because in the end the water cup is a aleatoric system at least as I conceived...</i>
FDZ	01:02:35	<i>Why is it an aleatoric system?</i>
TL	01:02:36	<i>Because you can't predict how molecules will go unless you study each molecule individually, you can't predict how things will evolve. It's purely left to chance in that sense, because you don't know where molecule B or molecule A might go if you just look macroscopically.</i>

TL is interpreting the aleatoric uncertainty as a statistic issue, despite he just reported a correct definition based on the impossibility of prediction as characteristic of deterministic chaos. What seems emerging from his profile is that he really understood the differences between the uncertainties, without questioning his initial epistemic belief. This may sometimes lead to confusing argumentations (as the one above) which try to combine the old epistemic belief and the new knowledge (framing in terms of prediction difficulties instead of impossibilities).

Considering the other narratives, three other cases appear to support an epistemic confirmation.

The first one is RF. His epistemic profile is characterized by three key aspects:

- 1) RF is aware that science does not produce absolute certainties, which means he is not an absolutist. He recognizes that scientific knowledge consists of the "least uncertain" conclusions based on evidence, and he is comfortable with the inherent uncertainty in scientific processes.

- 2) RF relies on scientific information because it helps him understand what to think and do in various situations. For him, science is the most reliable guide for making decisions and navigating the world. It provides a framework for interpreting reality and shaping his actions.
- 3) RF positions himself as an external observer of knowledge. He accepts scientific facts even when he doesn't fully understand them, trusting the authority from which they come. His faith in scientific expertise allows him to adopt a passive role in the learning process. This lack of full comprehension doesn't seem to trouble him; he feels calm and unbothered by the idea of accepting things "as they are" because they are endorsed by those with greater knowledge.

Concerning the course experience, he reacted in diverse ways, especially towards uncertainties.

The epistemic uncertainty is completely congruent with his epistemic belief, so he feels an epistemic emotion of "confidence":

RF 01:34:34 *Actually even the question of uncertainty, particularly the epistemic one, the aleatoric one I more or less talked about it earlier, but the epistemic one, that **also seemed quite close to me**, in the sense that it still concerns what... let's say more the acquaintance than the known...*

The ontological uncertainty instead provokes surprise, indicating a cognitive incongruity, even though he demonstrates a correct comprehension of the basic meaning of the uncertainty principle:

RF 01:04:08 *So let's say what I understood of this uncertainty here is that when I go to know one of the two things, of the two parameters that can be known, now I do not remember what they were, however, is not that I can not know the other for a defect related to my instrument or something like that, but rather because the object changes completely and **I did not expect** that there could be something like that. I expected more instead that all, how to say the errors, the uncertainties, the various things were more due to the method of how I know the object.*

He acknowledges the incongruity and does not seem to refuse it, but at the same time, he realizes the lack of instruments to fully understand the core message of ontological uncertainty and solve the cognitive incongruity.

RF 02:44 *[...] Then, from the point of view of the more... those lessons at the beginning of the uncertainty, those things there, if I have to be honest, it's not that I understood so much, I tried, but I tried a lot of things, how can I say... But they were things that I had never even heard of in my life, really zero. Maybe someone who has done a scientific high school, however much he is, at least has a vague idea, that's it.*

With respect to Figure 24, this uncertainty seems to activate a high surprise, followed by confusion because the complexity is greater than the perceived capacity. Hence, even if he admits that he did not understand, RF does not show an extra-cognitive effort but rather accepts what has been presented to

him (as he is used to doing in these cases). There are no elements to fully state a form of closure, but on the other hand it is quite evident the lack of “need for cognition” and revision of the epistemic belief.

Reflexive uncertainty is particular as it provokes both emotions of surprise and confidence:

- LM 01:05:18 OK. And what about reflexive uncertainty so the one related to human behaviour, how did you see it as uncertainty related to climate change, is that something that surprised you? Something you expected?
- RF 01:05:35 No, I actually expected it quite a bit, in the sense that in the end climate change, at least the one we're talking about, is man-made so...in the sense, it seemed to me, I mean I imagined it to be something very present and important as a type of uncertainty.
- RF 01:06:12 And then actually inverting the optics, so looking at it more from the point of view of a scientist who has to understand how they work, how to say... that is, he has to foresee how the situation will evolve actually makes me more strange the reflexive uncertainty because anyway it seems to me, at least for the idea of science that I have, there is hardly ever man involved and what his impact on reality may be directly.

In this case, we have no elements to argue what are the consequences of surprise, whereas the confidence felt confirms the left side of the mechanism displayed in Figure 24. As a consequence, the consideration of humans as a variable is reinforced (positive learning outcome).

Finally, the case of aleatoric uncertainty is quite interesting as it resembles the example of TL discussed previously. RF indeed seems to misinterpret the meaning of aleatoric uncertainty by associating that with the epistemic one:

- RF 01:01:42 The epistemic one and the aleatoric one I more or less vaguely imagined. In the sense that one related to the way of knowing things, the other related to the fact that there are so many things to know,

or

- RF 01:43:16 [...] this aleatoric uncertainty, the discovery of this aleatoric uncertainty has not had a particular effect on me because in practice I had already been unable to know the system due to epistemic limitations, so it has not particularly influenced me in that sense
- FDZ 01:43:57 Of course, but if I may say so, Pietro, if I know that I cannot know something because I cannot, that's one thing, but if I know that I cannot know something, not because it's up to me, but because that's how it is, that's another. I mean I feel a certain kind of sensation at that point maybe you feel another.
- RF 01:44:21 Yes and no in the sense that maybe the fact that... Actually, yes, the fact that, even in theory, you can't know that thing there, has surprised me a little... from a point of

view, how should I say, *astonished me, I didn't expect it to be something that, in theory, could be applied to anything, more or less. But in practice, like I said, it didn't really affect me that much*, so I actually thought about it...

This seems to be then a need for closure stronger than the previous one: at first, RF is surprised, but in the end, it forces aleatoric epistemic to “fit” into his epistemic belief by distorting its meaning, closing the sense of confusion. The narrative of SN is then interesting as it provides an example of how the absence of an emotional gap can be an indicator of a lack of learning. Her epistemic belief is absolutist as the whole Universe can be explained by the laws of Physics. Nonetheless, SN accepts and accommodates scientific knowledge as she manages to relate that with her own reality, what she experiences every day.

Starting with such epistemic belief, she is however not surprised by the forms of uncertainties presented in the course, but rather fascinated. When then asked to comment on the differences between them, she expressed in this way:

SN 47:17 *Then we saw three types of uncertainty I think, so epistemic uncertainty which was that concerning episteme therefore knowledge and the very act of knowing. Then we saw the ontological uncertainty which was instead linked more to knowledge therefore to essence, to reality, that is, to the knowledge of reality. And the aleatoric uncertainty which instead was the more aleatory therefore the more random uncertainty, the one we normally have. I was fascinated by the whole subdivision of this part, which I had never seen before, and therefore by the fact that there was not just one uncertainty, the standard uncertainty that we all know, which I think is the aleatoric one, but there are also other uncertainties, and therefore the epistemic uncertainty and the ontological uncertainty.*

She shows her misunderstanding of aleatoric uncertainty, replaced multiple times with the epistemic one. The lack of emotions of discontinuity seems then to be due to misunderstanding, which therefore does not challenge the epistemic belief.

As a consequence, she does not seem to have revised or questioned her initial epistemic belief.

There is also another interesting yet different mechanism of confirmation, displayed by FC. Previously, I discussed how FC was showing evidence of need for cognition, as the final step of an initial cognitive incongruity triggered by aleatoric uncertainty.

However, FC displays also a form of cognitive congruity. She has indeed the belief that science can be used to identify ethical forms of agency (that in her case means for instance becoming vegan). In the course, we stressed multiple times how science is connected to social, political, and ethical aspects, and the game was thought of as a context for training in balancing the different dimensions around sustainability (besides the technological aspects).

This connection between science and ethical issues is in agreement with FC’s initial epistemic belief, but the course seems also to have sustained and developed that positioning, making it more critical and mature.

For instance, commenting on her awareness of a needed shift in humans' mindsets, with respect to sustainability:

- FC 32:27 *Yes, I mean that it stems from these studies, that is, a bit like what happened for me during this course that I became more aware of the problem and that therefore also always concerning the game, I realised that there are certain things that have to be done in a way and that it is not easy to do them looking only at the ethical side of the situation.*
- OL 32:54 *Go on. In what sense the ethical side?*
- FC 32:55 *That is, precisely, the protection of the environment. So to stop using fossil fuels overnight, or to stop all intensive training and stop using planes because they pollute, these things here.*
- OL 33:14 *These things here, what did you realise during the game?*
- FC 33:16 *That it's a bit more complex to do it than I thought before, because we saw that there would be a lot of economic crisis, eh...*

Previously, only the ethical side was considered (still something beyond the pure technological aspect) but now she feels a sensibility also towards the social and political aspects.

- LM 34:20 *But still, you said that you have read several books before, it is a theme that you feel is yours, no? In the sense that you feel close to it, you said. And this reasoning had not been activated?*
- FC 34:26 *No, because before I was looking at them from the ethical point of view rather than from the social point of view, and what could have happened if these actions had been carried out.*

She used to examine the political dimension, but with less consciousness, leading to forms of disengagement:

- FC 59:52 *Let's just say as I said before in some ways in the same way for others a little bit changed mainly from the point of view of the decision-makers. Maybe I try to put myself in their shoes a little bit, understand why they took certain decisions instead of others that perhaps from the point of view of climate change would have had more effect.*
- FC 01:00:42 *(Regarding COP28) I didn't follow it, I heard before that they were talking about it but I didn't follow much what they were saying, so I don't know. But I do know, like, that the Arab countries gave the OK to decrease the use of coal and so that's a good thing, but at the same time even there maybe if they had said no I would have tried to understand a bit more why they said what they said.*
- FDZ 01:01:13 *Whereas before you wouldn't have asked that, you say?*

FC	01:01:15	<i>I used to say they just wanted to get richer and richer and who cares, in a nutshell.</i>
LM	01:01:24	<i>And do you think this change is important? I mean how do you perceive it?</i>
FC	01:01:29	<i>Yes in my opinion it's quite important anyway as a thing and let's say, how do I perceive it? I really perceive myself as grown up in quotes mentally.</i>

Hence the course and the game were a context in which she felt empowered in her critical ability to evaluate the socio-political issues related to scientific aspects:

FC	01:04:30	<i>[...] I mean, probably even here, when we have seen that climate change leads to a social uncertainty - yes to a, oh God I can't think of the word</i>
FDZ	01:05:50	<i>Uncertainty you mean?</i>
FC	01:05:52	<i>No. Inequality, here I don't get it, social. And exactly that also has done nothing but increase this sense of identity of mine in quotes, I don't really know how to put it. I mean in the sense, that, I know I made the right choice (being vegan, not taking the plane, etc.).</i>

5.4.3 Other

The last two profiles do not provide enough elements to claim for revision or confirmation, but they confirm again the mechanism “surprise -> confusion” illustrated in Figure 24.

GV's profile shows traces of confusion in front of the aleatoric uncertainty. GV conceives scientific knowledge as a way to explain practical issues of reality, and when she is able to see herself some applications of the concepts studied she feels more included in the scientific discourse. Besides this, she shares with CS a positivist belief, relying on the ability to find a solution anyway.

However, when she realises that no matter how hard one tries, there are certain cases with no exact solution, the first epistemic emotion is fascination (a positive surprise) but then fear and frustration emerge:

GV	54:55	<i>Both at the level that, at the positive level because... it's nice, well, it's still fascinating that not only at the mathematical level there is uncertainty [...]. At the same time, however, it frightened me a little bit because from one uncertainty, the uncertainty triples and then... From a certain point of view, it discourages me, the fact that it is there... it gives me less certainty there. It's not totally a bad thing, but having less uncertainty - less certainty is definitely a bit destabilising.</i>
GV	57:04	<i>Yes, but in my opinion it's different, because... the unpredictability, I see it very much as something negative, that is, the fact that I don't know something gives me anyway,</i>

gives me the drive to be able to try to explain it. On the other hand, the fact that something totally unpredictable can happen, scares me a little bit.

Thus, GV feels a strong form of incongruity which fascinates but more evidently frightens and confuses. However, even if GV shared in the interview her tendency to be anchored in her belief and determined to find anyway an explanation, there are no elements to claim a form of closure as a potential consequence of confusion.

This is also the case of MD. His epistemic belief conceives scientific knowledge as something which can be controlled and oriented. The knowledge is seen as something close to himself as far as it is controllable. He indeed expresses this way, when commenting on the reactions following the presentation of aleatoric uncertainty:

OL	01:08:18	<i>Something that makes you angry about science, if you think about science, something that touches your nerves of discomfort.</i>
MD	01:08:32	<i>Many things are not directly controllable, or modifiable. On the one hand, it can be fascinating, but sometimes it can still be frustrating, or create... However not to be, it may not create positive feelings, in general.</i>

Initial fascination, but then frustration becomes dominant, witnessing the effects of cognitive incongruity.

MD	01:09:22	<i>That is, from a certain point of view it is fascinating that it cannot be controlled. But if for some reason it could be useful for us to act on it, it is frustrating not to be able to do so.</i>

Anyhow, also in this case there are no elements to infer potential consequences to the emotion of confusion, even though the final belief seems neither questioned nor revised.

OL	01:23:20	<i>May I? I am curious. When you talk about scientific knowledge, OK, you can use a lot of adjectives. I'll tell you a few, can you tell me which ones seem closest to, which you like best to define it? Efficient, elegant, useful, objective, consistent, rigorous, practical, shared, true.</i>
MD	01:23:53	<i>could you repeat the first three?</i>
OL	01:23:56	<i>Efficient, Elegant, Useful. Efficient, Elegant, Useful, Objective, Consistent, Rigorous. Shared Practical.</i>
MD	01:24:08	<i>Maybe efficient, useful, practical...</i>

6. Discussion

The theoretical sampling step allowed to get extra elements to check and refine the theoretical hypothesis displayed in Figure 24.

First of all, neither the seven new narratives examined nor the two initial ones provided elements supporting the hypothesis of extra-cognitive effort as a possible consequence of the emotion of confusion. Sometimes confusion led directly to forms of closure (RF and TL), sometimes it was solved leading to curiosity (SB or LA) without evidence of extra cognitive instruments exploited. In three cases (MD, GV and RF⁴⁷), there were not enough elements to argue what happened after confusion came out.

Again linked to confusion, it does not seem to hold the functional role of the balance between complexity and perception of capacity. Whenever confusion is detected, it is an extension of the initial surprise; in the narratives examined, confusion is due to the cognitive incongruity between epistemic elements (almost all the time they are forms of uncertainties) and their initial epistemic belief. None of the profiles show instead episodes of confusion due to an unsuccessful evaluation of own's capacity with respect to the complexity at stake.

However, the balance between complexity and perception of capacity seems to hold in the case of curiosity. Considering as examples LA, CS and FC, it is visible how confusion has been managed and transformed into curiosity thanks to a high perception of capacity. These three profiles share a natural tendency to be active builders of new knowledge (the "sense-making networks" for LA, the navigation through contents for CS and the excitement of FC for new content to learn and deepen).

To some extent, they have in common a sort of "need for cognition", which is then re-activated in this case while the forms of uncertainties are faced with joy and curiosity. Still, in all cases where curiosity emerged, also some traces of "need for cognition" have arisen. In particular, the "need for cognition" is visible only in those cases where already the epistemic beliefs were manifesting more advanced learning strategies. This confirms how the need for cognition is a stable trait that activates under specific conditions (Cacioppo et al., 1996), rather than an emergent property.

Thus, focusing on the narratives of RF and TL, they highlight an interesting possible refinement for the structure of Figure 24. RF (more explicitly than TL), shows how confusion (in his case regarding aleatoric uncertainty) was easily addressed and "solved" (through a closure), hence leading to an emotional continuity and a problematic and confused learning. Therefore, when analyzing the epistemic emotions associated with an epistemic element it is crucial to trace back how they emerged: they could be a result of the first interaction or outcomes of learning strategies (as in this case).

Linked to the "need for closure", the narratives examined do not show evidence of the path connecting confusion and the need for closure through frustration and disengagement (this path was in fact suggested by the literature). The forms of frustration detected were connected to the confusion activated by the cognitive incongruity and reflected the resentment of having the epistemic belief deeply questioned.

Also, the example of FC also appears to suggest a possible extension for the initial theoretical structure. In her case, she felt a congruity between her "ethical connotation" of science and the many activities of

⁴⁷ RF appears with a twofold option here because different forms of uncertainties provoked different reactions following confusion. The epistemic emotions indeed are related each time to a unique epistemic element.

the course focusing on connecting science with socio-political, economic, and ethical issues. Such congruity confirmed her epistemic belief but also developed it as she revealed a more mature and critical position towards science, including social and political aspects besides ethics. This episode is noteworthy since it opens the possibility to connect cognitive congruity with epistemic revision; indeed FC's congruity allows her to go beyond confirmation towards an expansion of the epistemic belief (with outcomes similar to SB, CS, etc.).

In addition, it must be highlighted the difficulty for at least 4-5 narratives (GV, MD, TL, RF) to clearly understand what followed the initial epistemic emotions, advancing the need to reflect on what kind of data can be collected to further examine these or further profiles.

To conclude, it is worth considering the kind of connectors used in Figure 24. Initially, I suggested all arrows, meaning a sort of "implication" grounded both in the two case studies and in the literature discussed. However, the theoretical sampling brings me to confirm this interpretation just for some of them. The arrows remain indicators of implications in the case of:

- emotional continuity/emotional gap -> low surprise/high surprise
- high surprise -> curiosity (when mediated by a positive balance between capacity and complexity)
- curiosity/confusion -> need for cognition/need for closure
- cognitive congruity -> positive learning outcomes
- lack of understanding -> negative learning outcomes

For what concerns the connection "high surprise-> confusion" this has been discussed in light of data and rejected. Also the implications "need for cognition-> positive learning outcomes" and "positive learning outcomes -> epistemic belief revision" seem quite delicate, because of the difficulty of assessing learning through these data (it is indeed way easier to check for lack of understanding, as shown in the cases above, rather than evaluate if and to what extent learning occurred). According to the data analysis I feel just confident in saying that it seems to be a concomitance of "need for cognition" and the lack of explicit traces of misunderstanding. According to this point, the solid lines have been transformed into dashed lines (indicating hypotheses to be checked).

Hence, the new revised version of the theoretical hypothesis is shown in the Figure below.

The humble theoretical hypothesis suggested, emphasizes the cruciality of epistemic belief and epistemic emotions. The main core of the structure revolves around epistemic emotions, which are a product of the interaction between students' epistemic beliefs and the epistemic elements presented in the course.

From Figure 25, it is interesting to notice that epistemic elements such as the aleatoric, reflexive and ontological uncertainties, which bring forms of epistemologies radically different from those characterising classical mechanics (predictability, realism, determinism, linearism), can be beneficial in activating what Bendixen calls the "epistemic doubts" (Bendixen, 2002). These epistemic elements are often associated with confusion because of a cognitive incongruity with the epistemic belief.

It is emerging indeed that these forms of uncertainties were the starting points for some epistemic belief revisions, mediated through curiosity and supported by the activation of the need for cognition. Considering these, the choice of having centred the course and the game around them appears as positive.

The theoretical hypothesis suggested also illustrates the importance of studying what kind of epistemic emotions emerge and how, a process in which epistemic beliefs play a fundamental role. Indeed some forms of "emotional continuities", which can be seen as forms of closure and negation, may be instead evidence of cognitive congruity. Nonetheless, as Figure 25 hints, also the forms of emotional continuity are worthy to study, as they can be the premises for an epistemic development which ultimately may end up in an epistemic revision (as FC suggests). This last point in particular suggests a possible extension of the mechanism discussed by Muis and colleagues (2018), calling for deep insights also in the case of cognitive congruity, keeping the attention on the specific features of the initial epistemic belief.

One additional point, which I advance timidly due to the totally inadequate sample size, is the potential effect of gender. Indeed, the cases of confirmation (TL and RF) are two males whereas the cases of revision are all females (FC, CS, LA, SB). For the other cases: MD does not show evidence of confirmation but it shows a strong solidity of his position and repeats several times the importance of control in his way of dealing with scientific knowledge; SN shows confirmation but is due to a lack of understanding rather than a resistance in her belief; GV does not present enough element to claim for confirmation or revision. Anyway, the males' profiles seem to not question their epistemic beliefs whereas females seem to be more open to accepting the incongruities and addressing them by revising their initial epistemic positionings.

6.1 Considerations around the theoretical hypothesis test

The theoretical hypothesis illustrated in Figure 25, as tested within a limited empirical domain, demands a few considerations.

As Anfara and colleagues notably argue in their paper (Anfara et al., 2002), evaluating the validity of a qualitative theoretical structure requires a shift in the criteria used to assess quantitative data analysis. For this reason I will now consider the assessing categories presented in that work as a way to test the theoretical hypothesis shown in Figure 25.

- I. Long-term observation and engagement in the field: as discussed above, I was present at all the lectures together with Lorenzo, sometimes as a teacher, sometimes as a tutor, sometimes as an ethnographical observer. This constant participation and observation of the students (over roughly 2 months), helped me to develop a personal connection with most of them, again reinforced and carried on with the interviews in the following month.
- II. Peer debriefing: the first version of the structure (Figure 24) was discussed and triangulated with two different Research Groups, whereas the second version has been also discussed and triangulated with the Bologna PER Group.
- III. Triangulation: the narratives at the basis of the theoretical hypothesis construction, have been developed by considering multiple forms of data (questionnaires, in-group recordings, comments during the lectures, personal conversations and the interviews). Also, they have been enriched by the notes I took while observing students in class, the collective notes elaborated at the end of each interview session among me, OL and LM. Furthermore, the theoretical hypothesis has been also triangulated with elements coming from the literature, as discussed in Section 5.3.
- IV. Analysis of negative cases: when I first came across the interesting case of SB, which can be considered the starting point of the whole analysis, I knew that her evolution could have not been taken as a reference. The deep examination of TL's case then allowed to develop the initial structure of the theoretical hypothesis acting as a "negative scaffolding". In addition, once the first version was structured, this was refined and changed (disconfirming certain hypotheses) according to the new data analysed.
- V. Thick description: because of the qualitative nature of the analysis, I tried to add as much description as possible about the context of both the course and the interviews. In this respect, I also added the complete questionnaire and the interview protocol in the Appendices, including an example of how we asked students to comment on specific excerpts from the recordings.
- VI. Audit trail: in order to report as transparent as possible the outcomes emerging from the data analysis, I decided to add detailed descriptions of the design at the basis of the course (Section 2) and the game (Section 3), how the research objective drove the design of data collection and how the first data were considered to design the second data collection (Section 4), how data have been synthesized and arranged (the narratives in Section 5.1), the different analytical steps done (Sections 5.1, 5.2, 5.3 and 5.4) and how they are interconnected. For the sake of clarity, I also decided to constantly visualize the structure of the result of data analysis showing the multiple stages of the theoretical hypothesis' evolution.
- VII. Reflexivity: I am conscious that my research objectives led me to focus more on some aspects and neglect other possible foci of attention. Nonetheless, since the beginning of the Chapter, I clarified my intentions, mentioning also how other analyses have been done (more related to LM's research question) and that other interesting results may have come out.

Nonetheless, I have to reckon with a possible criticism. One could indeed argue how can I claim that the "initial epistemic beliefs" are really initial, based on the fact they have been reconstructed upon data collected *at the end* of the course. This certainly is a weakness of the data analysis, which must be addressed for the next implementations.

However, I claim that also the way we designed the interviews (aware of this possible risk) facilitated a distinction (first of all for students) between what happened until the course, during the course and after the course. Recalling Appendix C, we started with general questions, without even mentioning the course; then we addressed all the details of their experience (course, game, etc.) asking at the end to recall their initial positioning and comment about possible transitions or confirmations. This, with the specific aim of examining the process, without the assumption of having changed students' minds but with the curiosity to inquire local and epistemic-related shifts.

7. Conclusion

The theoretical hypothesis discussed and shown in the previous Sections, together with the narratives elaborated, appears to provide a sound answer to the analytical questions formulated for the course, introduced at the beginning of the data analysis:

- *What were the students' initial personal epistemic positioning at the beginning of the course?*
- *Were there any evolutions of these personal epistemic positionings?*
- *How did the course and the game enable and support this evolution? Is it possible to develop an explanation or a local theoretical hypothesis?*

In particular, having designed a course around uncertainties, to question the primacy of epistemic uncertainty and deterministic and positivist epistemology, produced interesting examples of cognitive incongruities. As discussed, the epistemic beliefs and other factors (such as the perception of capacity) determined then diverse paths of evolution, towards respectively a little shift in the epistemic belief or to forms of closures and confirmation of the initial epistemic belief.

Nonetheless, recalling students' words, the way uncertainties have been presented also played a role in such mechanisms. They were indeed not only introduced in lectures but they were embedded as structural elements in diverse activities (the volcano one and the game, for example). Students indeed referred that epistemic emotions with respect to uncertainties emerged in all these occasions, with the chance to not only learn the concepts but also to “feel them” (see Chapter 4, Section 3.1.2).

In general, as I tried to report in the Design section, we aimed to create a context where forms of physics epistemologies different from the standard one were available. I claim that this width of possible positionings perceived in the course created the chance for two positive emerging results:

- Cases of cognitive congruities (as TL or FC) which, as students also admitted, rarely happen at school. Students indeed may have epistemic beliefs developed and supported at school, or developed autonomously despite school, which usually proposes a normative epistemology. In the examples of TL and FC, part of their epistemic beliefs ended up being not only confirmed but also developed and they had also higher awareness of that.
- Cases of cognitive incongruities, which led to revision and development of the epistemic beliefs. Having created the condition for a clash between students' epistemic belief and new disciplinary concepts, but at the same time avoiding judging this incongruity and being always supportive and open, led to finally achieve a more mature epistemic belief (Muis et al., 2018).

8. Connection with the theoretical construct

This Chapter had the objective to address RQs concerning the ongoing reflection on the link between identity and the cognitive-epistemic core of scientific disciplines, and the role of epistemic emotions.

As regards RQ II.3 (*To what extent can the forms of uncertainty trigger epistemological-personal consonance?*), the narratives discussed previously show evidently the role of aleatoric, ontological and reflexive uncertainties in activating forms of cognitive dissonance. Due to their intrinsically questioning epistemology, students were surprised and felt epistemic doubts when trying to make sense of them through their epistemic beliefs.

Such forms of incongruities (or less frequently congruities) can be indeed interpreted as episodes of dissonances (or consonances) between the epistemic core of uncertainties and students' identities. As argued in Sections 4 and 5, epistemic beliefs are related to one's personal self-positioning with respect to scientific knowledge and its construction. In this sense, they are heavily informed by personal traits and experiences, namely identity. But also the opposite holds, since the dynamics of epistemic beliefs about scientific knowledge (which may be confirmed or questioned and even revised by experiences) informs how individuals evaluate knowledge construction in general, with unavoidable consequences on the way they act in society (again identity-related aspects).

Thus, based on the outcomes discussed, I claim that those three specific forms of uncertainty are quite likely to activate episodes of personal-epistemological consonance/dissonance.

For what concerns RQ IIa.2 (*In the PLS course, what does emerge concerning the potentiality of the 4-layer scheme in supporting identity development?*), the two previous studies showed interesting aspects. Within "Physics of Clouds" I started to recognize the importance of both cultural and disciplinary frameworks in creating the conditions for self-expression of students. This impression brought to the formulation of RQ IIa to address in Chapter 4 (*To what extent does a particular way of teaching physics concepts activate personal-epistemological consonances/dissonances?*). Hence, the Kairòs project provided new evidence of the crucial role that design principles may have in activating personal-epistemological consonances. In Section 3.1.3 (Chapter 4) I described more in detail the design structure characterised by 4 layers related to four dimensions (contents, science functioning through contents, content-based thinking, thinking-based agency). The analysis of the material collected in that project illustrated how steps 2,3 and 4 of the 4-layer scheme created the premises for students' personal reflection about how they struggle with normative forms of time and how they are seeking forms of time suitable to them. In particular, the design principles named "*Experiencing the contents: time*" and "*Experiencing the contents: complexity*" set a context where to "feel" the disciplinary nuances of the four images of time and relate with them, disclosing personal issues (see Section 4, Chapter 4 for details).

Grounding on these valuable experiences, we wanted to keep investigating the role of the 4-layer scheme, this time focused on different disciplinary concepts (uncertainties). Thus, to answer RQ IIa.2, I briefly introduce two other analyses we did with LM on the same data used previously (recordings, questionnaires, interviews, and individual notes).

In the first study, we did a thematic analysis to assess the impact of the course on students' understanding of decision-making in policy-making. In particular, we first identified 9 themes through a thematic analysis

(Braun & Clarke, 2006) and then categorized the data with those themes to evaluate thematic patterns (Miani et al., *major revisions*). The main goal was to evaluate how students' understanding of climate policy negotiation complexities and their appreciation for incorporating social and environmental justice in decision-making evolved through the course. The analysis indicated that students showed an increase in the awareness of the complexities involved in policy negotiations, acknowledging the importance of balancing various socio-ecological factors. Additionally, the game-based approach fostered a deeper appreciation for the need to incorporate justice and diverse stakeholder perspectives into decision-making. Overall, the study revealed that the way in which we implemented the future-oriented science education approach, particularly using scenarios and the game, can effectively enhance students' capability to recognise and address sustainability challenges.

In the second study (De Zuani et al., *submitted*), we focused both on the scenarios produced by students' groups in the game and on the processes at the basis of their construction. The study aimed to explore how the game FyouTURES could help students shift from linear and reductionist thinking to more systemic and comprehensive approaches to sustainability. Specifically, the objective was to identify how "harmful hope"—overly optimistic but unrealistic expectations about environmental solutions— can emerge but also how it can be identified and anticipated. The analysis, conducted through qualitative methods, revealed that students initially gravitated towards environmentally-focused solutions, often neglecting social and economic dimensions. This narrow focus led to the creation of unbalanced scenarios, reflecting "harmful hope". However, through metacognitive reflection during the game and the subsequent interviews, students recognized these limitations. They acknowledged the importance of balancing environmental goals with social and economic realities to create more realistic and sustainable futures.

These two works show the potentiality of the course structure in both scaffolding a critical perspective towards decision-making processes related to sustainability, and supporting the development of systemic thinking with does not disentangle the many features of complex issues such as climate change. I claim that both these results are consequences of the multi-layered structure of the course, as we stressed that uncertainty can be used to get insights about how science works and is linked to political issues, how it can be used to develop a systemic and probabilistic thinking and can be used as an instrument to evaluate possible decisions.

These results indeed display how the 4-layer scheme helped students to generate new perspectives and awareness useful to navigate the present society, make sense of that and make decisions with respect to intrinsically complex issues. In this sense, it led to forms of consonance (connection between science and politics) and dissonances (dystopic scenarios) which - if addressed (as I argued) - can support identity development.

Finally, as regards RQ III (*What role do epistemic emotions play in link activation?*), the theoretical hypothesis elaborated in this Chapter proved the centrality of epistemic emotions. Still, the analysis showed (also in agreement with the literature) that epistemic emotions are not *activators* of the consonances/dissonances but are rather *outputs* of them. Nonetheless, they are extremely useful in identifying episodes of consonance/dissonance, contributing also to strand I (methodology). Furthermore, they partially confirmed results from literature about their role as *mediators* between epistemic beliefs and learning strategies.

Finally, below is shown the scheme of Figure 17 integrated with the results emerged from the data analysis.

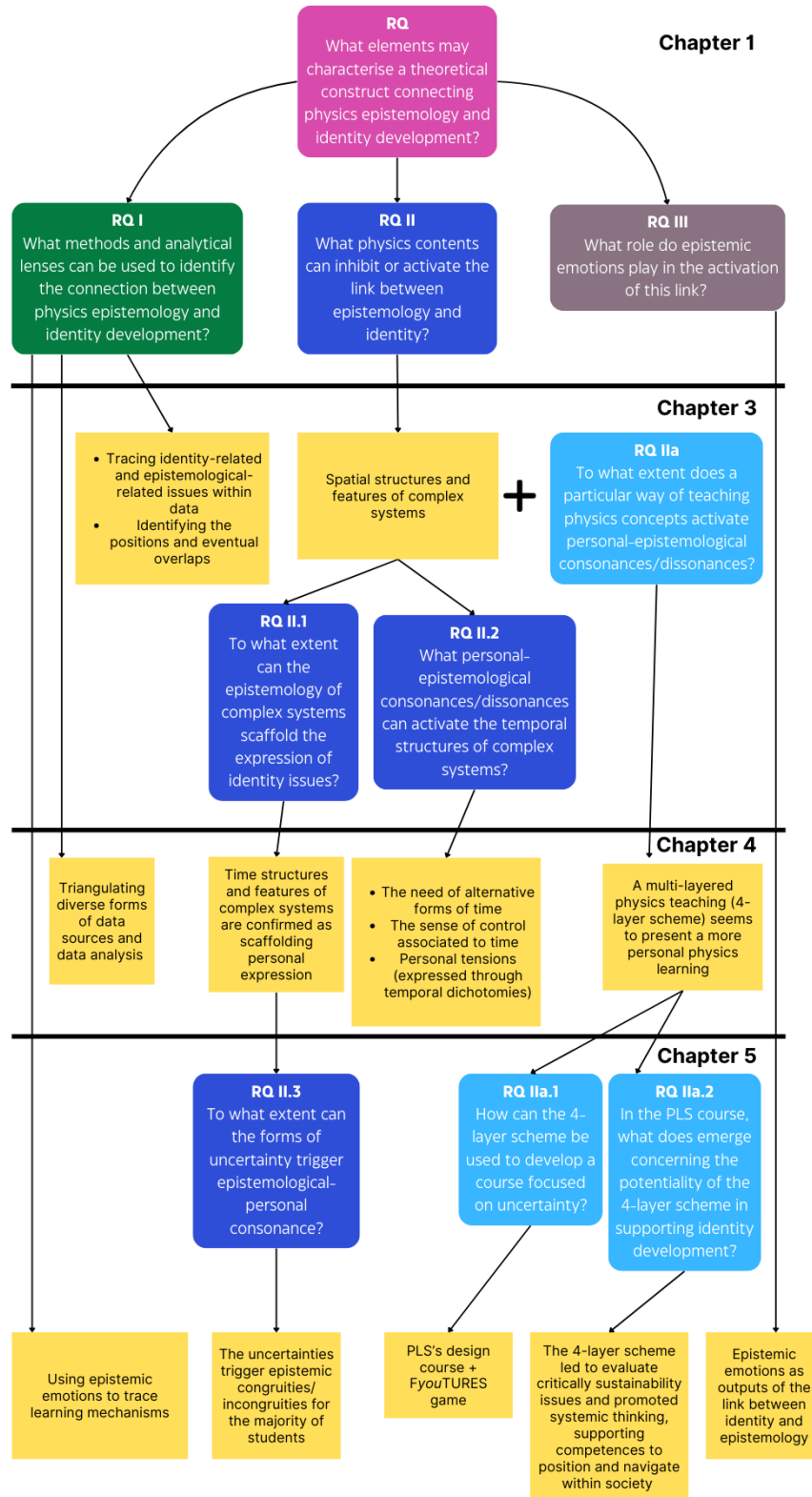


Figure 26: The scheme of Figure 17 expanded with the outcomes emerged from the data-analysis (represented by the yellow stickers).

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Appendixes

Appendix A

The questionnaire, which was delivered to 33 students, with 32 answers (originally transcribed from Italian).

	Please check the appropriate box if you agree with the underwriting statement: I confirm that I have read and understand the information on this page and agree to the following.
	Think of an event that relates to climate change. Share, through a story, a personal experience of yours that describes the impact of this event on your daily life. Your experience can be positive or negative, significant or not, routinary or special.
	If you had to describe this experience in a few words or if you wanted to give it a title, which words will you choose?
	This experience has been...
Q1	In your story, climate change issues are events that happen... Almost never = 0 Always = 10
Q2	The problem described in your story can be addressed: Making small changes to our current way of behaving = 0 Making big changes and sacrifices = 10
Q3	In your story, your personal values... Have nothing to do with sustainability-related values = 0 Are fully aligned with sustainability-related values = 10
Q4	In your story, values such as fairness, equality and social justice... Have no relevance = 0 They play a key role= 10

Q5	In your story, nature is seen as... Environment to be exploited for humans to thrive = 0 An inseparable part of the life of human beings, and inseparable from the social and technological dimension = 10
Q6	Regarding your story, can you identify the reasons behind the problems to face? No, I have the feeling that I don't understand the reasons for the problems around me = 0 Yes, I can clearly discern and understand the reasons of the problems I have around me = 10
Q7	Regarding your story, how do you perceive your ability to consider the variables of the problem at stake? I can't get an overview of the problem = 0 I feel very capable in understanding the interaction between the various elements of the problem = 10
Q8	Regarding your story, how successful do you think you are in framing the problem in terms of sustainability (managing the difficulties, coordinating the people involved, having a sense of the time required, aiming for achievable goals)? I don't think I can frame the problem in these terms = 0 I feel very capable in identifying sustainable approaches to deal with problems = 10
Q9	To address the problem described in your story, how much do you think your individual actions can contribute? Not at all = 0 Very much = 10
Q10	To address the problem described in your story, how much do you think your actions can influence political decisions? Not at all = 0 Very much = 10
Q11	To address the problem described in your story, how much do you think acting in partnership with others can help?

	Not at all = 0 Very much = 10
Q12	Looking back on your story and its possible developments in the future... I cannot think of any sustainable future scenario = 0 I can imagine many sustainable future scenarios = 10
Q13	Thinking back to the problem described in your story, the forms of uncertainty, ambiguity and risk connected... They completely block me from having to make decisions = 0 They are an incentive to make decisions = 10
Q14	Thinking back to your story... I don't think I can visualize the problem differently than I already have = 0 I think I can manage to see the problem in different lights, creatively = 10
	Enter today's date

Appendix B

The calibration sheet to move the sliders in the En-ROADS simulator.

The colours are the same used in the gameboard.

Action	Functioning	Calibration
Coal	Each notch is an increase in coal taxation (positive notches on the gameboard). Five notches in total: three notches available in the first round, four in the second, five in the third.	\$20
Oil	Each notch is an increase in oil's taxation (positive notches on the gameboard). Five notches in total: three notches available in the first round, four in the second, five in the third.	\$17
Natural gas	Each notch is an increase in natural gas' taxation (positive notches on the gameboard). Five notches in total: three notches available in the first round, four in the second, five in the third.	\$1
Bioenergy	Each notch is a reduction (negative notches on the gameboard) or increase (positive notches on the gameboard) in bioenergy taxation. Ten notches in total: three notches (negative/positive) available in the first round, four in the second (negative/positive), and five in the third (negative/positive).	\$5/barrel
Carbon price	Each notch is a \$50 increase in carbon price taxation (positive only). Five notches in total: three (positive) notches available in the first round, four in the second, and five in the third.	\$50
Agriculture emissions	Each notch is an improvement in CO2 removal potential through improved agricultural practices (negative ticks on the gameboard). Five notches in total: three (negative) notches available in the first round, four in the second, and five in the third.	20%

Technological CO2 removal	Each notch is an increase in CO2 removal potential (negative notches on the gameboard). Five notches in total: three (negative) notches available in the first round, four in the second, and five in the third.	20%
Waste and leakage	Each notch is an improvement in methane and nitrous oxide removal potential through improved industrial practices (negative notches on the gameboard). Five notches in total: three (negative) notches available in the first round, four in the second, and five in the third.	20%
Nature based	Each notch corresponds to an increase (negative notches on the gameboard) of natural practices (afforestation, innovative agricultural methods) useful for CO2 removal. Five notches in total: three (negative) notches available in the first round, four in the second, and five in the third.	20%
Deforestation	Each notch corresponds to a decrease (negative notches on the gameboard) of deforestation. Five notches in total: three (negative) notches available in the first round, four in the second, and five in the third.	2%
Electrification of transport	Each notch is an improvement of electrification for transport (negative notches on the gameboard). Five notches in total: three (negative) notches available in the first round, four in the second, five in the third.	10%
Electrification of homes and industries	Each notch is an improvement of electrification for homes and industries (negative notches on the gameboard). Five notches in total: three (negative) notches available in the first round, four in the second, and five in the third.	10%
Energy efficiency of building and industries	Each notch is an increase (negative notches on the gameboard) or decrease (positive notches on the gameboard) in the energy efficiency of houses. Eight notches in total: four notches (3 negative/1 negative) available in the first round, six in the second (4 negative/ 2 positive), and eight in the third (5 negative/3 positive).	0.7%
Energy efficiency of transports	Each notch is an increase (negative notches on the gameboard) or decrease (positive notches on the gameboard) in transport energy efficiency. Seven notches in total: four notches (3 negative/1 positive) available in the	0.8%

	first round, six in the second (4 negative/ 2 positive), and seven in the third (5 negative/ 2 positive).	
Nuclear	Each notch is a reduction (negative notches on the gameboard) or increase (notches on the gameboard) in nuclear taxation. Ten notches in total: three notches (negative/positive) available in the first round, four in the second (negative/positive), and five in the third (negative/positive).	0.014%
Renewables	Each notch is a decrease (notches on the gameboard) or an increase (positive notches on the gameboard) of renewable energies' taxation. Seven notches in total: four notches (3 negative/1 positive) available in the first round, six in the second (4 negative/2 positive), and seven in the third (5 negative/2 positive).	0.01\$
Extra-parameters calibration		
Economic growth	Each notch is an increase or decrease in the global economic growth.	0.2%
Population growth	Each notch is an increase or decrease in the global population.	0.4 billion
New Zero- Carbon	Each notch corresponds to a new discovery in the field of new technology to produce energy without carbon emissions.	0.4

Appendix C

Here the interview protocol, with the symbol *** indicating indications to interviewers. The protocol is divided into 5 Parts, and includes data from both the two questionnaire and the lecture recordings.

Introduction

Dear,

Thank you very much for your willingness to participate in this interview.

The purpose of this chat will be to review and discuss together some of the moments that marked the PLS course 'Towards new future scenarios: the role of physics in the study of climate change'.

The reason why we felt the need to ask you for this moment is because, as we mentioned to you during the course, this course is based on our doctoral projects, and through these interviews we would like to gain further insight into the meaning of what has been done and the potential of the course to develop the skills needed to deal with the societal challenges we are forced to interface with day after day.

To retrace these moments, we will use both the answers you gave to the questionnaires you filled in during the course and some moments recorded during group activities, such as playing games or making wild cards. We would like to make it clear that there is no judgement whatsoever on this data and information, but rather we would like to open up a space for comparison and discussion on the meaning of what we have done together.

Part 0 - Warm-up

Before we delve into the course content, we would like to ask a few context questions, also to understand why we are here. First of all, we would like to ask you:

Q0.1	Why did you choose this course?
Q0.2	What did you expect from this course when you signed up?
Q0.3	Did you find things you did not expect?
Q0.4	What kind of relationship do you have with science, and with physics in particular?
Q0.5	Did you find anything interesting for you from a personal perspective when dealing with science-related topics?
Q0.6	In relation to your view of science, how did you perceive the way physics was treated within the course?

Part 1 - Science

Let us turn to the questionnaire that we asked you to fill out in the first lesson and the last lesson. The questionnaire had a comparative purpose: to detect differences in your perception of the importance of certain areas, such as agency or values, between the beginning and the end of the course.

Q1.1	We always talk about climate change. It's a very broad topic. If you think about its scientific dimension covered in the course, are there any new themes/aspects that struck you and activated your thinking? Prompts: What differences do you see between climate change and weather variability?

(***graph is shown with answers and related pre-post stories***)

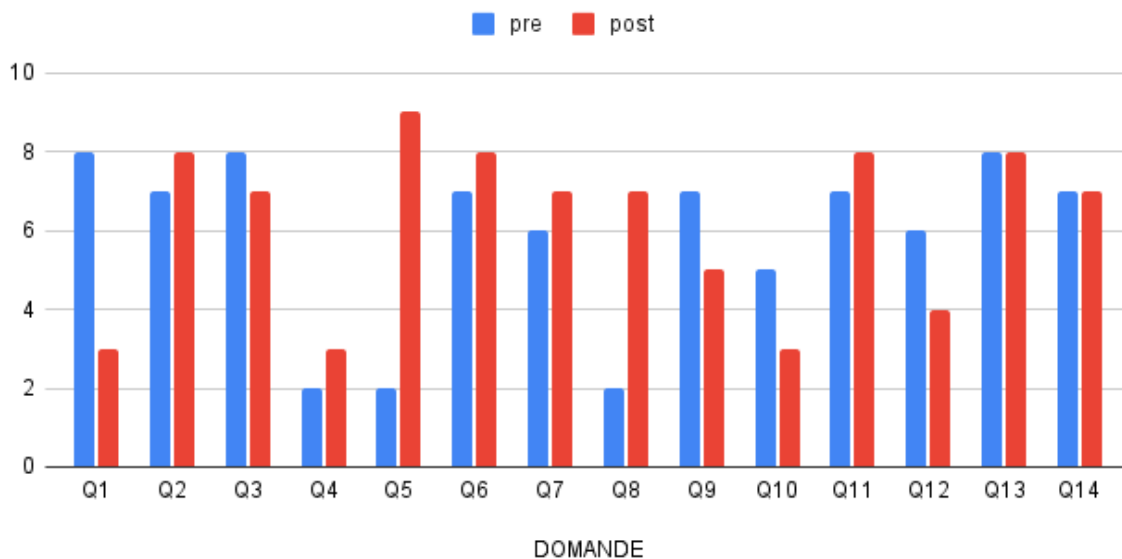
[An example of the pre-post stories and related answers]

LA			
Pre	In recent years, an increase in temperatures in the mid-season has been increasingly felt. This year in particular, temperatures did not drop significantly compared to summer temperatures until mid-October. This has caused imbalances in agriculture, for example, or in the animals. Being in contact with them very often, I have noticed that in many cases the hair change has not taken place correctly and this especially for wild animals can cause problems in the colder seasons. In addition to this there have been drought problems as there has been little rainfall and it has not been at regular intervals.		
Post	Thinking about the floods in Italy over the past year, one can still remember and see the great damage they caused. In fact, they harmed many people because of the damage it caused to houses and crops, and caused major transport problems for several days. In the light of what we did in this course I was able to better understand above all the fact that these extreme events, as unpredictable as they are, are bound to happen more and more often due to global warming. This is a subject that has unfortunately been talked about very little, as it has been said many times in broadcasts and radio that it is due to climate change, but rarely has the data been explored in depth or explained why.		
	QUESTIONS	pre	post
Q1	In your story, climate change issues are events that happen... Almost never = 0 Always = 10	8	3

Q2	The problem described in your story can be addressed: Making small changes to our current way of behaving = 0 Making big changes and sacrifices = 10	7	8
Q3	In your story, your personal values... Have nothing to do with sustainability-related values = 0 Are fully aligned with sustainability-related values = 10	8	7
Q4	In your story, values such as fairness, equality and social justice... Have no relevance = 0 They play a key role = 10	2	3
Q5	In your story, nature is seen as... Environment to be exploited for humans to thrive = 0 An inseparable part of the life of human beings, and inseparable from the social and technological dimension = 10	2	9
Q6	Regarding your story, can you identify the reasons behind the problems to face? No, I have the feeling that I don't understand the reasons for the problems around me = 0 Yes, I can clearly discern and understand the reasons of the problems I have around me = 10	7	8
Q7	Regarding your story, how do you perceive your ability to consider the variables of the problem at stake? I can't get an overview of the problem = 0 I feel very capable in understanding the interaction between the various elements of the problem = 10	6	7
Q8	Regarding your story, how successful do you think you are in framing the problem in terms of sustainability (managing the difficulties, coordinating the people involved, having a sense of the time required, aiming for achievable goals)? I don't think I can frame the problem in these terms = 0 I feel very capable in identifying sustainable approaches to deal with problems = 10	2	7
Q9	To address the problem described in your story, how much do you think your individual actions can contribute? Not at all = 0 Very much = 10	7	5
Q10	To address the problem described in your story, how much do you think your actions can influence political decisions? Not at all = 0	5	3

	Very much = 10		
Q11	To address the problem described in your story, how much do you think acting in partnership with others can help? Not at all = 0 Very much = 10	7	8
Q12	Looking back on your story and its possible developments in the future... I cannot think of any sustainable future scenario = 0 I can imagine many sustainable future scenarios = 10	6	4
Q13	Thinking back to the problem described in your story, the forms of uncertainty, ambiguity and risk connected... They completely block me from having to make decisions = 0 They are an incentive to make decisions = 10	8	8
Q14	Thinking back to your story... I don't think I can visualize the problem differently than I already have = 0 I think I can manage to see the problem in different lights, creatively = 10	7	7

DS



(***Question aimed at probing self-perception, such as: 'what do you think this level can be attributed to in this question?' especially for the questions with red indications; or 'Can you comment on these differences?' looking at the histogram***)

Part 2 - Future and agency

Let us now move on to the subject of the future and the world of future scenarios.

Q2.1	Has the course helped you to think about the future? What did you learn about the concept of future scenarios?
Q2.2	Thinking about your own case, do you think the course provided you with useful and interesting tools for thinking about the future? If so, which ones?

Let us try to see the answers you gave to the questionnaire on future scenarios, in particular on how you think we could aim for the ideal future rather than the potential future.

What is your image of the future 25 years from now?	What is your image of an ideal future 25 years from now?	What kind of decisions, choices and actions should be made to achieve your ideal future?	Thinking back to the two scenarios just described, which emotion(s) do you feel?
There will be a decrease in temperature, with related measures to reduce pollution, although not as great. There will, however, be an increase in extreme events for which more or less great precautions will be taken in many countries, leading to political and economic stability that will be little affected by these events. As far as crops are concerned, there will certainly have to be a change in certain realities, as the production of certain products is gradually becoming more difficult due to changes in the duration of certain climatic conditions. For the change in animal ecosystems there will be	A minimal increase in temperatures and a great response in taking sustainable measures. An increase in precautions for extreme events, partly even in poorer countries through donations of manpower and money from other nations, which can also be linked to the cessation of wars that would lead to less damage and more resources being available for other things. Having a global collaboration for these causes and finally being able through technology to find a way to re-establish certain habitats or at least halt their decay.	As partly already mentioned, primarily a global collaboration free of clashes and excessive individual interests, which is, however, very difficult to imagine in reality given the historical background.	Motivation ⁴⁸ ; the changes I make together with others can have an impact.

⁴⁸ There was a set of possible options among which to choose.

problems, but these may be more serious in the future and may be partly mitigated or adapted with technology. The point that will almost certainly remain unchanged will be that of war as it has characterised the entire history of mankind.			

Q2.3	Would you care explaining your answer to this question?

Part 3 - Uncertainty

Let us now turn to the main topic of the course, namely the concept of uncertainty. As you may have noticed, we have used some specific terminology to describe and categorise the different types of uncertainty that arise when dealing with topics such as climate change.

Q3.1	If you had to describe the differences between the three types of uncertainty related to climate change, what are the main elements you would use to distinguish them?
Q3.2	How did you perceive this differentiation? What reactions did it elicit from you? Prompt: Do you remember a particular moment in the course when you felt that this topic resonated with you (made clear to you) or did not resonate with you (made you confused)?

Let's focus now on the game in particular. If you remember, our goal was to create a tool that was able to bring together the different topics touched upon during the course, such as scenarios of the future, uncertainty, the complexity of climate phenomena and the relationship between science, politics and society.

Let us start with the first phase that saw you interact with the game, namely the construction of the Wildcards.

Q3.3	What did it mean for you to build the wildcards in groups?

	Did any difficulties emerge?

Part 4 - Game scenario

Let us now consider the main phase of the game.

One thing we noticed was the similarity between the various scenarios that developed between the various groups.

Q4.1	What was your opinion of the scenario your group built?
Q4.2	What kind of reaction did you have when you realised the world realised?
Q4.3	How would you change the choices you made to come closer to the description of ideal futures given in the ideal futures questionnaire? What values would you put at the centre in a possible reiteration of the game?
Q4.4	In light of your experience in the course, have you begun to see new aspects related to discussions around Climate Change, such as around Cop28?

Part 5 - Identity

Let us now turn to questions of a different kind.

We are interested in understanding how the scientific discipline, in this case physics, in what sense? In the sense of content, the methods it uses, the practices, the values it has, etc., come into contact, come into relation with what we are, with what our essence is as a person... that is, in what way, if and what content. And in particular we have invested in this course on complexity and uncertainty because we think these are very rich topics and because we think they leave room to enter into relationship with these contents. So the question is whether you ever had the impression that the science that you saw in your experience, so all that is meant science, the content, the scientific method, some practices, whatever you came into contact, was in line with some of your aspects of who you are, that is of you ***, of your identity, of what you feel to be. Either positively or negatively, i.e. that it came into consonance with you, that you felt that 'ah I feel this thing mine!' or not, 'this thing instead creates me a problem!'. So:

Q6.1	Have you ever felt that science (in terms of content, practices, methods, values) was in line with some of your personal aspects? Or on the contrary was in opposition to them?

Q6.2	Were there moments in your PLS course experience when you felt that the scientific aspects (at the level of content, practices, methods, values) were in line with some of your personal aspects? Or on the contrary were they in opposition to them?
Q6.3	(***An extract is proposed and you are asked to discuss the extract***). In this excerpt, when we were doing ... you expressed yourself like this. Could you better explain what you meant?
Q6.4	We come back to a more general level. I would ask you to frame the discussion you just had on the specific event within the general discourse you were having at the beginning. How would you return to your previous answer in light of this?
Q6.5	Do you feel that you have changed your image of physics in light of the topics covered in the course?
Q6.6	Were there times in your school experience of science subjects when you felt the need to play a role that was not yours? If so, could you tell us about this experience?

Excerpts:

1:46:32

MD: From the reports of the last few years, we have seen that what has been most problematic is petroleum and not so much coal. If we go and look at the costs, petroleum is considered oil in this case, we can see that the cost of electricity has risen sharply

LA: nooooo...

MD: only of oil...

LA: but then after that isn't it that if you lower the tax on oil they start using a lot of it?

MD: yes, but in my opinion it doesn't make sense to increase the tax on coal. We've still seen an increase in costs, but it's not excessive

TL: but consider that coal is the most polluting material (more pollution per kg).

MD: but at the moment we would still be within our target according to the provisions, so to burden the population now, we haven't yet passed the economic crisis, it would be negative. I would keep it that way and then in 2050...

TL: true so taxing on coal would not be a problem.

MD: no, it would be a problem

TL: no you said yourself that it's not used that much...

LA: we have to tax!

TL: Guys, the objective of the developer of conventional energy (TL himself) is to promote nuclear power, which we are clearly doing. Exactly!

MD: no one has a problem with that.

TL: the coal...

MD: For coal I propose to leave it at 3, not diminish it.

LA: Who wants coal to grow a bang?

(no one agrees, MD laugh because is confirmed)

TL: ok, then to help the world population, not to get into an anarchy collapse and things like that, we can reduce taxes on oil - since they are the most consumed - at +2

MD: and you still want to increase the...

TL: yes

LA: but that doesn't make sense, we just cut taxes from... if you then increase them here, it's as if we didn't do anything.

TL: but if you raise them over there you can stay like that with oil (as it was)

This excerpt is interesting as it shows the group discussing about the potential collateral effects of their decisions, reasoning about social and economic consequences. Nonetheless, they decide for taxation (even not as high as suggested by TL), but well aware of what that choice might entail.

2:27:40

MD: we are at 2050? The sea level (raise) is the same as originally predicted and is 0.24. Instead the predicted temperature (rise) is 1.86.

LA: so we did not reach it?

MD: our target was 2.2, so definitely yes! ... ah no sorry my fault, you're right. 2050 is still good, is 1.75.

FC: and what's different with the 1.9?

MD: it's because it refer to 2100

FC: earlier you said the right one?

MD: sea level was right.

FC: 0,24?

MD: yes.

TL: our council is succeeding, LA is missing. they murdered her politically to shut her up.

TL: the use of these (conventional energies) has been reduced

CS: 20 mins to go

TL: I would say, since I have to reduce by 4 notches

MD: we don't need points, even because... we've already reached the target in theory, so we can do a semi-realistic thing by removing some subsidies

CS: let's do some sums. nuclear is at -1

TL: another three points...

MD: we are at 2050. I can also put you the demand and the cost... in my opinion you can also reduce oil

TL: yes we still have three points

MD: semi-realistically in the sense that if you do a no coal thing (like a demonstration), and there is in theory

TL: but consider that the production, the consumption of coal to produce energy is something that doesn't count notches

MD: is that it decreases forever.

LA: what have you decided?

MD: so doing like this we can even subtract two points in coal because okay you burn stuff but ...

LA: so? what did you decide?

FC: MD, what was the predicted? What was the temperature increase?

MD: in fact, we have to do the report in 2050. Let's say the temperature increase compared to the pre-industrial era is of 1.75 instead of the 2 originally predicted. So, in 2023 we make the forecasts for 2050.

This excerpt is interesting again because the group is trying to find a balance between an environmental advantage (reducing the sea level and global temperature rises below a threshold they fixed) and a social welfare. They choose to put first environment, but still take in consideration this dimension, even if they were not explicitly asked to do so.

Conclusions

The present thesis aims to investigate the connection that might be established between physics epistemological issues and identity questions. The objective was to elaborate a theoretical construct able to show the conditions that can contribute to transforming physics learning into something personally relevant (Stuckey et al., 2013). Specifically, there was the intention to study what kind of disciplinary knowledge, what reflections around that and what teaching instruments can transform that into a useful tool for students' identity development. This perspective assumes that science education can play a role in supporting citizenship skills crucial for identity construction within a post-modern society dominated by complex challenges.

Thus, a perspective has been developed based on three frameworks:

- the FRA wheel (Erduran & Dagher, 2014), to focus on the cognitive-epistemic part of scientific disciplines.
- the Model of Educational Reconstruction (Duit et al., 2012), to embed in the reflection the idea that is possible to foster the epistemological richness of science to support students' visions, ideas and identities.
- epistemic emotions (Jaber & Hammer; 2016a), to include in the reflection also the affective dimension.

As a consequence, a first Research Question was formulated: *"What elements may characterise a theoretical construct connecting physics epistemology and identity development?"*.

To address this overarching question, three strands have been then identified (Figure 6, Chapter 1):

- strand I, related to methodologies to inquire about the connection between physics epistemology and identity development,
- strand II, related to the disciplinary contents that could activate such connection,
- strand III, related to the role of epistemic emotions.

An additional strand emerged then by the analysis of Chapter 3:

- strand IIa, related to the teaching strategies to introduce disciplinary contents.

For each strand, Research Questions have been formulated and addressed through the three case studies of Chapters 3, 4 and 5. In particular, strands II and IIa have been developed through the formulation of new Research Questions based on the findings of single case studies (see Figure 26, Chapter 5).

As Figure 26 of Chapter 5 shows, each strand was developed and provided outcomes for the characterization of the theoretical perspective (named from Chapter 3 onwards, *personal-epistemological consonance/dissonance*).

The outcomes linked to **strand I** suggest diverse strategies to inquire about the link that can be created between disciplinary epistemology and the identity dimension. One option could be to map in the data the issues related to the two poles, identify what kind of specificity they present (what epistemological elements and identity issues are expressed) and investigate if there is a connection between such poles.

By using for instance a codification process, it could be particularly interesting to focus on the sections where the labels of the two poles (identity and epistemology) are close to each other or overlap. This operation could show if specific and contextual mechanisms emerge.

A second methodology discussed in the thesis is the use of multiple analytical strategies performed on different portions of the dataset, with the aim to converge and toughen interpretations or to conversely question and refine them (as evidenced in Chapter 4 with the “prism-analysis”). Even if these two methodologies were useful in this case, they can be useful in general.

However, there is another option that is more closely related to this specific objective, which is the identification of the epistemic emotions visible in the data, as they could be the tip of the iceberg of an underlying process involving identity-related issues. As discussed in Chapter 5, epistemic emotions can be the consequence of the interaction between epistemic beliefs (which are informed and can also inform identity aspects) and disciplinary knowledge.

The outcomes linked to **strand II** suggest that the physics of complex systems (and in general the complexity paradigm) and the multidimensional concept of uncertainty, are physics concepts that can activate a connection between knowledge and the identity dimension. The analysis of Chapter 3 illustrated that the discourse around agent-to-agent local interactions and collective emergent behaviours of complex systems acted as a scaffolding to reconceptualize and express personal issues. In particular, this idea was in **consonance** with a tension students felt: a sense of belonging to the peer groups both comforting and limiting to the affirmation of one's own identity.

Chapter 4 analysis confirmed the capacity of the complexity paradigm in activating a deep reflection that ends involving also the personal dimension. In this case, the analysis showed how a physics teaching which introduces different forms of time - through specific design principles - can help to: i) understand how young people deal with time; ii) highlight what kinds of temporalities are felt as normative; iii) support the shift in time conception towards new temporalities that are less stressful and more consonant to individuals. Related to the last point, it has been shown that having introduced multiple images of time from physics created an “epistemological space” large enough to allow multiple positions for students: this gave the chance to express many different inner tensions mapped into dualities of times (Kairòs vs Eniautòs, Chrònos vs Eniautòs). The extent of the contents addressed during Kairòs in supporting the expression of personal issues is also witnessed by having found aspects of the students that can be considered “generational aspects”, checked against the control sample of the ONSCI implementation.

Finally, the theoretical hypothesis elaborated in Chapter 5 showed how reflexive, aleatoric and ontological uncertainties activated episodes of cognitive dissonance/consonance. The analysis showed that some dissonances led to a final shift of the epistemic belief, which can also impact (as the case of SB illustrates) the way individuals see the world and their position within it (identity dimension). This is the case also for the cognitive consonances which have been developed by the course experiences (as the case of FC shows). However, also the cases of cognitive dissonance which led rather to a “need for closure”, show the potentiality of such uncertainties to trigger a connection between epistemology and identity. The forms of dissonance indeed emerge due to the interaction between uncertainties and epistemic beliefs, which reflect aspects related to personal identity.

For what concerns **strand IIa**, the analysis of Chapters 4 and 5 contributed to arguing the efficacy of the 4-layer scheme in creating the conditions for a more relevant kind of learning, which starting from the

disciplinary concepts can end up supporting identity construction. Chapter 4 showed the efficiency of creative writing, focused on the process and informed by physics concepts, in providing the space for expressing personal issues related to time and its management. Chapter 5 instead showed that the course structure established an “epistemic space” large enough to accommodate many diverse epistemic positionings, which created all the forms of consonances and dissonances when interacting with the uncertainties. Having highlighted the epistemological dimension of all the activities (as *FyouTURES* for instance, or the volcano game) made emerge students’ epistemic beliefs and made them interact with the new contents.

As shown in Chapter 5, the structure of the course developed awareness of complex issues such as sustainability, allowed to identify what strategies can be more efficient when facing sustainability-related questions and illustrated possible forms of agency concerning them. As I claimed at the end of the previous Chapter, such skills can represent a boost for the development of citizens, hence impacting the identity dimension.

Regarding **strand III**, the theoretical hypothesis elaborated in Chapter 5 disconfirmed the initial guess of epistemic emotions being mediators for the link activation between epistemological and identity aspects. They appeared instead as products of the cognitive consonances/dissonances and mediators between them and subsequent learning strategies.

In general, the four strands contributed to the development of the theoretical perspective in the following sense. A possible name for such a construct has been introduced with the term *personal-epistemological consonance/dissonance*. The outcomes that emerged indeed revealed how the connection between epistemological and identity aspects takes the form of a consonance or a dissonance. “Physics of clouds” and “Kairòs” analyses illustrated how a specific aspect of the complexity epistemology was in consonance with a shared reflections of the students participating in that project. The outcomes from the PLS course instead may be considered the counterpart of the analyses discussed in Chapters 3 and 4. Even though they confirmed how some cognitive congruities (consonances) can establish a strong connection between physics and identity, more importantly, they evidenced how forms of cognitive incongruities (dissonances) can be still the chance of a personal connection with the contents. Such connection may lead to epistemic shifts and ultimately support identity development. This is certainly an option, as SB, LA and others witness, but is not the only one, as RF and TL demonstrate.

Thus, the analysis of the last Chapter contributed to the development of *personal-epistemological consonance/dissonance* in two ways:

- it confirmed the presence of dissonances and consonances as evidence of the link between epistemological and identity aspects.
- it enabled to overcome the first naïve idea of connecting consonances only with positive impact and dissonances only with negative impact, with respect to identity development. It is now evident that both the consonances and the dissonances (at least in this context) can inhibit or sustain identity development.

However, to address the consonances and dissonances it is crucial to first identify the epistemic beliefs and then trace their trajectories as they encounter new knowledge.

In addition, the findings reported in the thesis demonstrate the importance of teaching practices in activating *personal-epistemological consonances/dissonances*. It is crucial indeed to reshape and introduce the contents as something more than mere concepts (see the 4-layer scheme), to first allow space for an epistemic positioning and then create the conditions for an eventual *re-positioning*. This 4-layer framework is what allowed the *consonance/dissonance* to become chances to reflect on the society around us and the ways we look at it.

To conclude, a possible option to investigate to what extent and how the physics epistemology can be used to support identity development requires to:

- carefully choose physics contents epistemologically rich and reconstruct (Duit et al., 2012) them with a specific procedure (4-layer scheme).
- identify the initial epistemic beliefs of the individuals involved.
- identify the epistemic emotions activated by the contents introduced.
- study (through the epistemic emotions) the mechanisms of consonance/dissonance and what consequences they led to.

These conclusions open to the possibility to test the outcomes against new data collected in new environments and to study the scalability and generalizability of the construct of *personal-epistemological consonance/dissonance*.

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