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Identity development in physics classes: from community of practice towards nexus of multi-membership

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Abstract

The thesis aims to contribute to the general problem of the impact of physics education on students' *identity development*. Identity development has become more and more relevant in the last years and, according to OECD, it represents one of the main goals of education (OECD, 2018).

In STEM education, the issue resonates with the lack of relevance that most of the students still perceive in learning science at school (physics and mathematics in particular) (Stuckey, Hofstein, Mamlok-Naaman, Eilks, 2013).

Starting from this consideration, I carried out an analysis of the research literature to formulate the problem as a "research narrative" grounded on a selection of STEM literature theoretical constructs. The narrative is mainly centered around the idea of *community of practice* (Wenger, 1998), but is incorporates the constructs of *Discourse & Affinity identity* (J. Gee, 2000), *Practice-linked identity* (N. S. Nasir and Hand, 2008), *epistemic agency* (Stroupe, 2014), *socio-scientific norms* (Yackel and Cobb, 1996), *boundary crossing mechanisms* (Akkerman and Bakker, 2011; Wenger, 1998), and *appropriation* (Levrini, Fantini, Tasquier, Pecori & Levin, 2015)).

The narrative has been tested in two empirical studies with physics students attending the course in Physics Education in Bologna. Aims of the studies were: i) to test students' proximity of the problem and the effectiveness of its reformulation in the narrative (RQ1); ii) to collect suggestions, opinions, experiences to turn the narrative into an operational set of suggestions for teaching (RQ2).

The results show a great feeling of proximity and effectiveness of the narrative to stimulate profound personal re-elaborations concerning the nexus between learning physics and personal identity. As for RQ2, initial insights have been collected and directions for further investigations have been pointed out.

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Contents

A mia nonna Laura,
che un giorno ha scritto un'enciclopedia
perchè credeva nel valore dell'educazione.

Introduction

In the present time, that flows faster and faster and where the technological innovations become each day more central in people routines, the role and efficiency of education is questioned. The sense itself of school experience has to be redefined to as to become more and more sensible for students as citizens, future professionals, but also as persons. Even assuming that education has an impact on identity formation, the problem of analyzing such an impact is very complex, being dependent on diverse variables, sometimes even out of the control of the teachers. If the goal is to have a positive effect, education should provide students with the chance not only to navigate our complex society (for example being able to handle with modern artifacts), but also to find a way to become aware agents within a collective and social dimension.

It is well known that STEM education is a crucial driver to promote agency within modern society. Nevertheless, most of the students look at STEM learning as far from their personal life and without any potential to impact their personal identity and, hence, to activate a sense of agency. Stuckey and colleagues pointed out to what extent science is perceived to be taught just with the goal to select talents and they stressed the lack of relevance from a personal, social or vocational point of view (Eilks et al., 2013). Even about physics, the common feeling of the students is a perception of lack of relevance. From this point of view, students tend to feel physics or science different with respect to another subject matters, like humanities, for their role on the identity formation.

The starting point of this work is a naive sensation that emerged in my educational path and that I tried to transform into my "zero set of research questions" (RQ0): *«Is it possible to find a way to formalize the big issue of the lack of personal relevance of physics? What research constructs and tools, elaborated in STEM education, can be used to describe the process that leads or doesn't lead students to bring out knowledge from their physics classes and turn it into thinking tools for life? How can these constructs be combined to describe the problem in a way that can be addressed by the research?»*.

As we will show, the answer of this RQ0 has been built in terms of a narrative that explains in technical terms what I personally felt as a problem. Because of the very personal and idiosyncratic nature of the genesis of RQ0, I felt the need to share the narrative and check if what I saw as a crucial problem were considered as important also by other colleagues.

In this sense RQ0 has been followed by another set of research questions (RQ1): *«To what extent is the problem described in the narrative felt by the physics students? Is this "research narrative" effective to illustrate the problem?»*.

If a positive answer will be given to these initial questions (RQ0 and RQ1), then it would be possible to elaborate on what could be the main directions for physics teaching to give a possible contribution to facing this huge challenge. This is related to a third level of questions that the research aims to address: *«How can the problem be addressed in teaching? Can concrete examples be pointed out?»* (RQ2). RQ2 is the most specific level of investigation, linked with the operative directions of research. In dealing with RQ2, one possible direction appears the clarification about features, aspects and mechanisms that make physics learning relevant but also different from other kinds of learning. If we reveal what we can mean by learning physics from a personal perspective, it would be possible to choose the useful pieces of physics-learning-process and exploit them to make students aware of the impact that these aspects (which are representatives of their physics experience) can have on their identity formation. Thus, they could increase the awareness of the explicit positive effects of physics learning also on their role as persons and citizens.

To sum up, the research work addressed in this thesis pursues the following general goal: to investigate the processes that make learning physics relevant from a personal point of view and unique and find out examples of practices, thinking tools, knowledge elements that can specify and operationalize general claims such as: *«studying physics is important because it allows to develop fundamental tools for modern society, as problem solving, the ability to face complex dilemmas, rationality, the capability of divergent thinking...»* (OECD, 2018)[1].

Outline

The thesis is articulated in 5 chapters.

[1]Regarding this, the OECD - Organization for Economic Co-operation and Development - has launched in 2015 a project whose name was "Future of education and skills 2030", with the purpose to begin a global discussion about the nature of modern skills that students must possess to face future challenges, such as acquiring responsibility and contribute to the well being of society. Phase one was aimed to build a learning framework: the outcome of this part (2018) resulted in a learning compass, pointing to the common well being, made of different pieces, one of which is a series of transformative competencies. After three years of dialogue among all the stakeholders, three competencies in particular were set as crucial for students to shape the future: 1) creating new value, 2) reconciling tensions and dilemmas, 3) taking responsibility. These could be seen as general examples of what could be in physics divergent thinking, problem solving and so on. Besides these general skills, OECD designed other more specific competencies, such as numeracy, data literacy; all this to say that there is a widespread attention within all the stakeholders, focused on what could be the useful instruments with which provide students along their education.

In the first chapter, *State of art - Identity in STEM education*, the main literature references that guided my research work are presented. From these references, the key concepts, tools and constructs at the center of the present thesis are introduced. Special attention is paid on the construct of identity and its nuances, the link between identity and STEM education, the mechanisms of dialogue between "in class" and "out of the class", the idea of community of practice and its relationship with the school science class (i.e mathematics class, physics class).

In the second chapter, *Problem formalization: a research narrative*, I present the articulation of a research narrative to describe the temporal evolution that leads a student from the appropriation of concepts/themes/topics within a physics class, to their export, as competencies and thinking tools, out of the class. In this chapter the first research question (RQ0) is addressed and the other two (RQ1 and RQ2), that guided the design of the data collection, are introduced.

In the third chapter, *Empirical studies: context and methods*, two empirical studies are presented. For both the studies, that involved the students attending the master teaching course of Physics Education, the sample, the setting, and the methodologies of data collection are described.

In the fourth chapter, *Analysis and discussion*, the preliminary results, obtained both from the collective discussion and from the interviews to address the RQ1 and RQ2 are discussed.

Chapter 1

State of art - Identity in STEM education

Education has a fundamental role within society of all the times; it is thanks to education that people become agent, become citizens, become what they will be in their entire life. For sure we know that changing never ends, and formal education spans over only few years, but these are the years during which people are more malleable, not yet formed; hence the value of education at school is enormous.

The explicit feature of education thus seems to be the following: society requires school to teach the foundational values on which it is built upon, but also the ones that are temporal dependent, and that distinguish the different times of the history. For sure what can be considered a value right now, as for example the capability to live in a multiethnic world, where all the ethnicities are on the same level, with the same rights, is something that only two hundred years ago was unthinkable.

Thus, education appears as pivotal in creating what can be considered at least a social identity; but of course what happens is that also the personal identity comes to be formed along the time of education. In this chapter, the analysis of the literature carried out aims to highlight the contribution of STEM education and the role of the school (and active participation) in the identity formation.

1.1 Identity

When we speak about identity and education, we cannot avoid starting from the seminal paper by James Paul Gee (J. Gee, 2000), where he develops a discursive approach to analyze and compare possible ways to conceptualize identities. In this piece, Gee starts by assuming that "identity" can be loosely described as *«being recognized as a certain 'kind of person,' in a given context»* (J. Gee, 2000; p.99). The discourses that shape the identity are *«ways of behaving, interacting, valuing, thinking, believing, speaking, and*

TABLE 1 Four Ways to View Identity

Process		Power	Source of power
1. Nature-identity: a state	developed from	forces	in nature
2. Institution-identity: a position	authorized by	authorities	within institutions
3. Discourse-identity: an individual trait	recognized in	the discourse/ dialogue	of/with "rational" individuals
4. Affinity-identity: experiences	shared in	the practice	of "affinity groups"

Figure 1.1: The four shades of identity, according to Gee's interpretation (J. Gee, 2000; p. 100)

often reading and writing that are accepted as instantiations of particular roles (or 'types of people') by specific groups of people» (J. P. Gee, 2007; p. 3). Discourses shape the identity since they activate the process through which one is identified with *«families of a certain sort, lawyers of a certain sort, bikers of a certain sort, business people of a certain sort, church members of a certain sort, African-Americans of a certain sort, women or men of a certain sort, and so on through a very long list»* (J. P. Gee, 2007; p. 3).

In his paper he sets up an historical analysis of the discourses and, to manage the complexity of the theme, he points out four main categories of the discourse on identity:

- N-identity: natural-identity
- I-identity: institutions-identity
- D-identity: discourse-identity
- A-identity: affinity-identity

Each of these categories has its own source: for example the natural identity is shaped by those discourses that attach identity connotates by referring to physical properties such as hairs' color, eyes' color, "the talent for physics" , that are assumed to be originated by nature[1]; "being a student" is an identity nuance that emerges from the school

[1]even if these groups can be seen on the same level of importance in determining identity and all independent one from each other, focusing the eye on the natural identity helps to figure out that this kind of identity cannot be considered so, without the recognition of the other types. Only when someone groups me with the abstract group of blond men, from that moment the nature of my hair starts to be a trait of my identity.

institution, and is defined on the basis of the role played within the institutional rules; being a kind person, or an an empathic man comes out from the interaction with other people, and through a dialogue; being a "scout" emerges instead by the belonging to an affinity group.

Besides all the problematic issues discussed by Gee and that arise when we want to describe identity, this framework opens the eyes on what could be the role of school in building identities. The school can be active in all the four different ways: the school represents an important Institution, and in fact it has the great role to promote a "institution identity"; it is a place where the *discourse*, among classmates and between students and teachers, is crucial to develop the self-perception (Yackel and Cobb, 1996; Scardamalia, 2000; Stroupe, 2014; Tan and Calabrese Barton, 2008); it is also a place where students form groups and develop their sense of belonging (A-identity); finally, the disciplines can still play the role to strengthen the idea that some talents are mainly "by nature" (being a "physics-person" or a "math-person"). However, since social labels are being more and more dismissed during this accelerated world (Rosa, 2003) that erodes the power of institution, it seems compelling for school to follow the idea of being primarily a place where the Discourse identity and the Affinity identity become more and more important. The dialogue is the chance for the students to develop their own D-identity, the one that seems particularly important in the present time; as Calabrese Barton also reports (Tan and Calabrese Barton, 2008), *«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'»* (Tan and Calabrese Barton, 2008; p.569). What schools should provide to this purpose is, thus, the capability to make sense of this dialogue. As Gee states:

> *«The modern need for recognition, since it is an attempt to create achieved D-Identities, places a particular importance on discourse and dialogue. I work out my identity, in the modern sense, by making sense of, or interpreting, 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 within which to do so. As Wittgenstein (1958) made clear in his famous argument against "private languages," I cannot make up and sustain a language (or any other sort of representational system) all by myself.»*(J. Gee, 2000; p.112)

Furthermore, in this society of acceleration and uncertainty, where many institutional structures are questioned and are changing, we all feel the need to search for our affinity groups. The phenomenon of the echo-chambers seems to exacerbate the sense of A-Identity and, in any case, point out to what extent also this nuance of identity in the Gee framework is now relevant.

The framework of Gee is usually considered the main reference for the researches carried out in science and mathematics education. However, as we will argue in the follow, in the STEM education further nuances and constructs have been elaborated so as to orient the elaboration of teaching approach that can turn the learning in science classes into contexts where students can feel at home and encouraged to develop their identity.

1.2 Entering the physics class

The time spent by students at school consists in the largest part of their daily life, and it is relevant because it marks the daily routine. Thus, what often happens is that time-relevance does not match with the value-relevance (N. S. Nasir and Hand, 2008; Phelan et al., 1991). In particular the time spent in learning physics and mathematics is considered completely irrelevant to form any deep sense of identity. One question that Nasir and colleagues have addressed is the following: *«what makes sport training different from physics training, at school? why playing basket with the teammates makes me more aware of my identity as a player than what does physics about my sense of being a student, participant and stakeholder in that discipline?»*.

In order to address this question, Nasir and Hand (N. S. Nasir and Hand, 2008)[2] investigated what are the specific mechanisms that make two disciplines, such as maths and basketball, so different in the development of what is called **practice-linked-identity**, the identity that participants expand along the act of doing that practice. They participated at the basketball training and did also some interviews with students which were across the two communities: the sport team and the math class. From their analysis 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 and Hand, 2008). In the authors' idea the lack of these aspects inhibits the establishment of a math-linked-identity. In particular, it can be seen directly from students' words that they evaluate their level in math only by grades, whereas when referring to their level as players, they specifically relate it to different skills. This, indeed, is representative of the narrow access let free for student to the math domain. If it is not shown the whole structure of the discipline and how each skill and concept is interrelated with the others, enabling the structure to be robust, as it is done during the basketball training, this confusion carries to identify themselves with grades. In addition, this last fact is strongly related to the second feature, about the roles. Indeed grades are given by teachers, who exercise the authority inside the class. If the domain remains inaccessible, students have only grades as tools to build up a personal role within the group. Yet, being the grades out of their control, the students do not have any accountability on their path, or any recognized role (N. S. Nasir and Hand, 2008). The absence of any role among the group of schoolmates inhibits

[2] in their case they were comparing basketball with math class.

the chance to find a way for self-expression. Self-expression is indeed strictly related to being part of a community and to play an acknowledged role in that group, like being playmaker in a basketball team.

The concept of practice-liked identity of Nasir and Hand is a powerful lens through which classes dynamics can be read to find out principles to design a learning environment potentially able to develop identity also through science classes.

Inspired by the framework of Nasir and Hand, Levrini and colleagues (Levrini, Fantini, Tasquier, Pecori & Levin; 2015), developed an instruction-design approach to address this question, *«Can learning physics support students in the construction of their personal identities?»* (Levrini et al., 2015). As contribution to this question, they pointed out three design principles aimed to make the learning environment inclusive and rich enough to accommodate students with different interests and playing different roles. The design principles correspond to three forms of productive complexities: *multi-perspectiveness*, *multi-dimensionality* and *longitudinality*. *Multi-perspectiveness* means that the same concept can be seen from different points of view: mapped in thermodynamics, it means, for example, to address the same concepts from the macro (classical thermodynamics) and the micro (statistical mechanics) approach. *Multi-dimensionality* means to show the physics content on different levels, including for example the epistemological level, that allows pupils to debate and take a position. *Longitudinality* represents the need to link together the concepts of the program, building an explicit network of physics knowledge (Levrini et al., 2015).

Their notable outcome is that, after an implementation of activities designed on the basis of the three principles with secondary school students, they recognized an evolution of the students' learning experience, which they called *appropriation*. Different students showed to have learned the physics content in a different way with regard to traditional learning: they seem to have appropriated physics concepts in a **personal** way and were able to verbalize their learning through a discourse that was focused on an idiosyncratic, **non-incidental** idea, that was also **grounded** in physics and **thick**, in the sense that was expression of a personal epistemological view (Levrini et al., 2015). In fact these students, when interviewed, demonstrated to express the concepts with a proper language, without reporting teachers' words as it often happens; they seem comfortable in taking explicit and robust perspective on the domain, expressing positions argued with physics. These turned them to be *characters* in the classroom, with a role and with the possibility to establish relationships also thanks to physics. Such a dynamics contributed to developing, in students, a sense of agency in the class, with authority on the domain, to reinforcing their identity and allowing for new features of identity to grow; as the authors state:

> *«This process of positioning* (toward the subject/within the group) *is argued to foster identity formation, in the sense that this dynamic, if recurrent over time, creates a context in which a student must engage with questions like*

'Who am I?' 'Who do I want to become?' and 'Who do I want to be perceived as?» (Levrini et al., 2017; p.309)

About STEM-linked identity development, it is noteworthy to cite also the work by Paul Cobb and colleagues. Within the mathematics domain, they managed to describe a system of constraints (norms) that are implicitly or explicitly established in class: they call them sociomathematical norms (Yackel and Cobb, 1996). When we refer to norms, we usually think at something that is explicitly imposed from above, and must be accepted whatever is the degree of agreement, but of course this is not the case. In their idea, the norms are part of the disciplines (mathematics, in this case), but if they are made explicit and negotiated by all the members of the class, thus students, teachers and others, they become stronger. Indeed, the strength of a norm that is established within a group dynamics is much bigger than the one of a norm that is forced. But one can ask what a mathematical norm is, or even what a sociomathematical norm is.

The norms that they refer to are mathematical in the sense that they set up what is allowed or not allowed when doing math inside that class. For example, if the class is reflecting on the sense of a mathematical explanation and on the mathematical norms that allow robust reasoning, then in the class it can emerge the relevance and the sense, for example, of the tool of deduction. In such a way, whenever it will be presented an explanation that is in disagreement with these norms, it will be dismissed by students, even if it is the explanation of the teacher. Once there is a set of norms that are *taken as shared*, then all the subsequent discipline must be constructed upon and in coherence with these (Yackel and Cobb, 1996). For example, they speak about the idea of *mathematical difference*: a demonstration could be defined mathematically different only when the reasoning follows a different path, not when the path is the same and what changes is just the order of the building blocks.

Regarding the first piece, *social*, the reason is the following: when defining mathematical norms inside a classroom, these norms set the ways in which one has to deal with mathematical objects, mathematical knowledge. Of course, one can decide to stay alone at home and play with these concepts by oneself, in that case we will still respect the norms, but they will be only mathematical norms. They are extended to be sociomathematical norms when the student that negotiates these norms is able to use the knowledge, according to the norms, within the classroom, within that community and to find a relational role for the knowledge objects inside the interaction with the other members. The process of negotiation allows the students to gain a role and autonomy in the community. If this happens, the feeling of *intellectual autonomy*, as they say, is enhanced, since the students can handle the *repertoire* of the math-class because they are part of the process of establishment of that social repertoire. The capability to being agent and building norms inside the classroom is strongly linked with the notable concept of *epistemic agency* (Scardamalia, 2000; Stroupe, 2014). Epistemic agency is the capability to being agent, to having a field of action at an epistemological level. A possible definition is given by Scardamalia, (Scardamalia, 2000):

> *«Knowledge builders take charge of their own learning, taking responsibility for personal understanding and for the creation of knowledge artifacts. The starting point for epistemic agency is the ability to recognize a relation between what is in one's own mind (which may be a well-formed opinion or only a vague feeling) and something external (what others say, an established theory, etc.). Epistemic agency means working through that relationship between internal and external ideas to some resolution. Ideally, that resolution will consist of a revised idea, which then becomes the object of a further cycle of knowledge work. The great challenge for teachers is to turn this demanding work over to the learners, not to do all of the relating, negotiating, and reconciling for them»* (Scardamalia, 2000; pg.3)

Epistemic agency is what make possible to enrich a concept, for example something that is shown during a physics lecture in class, and enrich its established and context-independent meaning with a personal meaning. This enrichment passes through a tension (academic knowledge *vs* misconceptions) that has to be addressed, because it is precisely this tension that fosters the appropriation of a new meaning. This is related to what Scardamalia says:

> *«The concern is that when misconceptions appear (as they inevitably do when participants are advancing their own ideas) they will catch on and spread like wildfire. In 15 years we have seen no evidence that knowledge building communities hold tenaciously to misinformation, preferring weak ideas to better-developed ones. Once we replace a fear of misinformation with appreciation for continual improvement, we find that pride comes with demonstrations of advances in understanding [...] Discourse tuned to presenting the 'correct idea' is the antithesis of discourse that encourages epistemic agency and idea improvement.»* (Scardamalia, 2000; pg.5)

Working on personal ideas is useful for developing epistemic agency; epistemic agency, indeed, is related to the idea of making knowledge "public", relevant for the class and, hence, valuable. This kind of openness is highlighted by Stroupe, who points out how much **trust** is fundamental in setting down science as practice. Students must feel that they are able to become practitioners of the discipline, with a high level of mastery, but this can be allowed from those who have the authority (Miller et al., 2018).

Cultivating epistemic agency inside the physics class is coherent with the goal of establishing a dynamics similar to what is called *science as practice* (N. S. Nasir and Hand, 2008; Stroupe, 2014). When the learning is seen as a production instead of a reception, pupils become epistemic agents, as it is required by modern policies (OECD, 2018). As Calabrese-Barton states, the goal is to reach the situation in which pupils develop their *identities in practice*; identities are developed through taking agency in the practice and then by experiencing that practice, with a sense of engagement that cyclically reinforces the robustness of practice-identity (N. S. Nasir and Hand, 2008). It occurs a gradual increase in the awareness of self-regulation and self-determination (Jaber and Hammer, 2016), that allows students to build personal trajectories inside the community, toward integral roles.

Also the NGSS (Next Generation Science Standards)[3] seems to recommend an attention to identity development toward the formation of epistemic agency. NGSS delineates the scientific competencies US students have to acquire, to be prepared for college or work. The core of this reform is to allow the students to create personal trajectories during the classroom time, toward being doers of science rather than receivers, to become epistemic agents. However, to set down the place for agency is necessary but not sufficient (Miller et al., 2018). A process of guidance by teachers is needed. If we want to expand students-physics(science)-practice-linked identity at school, and we want to pass through the epistemic agency, we must be aware that the teachers should demand their authority to the community of learners, and they must be ready to accept that new directions could be taken, new norms could be produced. This is basically the idea of *epistemic justice* (Stroupe et al., 2019), that could be achieved by the mean of epistemic tools mentioned above (norms, distributed authority, openness and so on) in a process that is driven by students' sensemaking.

If canonical education methods have been conducted to the need for an improvement, as we can see by NGSS example, or by the OECD learning compass (OECD, 2018), it is clear that the degree of science-linked-identity measured so far in class is not sufficient. Policymakers are looking for new instruments and mechanisms that could enhance the appropriation of science practice, and increase the number of people that feel science-related. So these literature outcomes can be a possible starting point to follow, to reach this ambitious goal.

1.3 Exiting the physics class

So far, we have considered the learning process that happens inside the classroom. In particular, it has been highlighted the idea of science as a practice shared and negotiated by the members of the community, with an explicit focus centered around identity development (practice-linked-identity). Through the years, another strand of research in science education has grown, aimed to analyze the "topological nature" of the community of learning. When a community is formed, boundaries are established and a question that has been addressed is: *«What is the nature of the boundaries of a community of learners?»* (Brown, 1994)

[3] https://www.nextgenscience.org

The answer cannot be given in an absolute sense, since the way teachers, but also other agents that have power on these boundaries deal with those, is definitely crucial. Nevertheless, research community has been investigating this concept for years arguing that boundaries are an enormous source of educational improvement and identity development (Akkerman and Bakker, 2011).

In science education boundaries are borders that exist between two worlds (Phelan et al., 1991), communities (Wenger, 1998), groups (Akkerman and Bakker, 2011) of membership:

> *«A boundary can be seen as a sociocultural difference leading to discontinuity in action or interaction.»* (Akkerman and Bakker, 2011; p. 133)

Since a class can be modeled as a community of practitioners, two other key-concepts are important: **boundary objects** and **boundary people**.

The condition for being a boundary person is to be situated among different groups, at the intersection of these. This is a quite common situation for people. In fact, every day, everyone experiences his/her participation to several social groups in which he/she is a member, but not everyone can see interconnections between these and is able to match all the participations together coherently (Wenger, 2000). Applied to STEM education this means that, for example, there are students studying physics at secondary school, so members of that community of learners[4], that are also members of the community of math class, history class, and even out of school communities (peers, family). The boundary student, in this case, is the one who is able not only to cross the boundaries but also to get some extra value from his richness of memberships. Linked to the ways in which boundaries can be dealt with, an important work was done by Phelan and colleagues (Phelan et al., 1991). They elaborated the "Multiple World Model", that describes the boundary crossing for students between family, peers and school communities. In their research, authors found out four main types of crossing:

- congruent worlds-smooth transition
- different worlds-boundary crossing managed
- different worlds-boundary crossing hazardous
- borders impenetrable-boundary crossing insurmountable

The focus here is on the relevance of being a member of that community and of the repertoire that is developed inside it. For example, in the first category, *congruent worlds-smooth transition*, the transition between school and family or peers is smooth because being a member of the class community is seen relevant also among the out of

[4] we can consider to condition on the fact that there's a high degree of epistemic agency and justice.

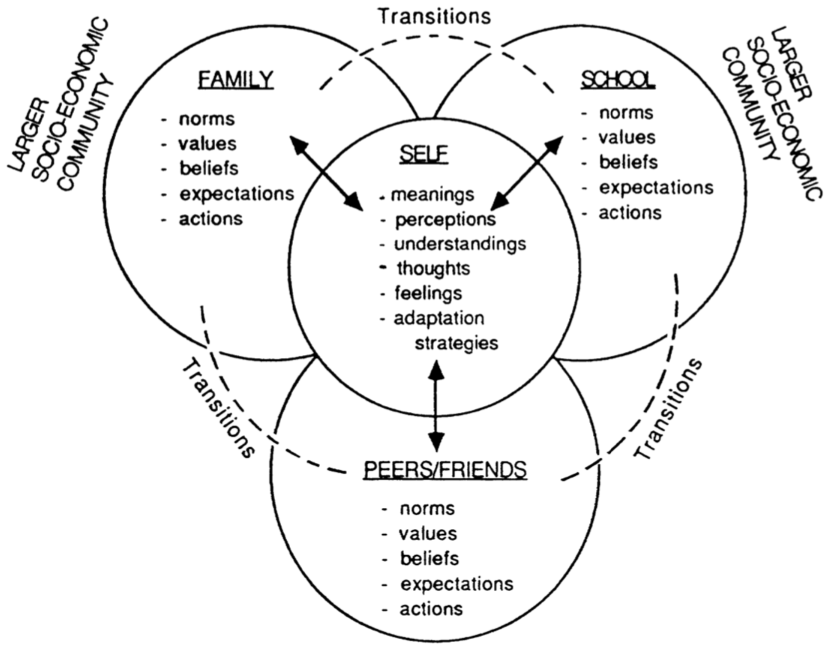

Figure 1.2: This figure shows in a immediate way the idea of Multiple World Model, by Phelan et al. (from *"Students' Multiple Worlds: Negotiating the Boundaries of Family, Peer, and School Cultures"*, Phelan et al., 1991, 1991; pg. 228)

school communities, and the repertoire built at school is coherent in terms of importance with the expectations of members of out of school communities. When this happens, the membership is expanded in terms of personal meaning, with a twofold evolution. Thus there is a bidirectional influence between school world and out of school world, based on the congruence (Costa, 1995). Costa in her work analyzed how much science classrooms were considered as separated worlds, starting with the model of Phelan and arriving to a subdivision of students according to the overlap degree between their groups. Passing through her 5 classes (Potential Scientists, Other Smart Kids, I Do not Know Students, Outsiders, Inside Outsiders), it is evident the bidirectionality of the boundary. Being a guy at home with definite norms and believes compasses toward in-class trajectories that are more or less central depending on the intensity of coherence; from the other hand roles acquired at school influence out of school choices in the community of origin; for example, one student told:

> *«I think that if you just stop and look around at how things are in their entirety, then you have an enhanced perspective of the way life really is. When you look at the big picture, things aren't as bad as they appear.»* (Costa, 1995; p.318)

or in a negative sense,

> *«I feel like chemistry is another world. You know what I mean?»* (Costa, 1995; pg.313)

> *«It's really confusing. And some people that understand me, they say, "It's really easy, what's wrong with you? It's easy." But it's hard, it's hard. Probably it depends on what kind of background you have, too, cause if you have parents that been to college, they've been prepared, and they're pretty much prepared, you pretty much have a better idea what's going on, you like understand things better, cause you grew up in the kind of environment that, you know, they understand more. But if you have parents that dropped out and stuff like that, you know, it's different, it's harder. Cause you try to get help from them, you know, when you're doing your homework. They don't understand what you're doing, they don't know. And it's hard, it's harder»* (Phelan et al., 1991; p.242)

About coherence, there have been many educational projects that try to operate to build in-school expertise, learning the discipline, upon out-of-school experiences, upon repertoires coming from other worlds. If coherence is forced between communities of students' belonging, grounding the subject on everyday cultural practices, it could happen that this congruency reinforces also the participations to the communities involved in the process. This can enable the construction of new shapes of identity, and the participation at the intersection of these, where there is the self (Phelan et al., 1991). As a notable example of this, Nasir takes the AP Project by Dr. Robert Moses, which explores *«translating from students' everyday language to the symbolic inscriptions that characterize the discourse of mathematics[...]in doing so, students are positioned as competent members of both their home communities and the academic community of "doers of mathematics".»* (N. Nasir et al., 2014; p.498). This is a process that must not be shallowed, indeed a depth analysis is needed of what are the instruments **appropriated** and **mastered** in the community of origin and work with them in the educational moment. As Polman highlights, putting identity trajectories together is not a trivial process of mixing all the practices together; the role of the educator is to guide the learner to make sense of the possible chances rising from the intertwining of practice-linked-identities (Polman, 2006). Following a Vygotskijan approach (ZPD) teachers or people with the authority to guide pupils, are asked to enter themselves in the communities of origin and build bridges between them and the discipline. In other words, they have to use the knowledge of that community and that repertoire to be effective identity growers:

> *«Educators cannot merely bring in artifacts from domains of persistent engagement in hopes of learners' positive disposition toward the material "infecting" identity trajectories in a wholly different community of practice[...]Ideally,*

> *the facilitators of learning need to help the learners see how their existing identity trajectory can reinforce and combine with new possibilities»* (Polman, 2006; p.250)

Taking this perspective, it seems that the evolution of learning passes also through the ability to move across different practices, rather than stay always inside the communities, as if they were separated compartments. To trigger the practice of moving, one way is represented by boundary objects.

Boundary objects are instruments, tools, objects of a repertoire of a specific practice, that belongs also to one or more other practices. They are *«both plastic enough to adapt to local needs* (local practice) *[...] yet robust enough to maintain a common identity across sites»* (Akkerman and Bakker, 2011; p. 134). The typical feature of this kind of objects is that they keep some value among different local communities since they have a meaning in all these. Take for example a forest (Wenger, 1998): in what sense is it a boundary object? If we consider the community of forester, the community of hikers, the community of biologists, they all have the object forest in their repertoire, with different meanings and from different points of view. The forest is at the intersection of these worlds, and allows to move across the boundaries. Thus the usefulness of boundary objects is that they allow and facilitate the crossing process mentioned in the Multiple World Model, as a boat with which navigate between groups.

To sum up, what is the potential carried by the use of the boundary metaphor? Why should we want physics students to be boundary people that negotiate upon a practice rich of boundary objects? The reason is that the act of negotiating, as we have seen inside the class with sociomathematical norms, and the idea of *solve tensions and dilemmas* (OECD, 2018) are the fuel for an improvement in students' agency. If we refer to the scheme of Multiple Worlds we see that, at the intersection of the different instances of the worlds a student belongs to, there is the **self**; so being used to match these memberships, without confusing them and without dismissing one, improves the expansion of personal identity. As Gee argues, it is properly the fact that we belong to communities with diverse repertoires, that makes possible the creation of something new and the creation of a new identity aspect.

> *«Hence, boundary crossing should not be seen as a process of moving from initial diversity and multiplicity to homogeneity and unity but rather as a process of establishing continuity in a situation of sociocultural difference. This holds also for the transformation mechanism, in which something new is generated in the interchange of the existing practices, precisely by virtue of their differences.»* (J. Gee, 2000; p.152)

1.4 Community of practice

In this section the theoretical framework of community of practice, build up By Etiènne Wenger more than 20 years ago, is presented (Wenger, 1998).

The concept of community of practice was born outside the domain of STEM disciplines, and even outside the general domain of education. It was born within working and entrepreneurial world, especially related to people working in specific office for an international U.S. company. The strength of the concept and the utility that the instruments developed in this framework have, in order to catch group dynamics and chance of intervention, has widened its range of application, up to the field of physics education.

Communities of practice are basically groups of people (communities) that share a practice. An example of community of practice could be people working in the same office, a family, a group of peers, a sport team, scout group, an orchestra, etc. An orchestra, for example, is made by players which play together, following some rules (being tuned, play at the same tempo, respect the dynamics of musical volume...), but 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, and without the practice there will never be that community. A further feature is that the practice is carried on by the actions of members, by the means of a repertoire, that is either concrete (the object of the practice, such the stands) or even abstract as the rules, the roles, the habits (Wenger, 1998).

Still, the example of the orchestra shows the fact that practice is negotiated within the members. It is not something that is taken from above and respected without free space for interpretation and little adjustments. As an orchestra that plays a symphony, in spite of the constraints and the established rules, there is wide space for personal interpretations, guided by the director and performed by the musicians.

What has been shown so far make it evident some of the characteristics that were formalized by Wenger; he indeed states that communities of practice, to be considered so, must be based on the following criteria:

- **Mutuality**: members must have interconnections; they cannot be isolated if we want that group to be a community of practice. Everyone has his own role, with related pieces of practice to be done, and it is in the dialogue and relationship that the practice is kept alive and negotiated.

- **Enterprise**: the group must have a shared idea of the global mission, a task to accomplish, a common enterprise to which each person has to contribute.

- **Repertoire**:the groups must have a diffuse consciousness of the tools that can be used, in what ways they can be used, for which local purpose, what is the language of the community (take for example doctors speaking in technical terms about a patient).

Now for the researcher interested in the application of the concept in his/her specific field, two questions should be addressed:

1. Are there ways in which I can distinguish between communities and communities of practice? Who decides whether a group of people is a community of practice?

2. Which is the advantage to read with this lens the social group I am interested in?

Since communities of practice can be ordinary group of people, all of us are members of a community of practice, even if we are not always aware of that. The perfect example is represented by office workers; this group matches with good agreement all the conditions mentioned before, Thus, the group can be considered with good approximation a community of practice even if workers do not refer this way when speaking of the colleagues. According to this perspective, the answer to the first question can be that a criterion for a group of people to be a community of practice is that previous conditions (mutuality, enterprise, repertoire) hold. As for the second part of the first question concerning who decides if that group is a community of practice, the answer is that the participants are the real responsible to establish all those characteristics, so the authority is mainly internal.

My research work starts from the assumption that physics classes can be considered communities of practice. The idea is that maybe these groups are not ideal communities of practice, for example, looking at the *enterprise* condition, that can be considered related to the Affinity dimension of identity. As Gee states: *«It would seem that an affinity group [or the enterprise condition]is something that one must actively choose to join. While I could force someone to engage in specific practices, I really cannot coerce anyone into seeing the particular experiences connected to those practices as constitutive (in part) of the "kind of person" they are»* (J. Gee, 2000; p.106).

However proper educational intervention can turn a class into a real community of practice.

In the literature, this thesis is supported by several authors, like Irving and colleagues. They have shown that setting up physics laboratory in a particular way can reproduce the typical features of communities of practice: mutuality, repertoire, enterprise (Irving and Sayre, 2014). They realized that certain educational strategies implemented in the class were useful to *«provide students with the opportunity to have an accelerated trajectory towards being a more central participant of the community of a practice of physicists»* (Irving and Sayre, 2014; p.1). They enlarge the horizon by saying that having a more participant role in the physics class means having a role in the large community of physicists too. Regardless this assumption, here what it is important is the evidence that physics classes as communities of practice are actually existing or at least can be induced. The four structural features, shown as useful in that case, were: “paucity of instructor time,” “all in a room together,” “long and difficult experiments,” and “same experiments at different times" (Irving and Sayre, 2014). Looking in detail to each of this educational choice we can see their relationship with the ingredients of ideal communities of practice: little time for instruction for example, and even the length of the experiment session, means letting space and time for negotiation and discussion around the practice, that must be made all together, with mutuality. The different time devoted for each group to the same experiment allows instead to establish the idea of enterprise, in the sense that the first group will help the next group to solve typical difficulties, for example related to the set-up, properly because they already solved the same problem. Then maybe the two groups will discuss together for the best solution to pass to the third group and so on, toward the enterprise of *being all able to complete that experiment*, or in other words being able to handle with that particular piece of practice. Now, continuing with the focus centered around the example of a community of practice of a physics class, it is convenient to explicit how this is related to physics identity development, since the ultimate goal of this analysis is to find strategies that can make identity expand and grow both in a local (discipline at school) and general (society) dimension. This evolution passes naturally through a negotiation based on the mutuality between the members. When students are presented the classical meaning that can have an object of that repertoire, such as the Lorentz transformation, they gradually appropriate (Levrini et al., 2015) that piece of the repertoire with their images and ideas. They acquire the ownership of meaning, that is valuable in the class and which they can spend in the negotiation process.

Putting together all the ownerships of meaning that each of the students has (as they were doing in Cobb example) leads to the construction of what is called *economy of meaning* (Wenger, 2000), that expands and enriches the initial economy of meaning of the tool of repertoire, when it was presented the first time. Basically the object of the repertoire is still the same but is enlarged in its meaning, because of the transformative action of the community. In this cyclical process students experience the intellectual autonomy that empowers the physics-linked-identity.

From the other side in the construction of the economy of meaning, the interaction between members, guaranteed by the feature of mutuality, means a negotiation of the self, of the proper role inside the community, and draws definite trajectories inside the community, mostly from peripheral to central participation (Tan and Calabrese Barton, 2008).

As also Zahari and Potvin argue: *«for students, physics identity is most often a social identity derived from associations and recognition within a physics-related community of practice»* (Potvin and Hazari, 2013; p.282). The authors in their work designed a framework of physics-identity grounded on the ideas of Gee, Carlone and others, and looked for the elements within this framework that could be predictive of an eventual future career in physics. What seems important here, is to notice that they recognize how much physics-related-identity grows through the dialogue with other members: *«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)*, but also on the access to the economy of meaning and a feeling of intellectual autonomy: *«their beliefs in their ability to comprehend physics content» (competence factor)* (Potvin and Hazari, 2013; p.282).

Now entering the inner elements of the concept of community of practice, Wenger highlights that the fuel for communities to stay alive and continue to being open to renegotiation is the *presence of corners of duality.* These tensions allow the structure to renew the repertoire according to time and changes, otherwise there will be a rigidity that brings to the dissolution of the community itself, or at least at the loss of meaning. He delineates four dualities (Wenger, 1998):

- Local/Global: these adjectives are related to the nature of the practice. There must a global view upon the goal of the enterprise, but with an explicit clarification about the processes in which the local tasks, that are the ones that practically members do every day, take part in the accomplishment of the global work.
- Designed/Emergent: we have seen examples in which there have been used strategies to actually force the birth of a community of that kind; of course, as previously said, this success can be at the maximum an answer and not a consequence, so in this sense the idea of emergence. What occurs most of the time is that naturally a community emerges from embryonal group interaction.
- Identification/Negotiability: also these features have been discussed in detail; there's the typical dualism of being a member of the community that accepts the repertoire and respect bonds of the practice, identifying him/herself with the participation, but the process of participation itself is an act where negotiation of new meanings and new role trajectories occurs.
- Participation/Reification: it is always about a balance between the importance given to members (participation) and to the tools available to them, that are reifications from the general practice. For example, the community of physicists have reified the idea of "measuring time" (from repertoire) with clocks, have reified the idea of "measuring lengths" with meters, or whatever.

The communities of practice show their strong utility to the research purpose, that will be discussed later, because they are useful to operationalize identity formation (Wenger, 1998). In particular, in author's opinion, there is a direct correspondence between aspects of the practice and aspects of identity formation (see table 1.1), following the mentioned path of practice-linked-identity; so practice and growth follow each other intertwined.

practice as	**identity as**
negotiation of meaning (through participation and reification)	negotiated experience of self (through participation and reification)
community	membership
shared history of learning	learning trajectory
boundary and landscape	nexus of multimembership
constellations	belonging defined globally but experienced locally

Table 1.1: Practice and identity

It can be seen, for example, that sharing the learning process with the other members, both a personal and a distributed learning, makes it possible to create roles and trajectories, as we have seen in practical examples (N. S. Nasir and Hand, 2008; Levrini et al., 2015). As we can observe, one of the elements that characterizes identity is the **nexus of multimembership**. To capture the meaning of this concept, one can imagine a physics class to which one person belongs to, but at the same time he/she belongs to other worlds (as we can see with the Multiple World Model); at the nexus of these diverse memberships (here we consider all the worlds as communities of practice), there is the self, the identity.

What happens at this junction? The nexus can be imagined as an hybrid place, even a physical place, where the person tries to coordinate all the instances coming from his/her worlds, to match them in terms of coherence and value, to mix them in an original and unique fashion. In that place the person is alone, but with the different pieces of practice-linked-identities that all together build up the identity. As we can see the process of passing between different communities relies upon boundary objects (as we discussed before) and brokering (boundary people dealing with specific repertoires).

The strength of these concepts is that they allow to study with precision what happens between borders, assuming that they are dividing communities of practice.

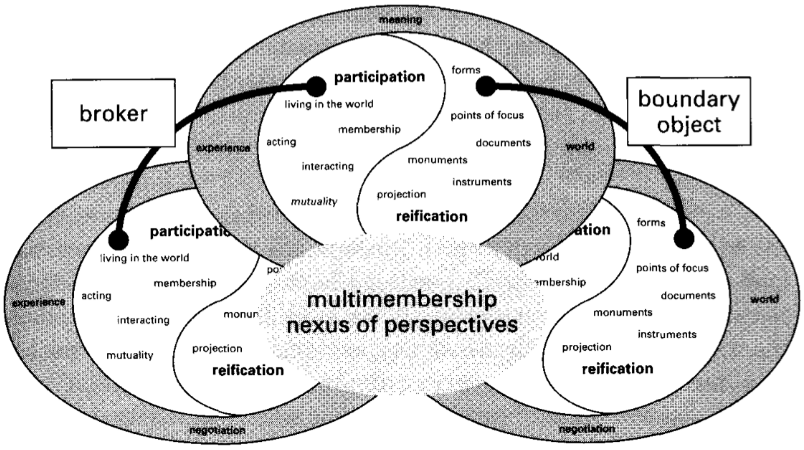

Figure 1.3: Nexus of multimembership at the intersection of different communities (from *"Communities of practice: Learning, Meaning, and Identity"*, Etiènne Wenger, Cambridge University Press, 1998; pag. 105)

Chapter 2

Problem formalization: a research narrative

This chapter aims to address the first set of questions: *Is it possible to find a way to formalize the big issue of the lack of personal relevance of physics? What research constructs and tools, elaborated in STEM education, can be used to describe the process that leads/doesn't lead students to bring knowledge out from their physics classes and turn it into thinking tools for life? How can these constructs be combined to describe the problem in a way that can be addressed by the research?* (RQ0).

The questions are related to the general problem of the detachment that students feel between learning physics and the formation of their personal identity.

Starting from this issue, in the chapter one I firstly presented the main literature outcomes in STEM Education that seem to be crucial to investigate the relationship between physics learning at school and identity development. Then the most important tools to describe and address the scaffolding of the general issue are discussed.

Here I try to build a research narrative that can translate the problem I felt into a research language so as to be able both to communicate it and to make it more and more addressable with research tools. This chapter is crucial for and motivates the experimental sessions that we have designed to check the relevance and applicability of the approach.

As it will become more evident in the following, by *narrative* we mean a story-telling that starts by imagining a "character" (a student) entering a physics class, with the aim to develop his/her personal identity, and making the experiences that can support him/her to make sense of physics in a personal sense also out of school. The narrative is a rhetoric way to re-organize the problem and give it a structure made grounded on theoretical instruments.

Identity will be the leading thread and, with respect to the literature review we have illustrated in the previous chapter, a special role is attached to the two nuances of Gee called D-Identity and A-Identity, being the two most context-dependent nuances and the most "malleable" by the experiences, practices, and relationships. Their connections with school and STEM practices and norms are stressed so as to link the individual dimension identity to the social dynamics of a class.

2.1 STEM class

Let us imagine that our "character" enters the class, to say our student gets first in touch with physics discipline, and let us follow him/her in his/her exploring process. Physics class is the first scene of our narrative and here we will formalize what "being in a physics class" means, by using the tools that STEM education provides.

Following the position discussed in chapter 1, the class can be interpreted as a community of practice, where the practice is **learning physics**; by referring to the pillars of this concept, let us read them in this specific situation. *Mutuality* becomes the interaction process among classmates and between them and the teacher, with the recognition of all the roles. The *enterprise* becomes the fact that all the members want to learn something of physics, enriched by personal meaning, and maybe they want to do that together with reciprocal help (Irving and Sayre, 2014). The *repertoire* is intended as constituted by the objects of knowledge (the physics concepts, instruments such as equations...), but also the various representations and languages that are used (formal, visual, gesture, and natural languages. . .), as well as the socio-scientific norms that can be negotiated in the class and the practices. The immersion in this environment lead competences to be developed. Maybe some of them are content-specific, other are transversal (soft skills), other are what we call as "products of **collateral learning**".

The meaning of collateral, in this case, is to be intended as processes that are not designed, not explained to students, something that they can notice, in case, only in a second moment when these competences appear in another context.

It is useful to remind that, regardless these dynamics of collateral learning can be effectively established in some way, these competencies are practice-linked, in our case typical of physics. These competences can be thought as thinking tools: instruments that expand the range of action of the scientific thinking of the student. For example the act of studying thermodynamics from both a macroscopic and point of view (Levrini et al., 2015) develops, in a collateral way (besides the objects of knowledge such as temperature, pressure, distribution, phase of matter) the ability to look at what can be done, what can be asked and what can be answered from different perspectives, to recognize and compare the assumptions that stay behind different models or approach, to discriminate between important and less important variables, and so on. Or for example by studying the Hartree-Fock approximation, one student can add to his/her baggage of thought, in a collateral way, the idea of simplifying, selecting just few variables according to what is needed.

Another piece that comes to complete the description of in-class scene, is the idea of epistemic agency. This element is fundamental to assess the interpretation of self-construction of the sense of belonging to the community, that passes through the appropriation of physics. Here, acquiring a practice-linked-identity is interpreted as the achievement of an intellectual autonomy and epistemic agency.

So, we can imagine that the student has entered a classroom that can be considered as a community of practice, where the practice is to learn a physics topic, using the repertoire initially provided by the teacher and then negotiated by the members (our student included); the act of appropriation is fostered if the overall climate promotes epistemic agency and leaves room for negotiation of the meaning thanks also to the negotiation of the scientific and socio-scientific norms. If this actually happens, our student has the chance not only to learn the objects of the repertoire but also to develop *collateral skills* that expands his/her set of scientific thinking tools. In this sense, the student has an occasion for developing and/or increasing the physics-linked-identity.

2.2 Borders of a STEM class

The research narrative then proceeds with the second scene, involving the character (student's identity in evolution) to deal with the boundaries of the classroom. This part represents what previously has been called as *outgoing* process, the time at which the membership of the community of practice of physics has been established and the trouble is to manage the relationships with other communities.

To describe this second scene, the essential literature that allows conceptualization of the boundaries of a physics class can be used. The description is dependent on the kind of social and institutional setting (e.g. secondary or university classes, classes in technical, vocational schools or Lyceum) but specific boundaries that identify a physics community can be related to the physics epistemology itself and, in this sense, are intrinsic to the knowledge and the practice.

The boundaries of a community of practice can be divided into **proper** and **improper**. The proper boundary occurs between two communities that can be easily recognized as such and that share some of their practices. For example, considering a physics teacher, he/she is both a member of the community of practice of the physics class, and a member of the community of teachers. In this sense the boundary between class and teaching staff is proper and institutionally defined and recognized. The improper boundary of a community of practice is instead experienced at a personal level. Considering for example a physics student that belongs to a basketball team in free time, he/she finds an improper boundary between physics-class community of practice and basket-team community of practice. It is a kind of boundary that is uniquely dependent on the student, since the communities by themselves do not share anything.

For the purpose of our study, it is also important to assign a direction of crossing boundaries; indeed one of the sub-problems shown before was related to understand what can be extracted from physics communities in terms of knowledge. Thus, as already discussed, the repertoire of the community of practice includes also collateral competencies. Then, assuming that the competencies are more likely to be taken away from a class, it is useful to consider the idea of *outgoing/ingoing* flux of competencies, as the dynamics through which skills of this type both exit and enter the physics class keeping a meaning[1].

Once described the boundaries, we need to consider the crossing boundary mechanisms that students can activate and find a way to operationalize them. For this purpose, the theoretical work by Akkerman and Bakker (2011), and the nexus of multimembership are the pillars we have chosen to describe the crossing boundaries processes and their crossroads. In other words, retrieving what also Wenger stated, boundaries can be directly crossed by the student who can play the role as boundary person, or indirectly by the use of a boundary object that widens the meaning of the practice.

Once the person is capable of being a member of different communities and inhabit consciously the nexus, then can be considered as a pioneer (Wenger, 1998).

So, resuming the path followed so far by our character: the first step was to identify and describe in what sense is intended the evolution of a student. Then the first-scene occurs when the student enters the class and start to interact with physics. The subsequent step is the moment in which, after starting the establishment of a practice-linked-identity within the physics community of practice, the character pays attention to the interaction which the new practice-linked-identity has with his/her other identities coming from other communities of practice. So the narrative flows with the dealing of boundaries and the exit process from the classroom. Once the character understood how to treat the intersection of different worlds and the exit process, he/she can finally reach his destination: a personal state placed at the nexus of multi-membership, acquiring the title of pioneer, in the sense of a person who is exploring the state of multi-membership in an idiosyncratic way.

The narrative summarized above tells one of the possible routes that student's identity could follow, when fostered by physics education. It represents a way to touch the crucial aspects that allows finally to translate the initial problem, on the basis of STEM literature, and close to physics student experience.

In other words, the line built so far, expressed in a more academic language, represents a possible answer to RQ0 and paves the way to addressing the second set of Research Questions (RQ1): *«To what extent is the problem described in the narrative felt by the physics students? Is this "research narrative" effective to illustrate the problem?»*.

On the basis of the narrative, we can also reformulate the question *«How can the problem be addressed in teaching? Can concrete examples be pointed out?»* (RQ2) into:

[1] this is actually what happens in the first scene, when the character enters the class with some personal abilities that he took from his set of out-of-school experiences.

«what are examples of thinking tools that can be developed in a collateral way inside the community of practice of a physics class, and that contribute to the outgoing flux of competencies and, hence, that can be considered as part of the repertoire of the pioneer, living at the nexus of multi-membership?»

In the next chapters the ways to address RQ1 and RQ2 are described. As regards RQ1, we decided to find a sample of students to test how much they share the problem formalized by the narrative and how much the problem itself is meaningful for them. Concerning RQ2, we found important to zoom into the narrative, and subdivide the general RQ2 in two parts that can be more fruitful for the inquiry process. Thus starting from the research flow carried out to address RQ0 (the reformulation in academic terms), one possible useful specification could be carried by the next two questions (RQ2-A and RQ2-B):

- RQ2-A) What are examples of collateral thinking tools, developed by the study of physics, that are educationally relevant concerning the physics epistemology? From which objects of the repertoire they come from? Which ones of these and why do they have more chances to be taken out from the classroom keeping some value when placed at the nexus of multimembership?

- RQ2-B) In which ways these physics-thinking tools can be placed inside the nexus and made part of repertoire of the pioneer? Do they bring with themselves an intrinsic character of danger or opportunity? What does it mean being pioneer on the basis of physics repertoire?

Chapter 3

Empirical studies: context and methods

This chapter regards the presentation of the context and the methods followed in the empirical sessions that have been carried out to address the research questions. The first session concerns a class discussion with master physics students and has been carried out to answer to RQ1, that is to check if the problem and its formulation were meaningful and important for them. The second session concerns in-depth interviews, carried out to collect fruitful experiences upon which try to address RQ2, about possible directions to follow in order to fill in the gap between students and their perception of the value of physics learning. For reasons that rely on the pandemic situation in which we are stuck nowadays and even more during the periods of empirical session, either the collective discussion either the interviews were held at a distance.

Collective discussion

The class discussion was held on the 21st of April, 2021; the setting was a lecture of the course "Physics Education"[1] of prof. Olivia Levrini. The sample was quite heterogeneous. In fact, it was composed by 44 students that attended different curricula (theoretical physics, applied physics, history of physics and physics education, nuclear and subnuclear physics, material physics and nanoscience, astrophysics).

The sample was somehow representative of people that study physics with different perspective and approaches.

[1] Within this course the students usually face arguments that are typical of the physics' curriculum of italian secondary schools, but from a perspective that could be profitable for an aspiring secondary school physics teacher: in particular, since every student already knows the topics, that have been studied during the bachelor, the focus is on teaching techniques, possible difficulties of students placed at different levels (cognitive, disciplinary, epistemological, didactic) and classroom settings that can foster a better appropriation (Levrini et al., 2015) of the discipline.

The collective discussion lasted about half an hour and consisted in two phases. In the first phase the research narrative and the formalized problem were introduced. In the second phase the students were asked to answer questions through Wooclap and the Jamboard. The tools for collecting the data are presented in section 3.1.

The first phase consisted in a presentation of the core concepts extrapolated from the literature that are the pillars of the research narrative. In particular, firstly the research problem at the center of my thesis was introduced. Then the fundamental concept of community of practice was presented, to show how this can be a lens by which to read class dynamics, and how the *practice* affects identity development (*practice-linked-identity*). Thus, the concept of epistemic agency was mentioned to see how students can relate themselves with the practice in a way that expands their practice-linked-identity.

Then the metaphor of the boundary and the figure of pioneer were introduced to describe, respectively, the intersection that a student feels about the groups within which he is a member, and the metaphor of the *pioneer* was shown, representing the condition of a student who has appropriated physics concepts/tools and uses them in another community of practice.

Finally the concept of nexus of multi-membership was illustrated to describe the situation, the moment, in which the student deals with pieces of repertoires of his different communities of practice; this is the condition where he has to manage effectively competences that come from different worlds.

After building a common vocabulary, the metaphor of the pioneer was presented in order to foster them to assume an "epistemological position" as members of one or more community of practice who each day have to deal with other communities of practice and, sometimes, share ideas, concepts, tools, methods, practices (etc.) with the others (see Fig. 3.1). In other words, I used metaphor to trigger students' impersonation in the pioneer and make the presented concepts root in their personal stories and experiences about studying physics.

The second phase is the phase of data collection. It aims to collect data about the degree of proximity of the sample with respect to the problem and about the effectiveness of the research narrative displayed. This phase was divided in 3 parts, as summarized in table 3.1.

In the first, the questions, investigated through Wooclap, were:

1. To what extent from 1 (not at all) to 6 (completely) do you feel close to the approach presented?

2. To what extent from 1 (not at all) to 6 (completely) do you think it is effective/fruitful to describe physics class as a community of practice?

3. To what extent from 1 (not at all) to 6 (completely) do you feel as yours a discourse of multi-membership to different communities?

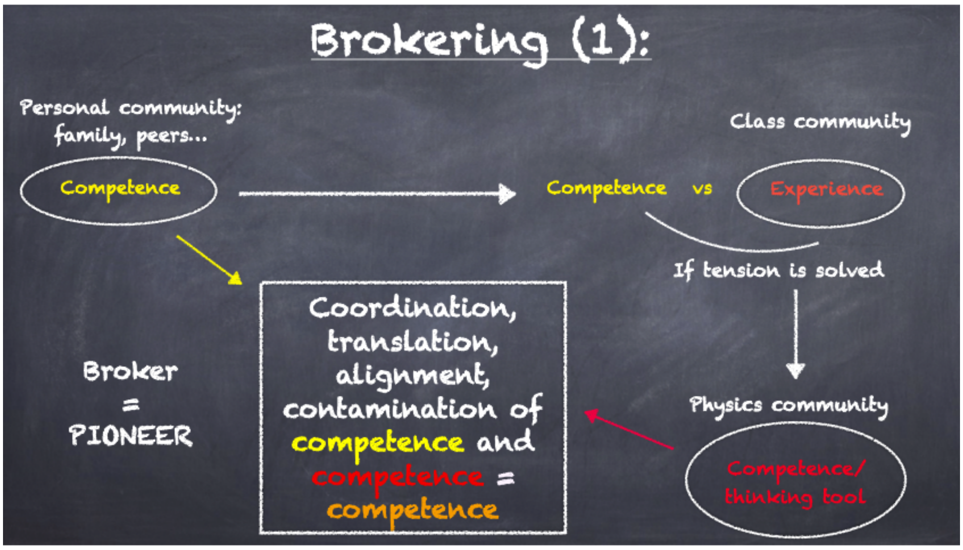

Figure 3.1: One of the slides showed in class: we notice how much discussion is centered around images representative of the research narrative

The second part is aimed to collect words, feelings, opinions about the presented approach, the formalization of the problem and personal experiences related to boundaries in physics education. The collection was made by Wooclap by asking the following question:

> *«This approach place emphasis on terms such as "imagination", "multimembership", "boundary", "community", "brokering"... How do you feel this vocabulary? In other words which adjectives you feel connected to the vocabulary used in the approach? (For example fruitful, productive, annoying, stimulating, useless...)»*

The third part aimed to collect data more linked to RQ2 (using the google Jamboard). In the specific three questions were asked to the students:

1. How can be stimulated, within a physics class, a participation for imagination?
2. Among the thinking tools that can be appropriated within a physics course, which ones do you think are more exportable and coordinable with competencies from other communities?
3. Which of the objects of a physics course can be treated as boundary objects?

Part	Questions	Tools of data collection	RQ-Addressed
1	To what extent from 1 (not at all) to 6 (completely) do you feel close to the approach presented? To what extent from 1 (not at all) to 6 (completely) do you think it is effective/fruitful to describe physics class as a community of practice? To what extent from 1 (not at all) to 6 (completely) do you feel as yours a discourse of multi-membership to different communities?	Wclap	RQ1
2	This approach place emphasis on terms such as "imagination", "multimembership", "boundary", "community", "brokering"... How do you feel this vocabulary? In other words which adjectives you feel connected to the vocabulary used in the approach? (For example fruitful, productive, annoying, stimulating, useless...)	Wclap	RQ1
3	How can be stimulated, within a physics class, a participation for imagination? Among the thinking tools that can be appropriated within a physics course, which ones do you think are more exportable and coordinable with competencies from other communities? Which of the objects of a physics course can be treated as boundary objects?	Jamboard	RQ2

Table 3.1: Collective discussion

The audio and the video of the entire activity were recorded, transcribed and pseudo-anomized.

Interviews

The interviews that we carried out were semi-structured and individual. The protocol has been designed with the goal of addressing RQ2A and RQ2B and was built according to the methodology described in Castillo-Montoya (Castillo-Montoya, 2016). Starting from the general question and then build up easier and more answerable sub-questions related to single pieces of information that combined all together could stand for a full answer to the research question. The author in his work sets up a matrix in which each column represents a different piece of information regarding the general questions to be addressed, and each row stands for the specific questions of the protocol, the ones that are asked during the interview. Each row can be useful for none or all the pieces of information displayed in the columns (e.g. 1 or 0 if it answers or not).

The final interview protocol (see Appendix A, table 2) is divided in two parts. The first aims to investigate what happens inside the classroom (first scene of the narrative); thus questions are devoted to asks for personal experiences of students that could be related to the objects which compose the first scene of the narrative.

The second aims to investigate what occurs at the boundaries and also outside the class (second scene of the narrative).

Before starting with the session of interviews, a pilot interview was held in the second half of July with a student at the second year of the Master in History of Physics and Physics Education of Alma Mater Studiorum. After the pilot, the questionnaire was refined and changed into the version here presented.

Seven volunteer students were interviewed between the end of July and the first half of August, on the Zoom platform. The students agreed to use the interviews for research purposes, and accepted to be audio-video recorded. The interviews lasted about one hour each, but some of them were even much longer because of the informality of the environment and of the kinds of chords that the questions and the problem touch.

The seven interviewees had participated in the collective discussion that took place in April. The students, interviewed on voluntary basis, were 1 female and 6 males, that attend different curricula (theoretical physics, History of physics and physics education and astrophysics). Also in the collective discussion, these students proved to have a particular sensitivity and interest toward physics education and identity development.

In the following the main results were presented referring to them with pseudonyms.

Chapter 4

Analysis & Discussion

In this chapter the data are analyzed and discussed, in the light of the research narrative designed in chapter 2. In particular, the students' reactions about the presented research narrative and the formalization of the problem are investigated.

The results are not intended to be exhaustive but they represent a starting point for a work that will be further developed.

The chapter is divided into two sections, each of them related to one of the questions (*Addressing RQ1* and *Contributions for a possible answer to RQ2*) in which the main results of both the experimental studies are presented.

The graphs are reported as a synthetic way to represent what emerged in the class. It doesn't have, of course, any statistical value.

4.1 Addressing RQ1

4.1.1 Collective discussion

In the following the main results emerged from the collective discussion are reported. As shown in table 3.1, here are reported the analysis of the part 1 and 2 of table 3.1.

The figures 4.1, 4.2, 4.3 show, respectively, the answers to the questions:

1. To what extent from 1 (not at all) to 6 (completely) do you feel close to the approach presented?

2. To what extent from 1 (not at all) to 6 (completely) do you think it is effective/fruitful to describe physics class as a community of practice?

3. To what extent from 1 (not at all) to 6 (completely) do you feel as yours a discourse of multi-membership to different communities?

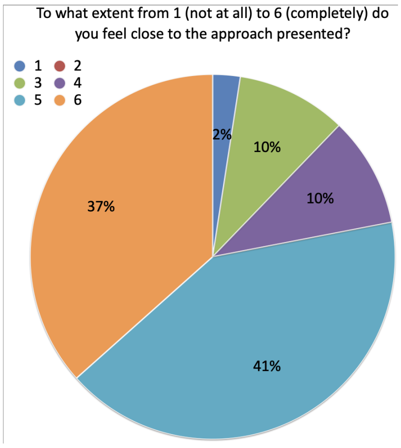

Figure 4.1: Wooclap 1

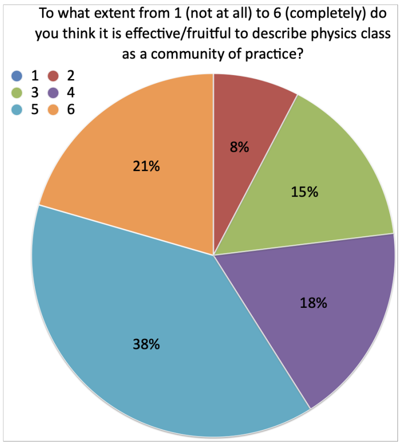

Figure 4.2: Wooclap 2

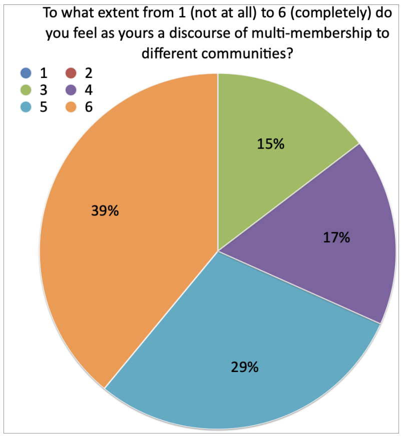

Figure 4.3: Wooclap 3

Moving from one question to another, the students were asked to comment and explain their ideas.

As for figure 4.1, most of the students manifested a certain closeness to the approach, in fact the large majority (88%) of the students voted 4 (close), 5 (very close) and 6 (completely close). Only a small part of the students proved to be not close or not familiar with the approach.

As regards the figure 4.2, the 77% of the students agreed that the community of practice can be a proper construct to describe a physics class while the 23% showed a certain hesitation. Between this 23% of students, two in particular commented that they did not share the idea that the concept of enterprise can effectively be applied to a classroom at secondary school. A student in particular reported:

> *«Concerning this I am a little surprised by the outcome of the poll about how much is realistic defining a physics class as a community of practice, since actually it is not, at secondary school it isn't, nobody wants to do physics, well maybe few... it could be a community the one of the teachers, instead the majority of the students are there because they have to. So there is the common repertoire, and also the other thing that now I don't remember, but the enterprise is missing...»*

Therefore, as figure 4.3 shows, the large majority (85%) of the students did not only resonate with the sense of community of practice, but it seems that they also found the construct effective to describe their personal experiences. Furthermore, the idea of nexus of multi-membership was perceived as a natural clarification of something that usually is just not addressed with formal language.

On the whole, the research narrative about community of practice and the idea of the nexus of multi-membership proved to be effective for the students (RQ1). The result was quite unexpected because of the heterogeneity of the students and the language of the approach that could sound rather far from physics and maybe too much sociological or anthropological. Instead, it seems that physics students largely resonated with the problem.

This result emerged also from the second part of data collection (Part 2, table 3.1) In the second part, students were asked to write through Wooclap some adjectives that could describe their feelings about the presented approach.

In figure 4.4, the words cloud shows the chosen adjectives. The thickness of words' character is related to the number of students that had wrote it. The most "popular" and positive adjectives used were *stimulating, productive, fruitful, inclusive, necessary, innovative, actual, effective, fluid.* Some of the most "popular" adjectives express some hesitation, as happened in part 1, such as *difficult, far, risky, tiring, annoying, complex.*

Figure 4.4: Adjectives about the approach

Some of the students motivated the adjectives that they chose. In particular a student, who chose the word *humanity*, said:

> *«I said humanity, as the group of humans, because these words but also the concept of community...I feel like characteristics of the human being and so*

[...] well the intermediation between communities, finding contact points, they seem typical of human structure»

Another, who chose the word *natural*, said:

> *«well I wrote natural because [...] this way of presenting that you used, in my opinion...I feel like natural, it seems absolutely natural the manner in which you describe our way to progress, the way through which proceeds our knowledge... »*

Another student, who chose the word *visual*:

> *«in my opinion the fact that gives images as community, alignment, pioneer too, they are all things with a well formed idea in our mind...maybe the meaning is a little bit changed, in the sense that it is expanded, but this approach is truly visual»*

To sum up, from this analysis it emerges that the research problem is a shared problem and that the tools extrapolated from the literature and the research narrative can be considered effective.

4.1.2 Interviews

In this section, other results about the proximity and the effectiveness of the approach (RQ1) are presented. In particular, out of the seven interviews[1], two were chosen because the students did not only appropriate the vocabulary, but they also showed a personal rielaboration of the main constructs in talking about their experiences.

The first student can be called the *self-questioning student* (S1) because from the interview it emerged that for S1 the "self-questioning skill" is one of the main product of physics collateral learning. In S1 words:

> *«I think that is something general [...] the fact to be able to* ***question ourselves****, physics teaches us to question ourselves again about concepts that we saw a lot of times, I think that this is some of those collateral learning (outcomes), one of those abilities that most of the people do not have; we do not take it for good a law, an equation, we continuously* ***question it****, find its validity, try to re-demonstrate, and when something does not make sense there is not that being reluctant to* ***question ourselves****...»*

[1]We remind that all the students were asked to review the slides seen in class during the first activity carried out in April; then at the beginning of each interview a brief summary of the theoretical pillars of the formalization was presented.

This idea continues throughout the interview:

> *«I think it is one of the greatest skills that I feel I have personally developed, to say this desire to **question myself**, I feel it can be considered a collateral ability, as we said...»*
>
> *«Well, related to Lorentz I think it is to **question**, to **question yourself**...»*
>
> *«I mean, not only physics gives you the opportunity to see how is it possible to **question yourself**, that's what I mean [...] and I think that they are some of the competencies, the value of error, to be able to **question yourself**, that I think are fundamental in everyday life [...] in general for the person, for his development, I think it is better to deal with people that are able to **question themselves**»*
>
> *«I think that I actually have this capability of...as many other colleagues, not all but many, to look at things from different points of view, to be able to go beyond and **question yourself**...»*

The specific attitude of self-questioning is an important aspect of the research narrative (chapter 2) because it recalls the active role of the student who first appropriates a concept/tool/method/theme and then "takes it out" of the physics class bringing it into the nexus of multi-membership, in *everyday-life*, as he said.

The second student can be called the *structuring student* (S2) because from the interview emerged that for S2 one of the most important effect of *collateral learning* is that "physics structures the mind and the person".

In S2 words:

> *«this collateral learning I see it as a **structure** of the person, thus which gives some tools to read external reality...I think that exists (collateral learning), and I think it is fundamental, and should be teacher's responsibility to realize that they (collateral competencies) are present and push (education) more with these»*

Physics provides tools that structure a mindset and that can be used in other reality (outside the physics community of practices). As in the previous case, this idea continues throughout the interview:

*«so we can say that from physics structures I probably took out an introspection which then leads to externalization... And this in my opinion means to catch physics, not only catch the inquiry method, that surely is very useful, but also **intimately structuring a person**...»*

*«I actually am good in communicating with people, or better I have become because in my mind I **took structures** that I had learned in physics, I am referring now to reasoning and inquiry, and I had **brought them** in the communication field»*

These two case studies are emblematic of how these students immediately recognized and shared the problem and how they resonate with the approach. In these cases the effective of the narrative seemed to pave the way to the re-elaboration of some ideas through their experience, suggesting some kind the effectiveness of the approach.

The way in which S2 used and re-elaborated the narrative vocabulary, his discourse's articulation, deserves a special attention, that will be devoted in the subsection below.

The case of S2: fine-grained analysis aimed to unpack how a student interpreted and used the narrative to describe his personal experience with physics

The interview of S2 has been analysed at a particular fine-grained level to investigate if and how the narrative could be experienced by a student. The analysis has been carried out with the lens of the theoretical framework and their key constructs: identity, community of practice, collateral thinking, boundary crossing, nexus of multimembership.

Operationally, the excerpts that touched these constructs have been selected from the interview and rephrased with two aims: to extract their core message in a way that can be comprehensible also out of the entire interview; to highlight the relation the analysts saw with the construct. Then, a reflection has been carried out to check if and how the student was contributing to elaborating the construct and the theoretical framework.

The result of the analysis is the table reported in the table 4.1.

At the basis of the analysis, there is this assumption: the narrative represents a sort of skeleton made of "placeholder words" that can be enriched by particular and specific experiences.

As we will show, the interview of S2 is an example of how the research narrative was effective, in the sense that the student did not only resonate with it but it also stimulated deep and wide reasoning on personal experiences that led to enriching the narrative itself.

Table 4.1: Fine-grained analysis of S2 interview

Original sentences (translated)	**Construct to which the sentence refers to**	**Construct enrichment**	**Core message (sentence rephrased to make its meaning and its relations to the construct more evident)**
[A collateral learning tool] can be even made explicit for *purposes,* to tempt… I don't know.... that which can be *his purpose* make it explicit	Collateral learning	Confirmation of the relevance of collateral thinking and the need to negotiate in class the aims and goals of collateral thinking and to address explicitly the development of collateral thinking into classroom norms, by sharing their goals	The purposes of tools of collateral thinking have to be made explicit in class.
I associate it (collateral learning) mostly to the danger, collateral danger. In this sense, collateral appears almost as undesirable but instead to me it is desirable or even necessary […] Inquiry tools...this definition....can be considered as transfer; thus which you can take it and make it yours in different fields. . . I would define it this way: a cognitive transfer that you steal from physics, and the collateral danger is that you can apply it effectively in other areas of life, from which scooter to buy to moral questions....a wide range...	Collateral learning	The term "cognitive transfer" can be better than "activation of collateral thinking"	The term "collateral thinking" evokes "collateral damages" and it seems that they are neither pursued nor explicit. "Cognitive transfer" is a better word.

With a risk related to this transfer, for this reason, I wanted to say this; that learning physics in a certain way, and mathematics too, a very *strict* way and so when the formal part, the part of the *rigor*, the part of *truth* strongly emerges, you structure (to my opinion), and you take it out, a *mindset which closes you rather than opening*, since you *reason properly*, you say true things and so you are less willing to see *diverse points of view*, you are less willing to have a communication made by one who speaks and one who receives, but you move more through absolutes, much more through dictates.	Crossing boundaries and nexus of multimembership	A few epistemological aspects of physics (rigor, the search for truth, absolute) can lead to structure a mindset that contributes to close the perspectives, instead of opening toward the diversity	A special way to learn physics, that focuses mainly on a few aspects of physics (like rigor, truth, formalism), can structure a mindset to foster closeness instead of opening to the willingness to accept and recognize different points of view.
A logic that is extremely *economic and strict* [...] is deleterious in the moment in which you take this arrogance inside a relationship [...] because when you take this concept from physics and you apply for a purpose, *that purpose you must care that resonate with what you are doing;* [...] you end up to win every discussion because at a certain moment you make the discussion a competition, impoverishing the discussion itself.	Crossing boundaries	A different context has different purposes. A piece of practice repertoire, like a rigorous form of physics reasoning, can be powerful to pursue some goals in the physics community, like to contribute to building strong, coherent, and consistent argumentations. If you use it in a different context, you have to renegotiate the purposes, otherwise, the same piece of repertoire can lead to opposite effects.	*Economic and strict* logic is fundamental in science to “win” in a scientific dispute. If you use it in another context where the purpose is not to confront the strength of arguments, is deleterious since you turn the discussion into a competition and impoverish it...

Thus, even though your instrument is powerful, even though used in a certain way, takes you to impoverish also there (in discussion), since you *lose other opinions, since you lose other reasonings, other values* and this is really deleterious It is useful to show utility but also risks that one tool brings [...] use it (the instrument) improperly is always very risky	Nexus of multimemberships		… indeed, if one uses a strict and economic logic (that is a good practice in a scientific dispute) in another context, it can lead to impoverishment of oneself because it leads to losing other opinions, other reasonings, other values.
Actually it (the strict and economic logic) is flagship instrument about *why* a student should study physics and mathematics, since you structure a logic to being able to *discern reality and in some sense to have a discussion-capacity very strong to being able to win*; but we should be able to *separate the capacity from the aim and the purpose, so you should have an ability of critical analysis*, this is what should bring (the strict and economic logic), not an ability [...] to reach the truth...	nexus of multi-memeberships	An ability that is needed to cross the boundaries and inhabit the nexus of multi-membership is the ability to separate the form of reasoning, from its aim and purposes: the *ability of critical analysis of reasoning*, not (only) the ability to build strong reasoning that leads you to reach the truth.	Today, the main reason to study physics still appears the need to form a structured, logical form of thinking that is supposed to enable you to *discern reality, have a strong discussion capacity* and win a discussion. Instead, we should learn to be able to separate the form of reasoning per se, from the aim and the purpose of such reasoning. Today you should *have an ability of critical analysis*, not (only) the ability [...] to reach the truth.

This reasoning (strict and economic logic), when applied *outside*, leads you to *define everything*, when essentially seen in a certain light, *nothing is definable* [...] so it leads you to have *ideal monsters*, it leads you to have truths, absolutes, which *is not that which you must reach,* it is not the objective because you are within a reality which uses different instruments and wants to reach *different objectives*, but not necessarily defined and not necessarily truths	crossing	Dealing with other communities of practices requires rethinking, "translating", negotiating personal norms, aims and values that frame that community.	When the strict and economic logic is applied out of the physics community of practices, foundational issues have to be re-defined. (Physics) reasoning (due to the strict and economic logic) implies ideals, that include the search for truths, or "absolutes". Out of the physics community, where the perspectives, the ideals, the objectives are different, other tools are used to reach those objectives. We cannot take for granted that the ideals of a scientific community fit with the ideals of other communities of practice that, consistently, have other aims and other tools.
That (determinism approach, cause-effect) is surely the most effective (collateral thinking tool) but with the *risk* that it becomes also the *driest* from a certain point of view, because it can also be *so true that it can be limiting*, it is so this way (how world works), *so cause-effect,* it is so back and forth, it is so action-reaction that there's not an *other way*… thus *a model which works so good in that field (physics)*, can be limiting when transferred in other fields; very *practical, economic*, but in some case *limiting*…	community, socio-scientific norms, crossing	Some epistemological norms that characterize physics (like determinism and a linear structure of cause-effect) structure a community. They are difficult to transfer to other contexts without losing their effectiveness and their coherence with the goals of the practice. Thus, they can create barriers. Some epistemological norms of physics can foster closure, instead of openness and divergent thinking.	Features like determinism, cause-effect relations, characterize a type of physics and make reasoning effective, operational, practical, and economical. However, they can be also limiting when these practices are used with different scopes and goals.
(about Lorentz transformation) when instead you talk about Lorentz transformations, something like this, they are much more *open*	crossing	In the XX century physics (e.g. relativity and quantum physics) there are themes that stress to what extent in physics there are also epistemic norms that make some pieces of practice repertoire be transferred. Openness can be found within the epistemic structure of physics.	Themes like the Lorentz transformation (due to their different historical interpretation and their role in breaking down some sense of absoluteness) can lead to a sense of openness and leave space to translate them into other communities.
[...]the *need* to find answers in these structures which actually inside physics appear *perfect and true*, and thus (the student) will use those (outside) in a very strict way, when he will manage to use	Community, A-identity	The perfection and rigor of the scientific norms give you the illusion that they can answer all your needs and that they can be used everywhere in the same way without any form of re-negotiations.	The structures within physics seem to be so *perfect* and *true* that can give you the idea that they satisfy all your needs of *finding answers*. Thus, you tend to appropriate them and use them everywhere in the same way.
and to use (the instrument, for example economic and strict logic) it in a conscious way also know when *it is not to be used*, in this sense I was talking about *having antibodies*	nexus	The export of a physics structure in another context requires a caution principle and to know when it is productive and when it should not be used.	In order to use physics structure in a *conscious way* there is the need to have "antibodies". It is important to be aware of when that structure should not be used.

[I tried to] not identify myself within physics community of practice [...] it was a *defensive weapon quite important* and also the idea of not identifying myself is related to don't want to *deplete myself* (with the physics practice)	community and identity	Physics, with its norms, can create a very strong sense of belonging and, hence, can encourage a student to develop a strong A-identity as a member of that community. An "antibody" to avoid that your identity collapses into that A-identity is to try to avoid being a member of that community.	A physics community of practice can become a place where a student can identify her/himself completely with it. If you don't want to develop that strong sense of physics identity, that is if you do not want that your personal identity is completely depleted, one "weapon" is to try to avoid identifying yourself with that community.
I applied mostly within myself, and this in the past, in the moment in which I was using outside me a *strict logic and a truth, within myself too I was looking for a strict logic and a truth, until to have ideals… but when it turned on in my mind a perspective that I took from Physics, but I am taking a new one from a new form of physics, a new perspective upon physics which is much more open, then it changes both what is inside me and outside me, and thus an inquiry different to me, with coexistences that were not allowed previously*	nexus, D-Identity	Physics discourse can shape identity. It can be used to analyze yourself and the epistemic norms of physics can lead to very different discourses, and hence to shape identity in a very different way.	Physics thinking tools can be applied to analyze ourselves. Physics strict logic and the search for truth also can be used as personal ideals. Then it is possible to find a new perspective, a new physics, more open and where there is a place for the coexistence of different points of view. This can encourage students to pursue a new type of inquiry inside and outside them.

so even if I practically do not negotiate anything with someone, I am implicitly negotiating since I negotiated with myself certain aspects of my life, and this in my opinion is the core of what should do the teaching	negotiation, identity	Teaching can be a fuel for identity development, by paving the way for self-negotiation.	The main role of teaching should be to give tools to understand yourself, to renegotiate with you certain aspects of yourself and your life.

And so the value of *opinion* and so the value of yourself [...] and it is not only about "right" or "wrong", but you pass through an analysis… even a *necessity to pass through the community in order to know if it (opinion) is right or wrong if it needs something more, it is along a right or wrong direction* with the awareness that my opinion could be considered and could pass through *reasoning (of the community), an additional inquiry beyond a simple "yes" or "no".*	negotiation, epistemic agency	In order to turn a class into an effective community, a student has to have the feeling that her/his opinions matter and are considered. In the community, there must also be space for negotiating an opinion and validating it.	In class, it is important to find a space where there are not only "right" or "wrong" ideas, but you can find a community that supports you to analyze an opinion and validate it. A student has to have the feeling that her/his *opinion matters* and that an opinion has to *pass through collective reasoning* which is beyond a *yes or no.*
stimulate the *process, the inquiry…* [...] the inquiry and the process are accompanied, structured by these arms, by these instruments that are taken from the teaching proper of the discipline, so with this collateral teaching	Collateral thinking	Unveiling and analysing the process of inquiry and how it is structured by disciplinary norms can be part of the development of collateral thinking.	The process of inquiry, structured by disciplinary rules, can foster collateral thinking.

to expand [an inquiry tool] to a pattern, something that I recognize in a certain shape	Collateral thinking	Tools of the process of inquiry become elements of collateral thinking if one is also able to recognise a shape, a pattern of them.	An inquiry tool becomes collateral thinking if you turn it into a "pattern", that is if you recognize a certain shape that can be applied to other contexts
in my opinion certain things that I took from physics community of practice are actually *reasoning structures, inquiry structures* [...] in my mind I had taken some structures that I had learned in physics [...] and I was bringing them back in the communication field	Collateral thinking	Examples of general collateral tools that one can take from the physics community are *reasoning structures, inquiry structures.*	An example of what has *been taken out* is a set of *reasoning/inquiry structures.* In this case, this tool has been exported within a *communication field.*
The concept of unity, to see opposites, gives you a different vision [...] You can apply a concept that you took by modern physics, it can be for example the wave-particle dualism or a unitary vision of all, or an approach towards special relativity... The parallelism [...] complementarity, thus a coexistence of two models [...] a coexistence of divergent thinkings (produces to) have different points of view	collateral thinking	XX Century physics is rich of concepts that can trigger collateral thinking and foster openness and crossing boundaries.	Other elements of collateral thinking are *unitary vision* as (the ability) *to see the opposites (such as dualism), complementarity, coexistence of divergent thinking* can lead to develop the ability to have different points of view.

Another concept which can be taken out (from the Lorentz transformation) is the destruction of the absolutes, as time and space seen as completely independent, but (instead) looking at how one can influence the other; this to me is an enormous transfer, through which analyze life too...and being able to see not all as absolutes and independent, but having the ability or at least the intention to find out how one depends on the other and see the relationships that are present	collateral tool	Example of Lorentz-related collateral tool are *dismantling absolutes* and to see a relational nature of objects.	Being able to *dismantle absolutes* and to see how physics objects *can influence each other* is a *huge transfer* (thinking tool that can be useful outside, for example to *analyze life*)

The analysis reveals to what extent the narrative was effective to stimulate the student to find his words to unpack if and how physics learning contributed or hindered him to develop a sense of personal identity.

S2 is so resonant with the approach that he starts his interview by suggesting to change the name "collateral thinking" since it recalls the expression "collateral damages" and, hence, something that is neither desired nor explicit. Instead, for the student, the activation of "collateral thinking" or, as he prefers, of "cognitive transfer" has to be explicitly addressed by a teacher in class.

He provides examples of "collateral thinking" and of "teaching strategies to foster it". In particular, he mentions the structures of reasoning that can be learned in physics and structures that characterize the process of inquiry in physics. They, he said, can be part of collateral thinking if teaching makes them explicit and encourage the student to recognise patterns across domains and contexts. Moreover, to turn them into collateral thinking, a class does not have to be only the place of "yes-no", "correct-wrong" answers, but a safe context where students can feel that their opinions count and are guided and encouraged to negotiate and value them within a community.

The most original and deep contribution of the student refers to the constructs of "identity", "community of practice", "boundary crossing" and "nexus of multimembership". He is very focused to stress to what extent a community of practice is grounded in ideals, values, and aims. These, for a matter of coherence and consistency, motivate the choice of specific tools, forms of reasoning, pieces of a repertoire. For example, a physics community of practice coheres with ideals of rationality, logic, rigor and, according to that, practices and tools have been developed. In science, strong and rigorous reasoning is appropriate to reach to goal to confront the strength of different argumentations and decide which is the winner. Yet, when these arguments are used in another context (community), where the goal is not to compare the strength of argumentations but explore many of them, a logic reasoning can have the effect to impoverish the discussion. It can become a sort of "authority principle" that closes up the discussion. Because of that, the student deeply suggests that inhabiting the nexus of multi-membership and being an agent in crossing the boundaries requires rethinking, "translating", negotiating personal norms, aims and values that frame the new community.

When he explicitly talks about the community of practices created by physics, he distinguishes between the community shaped by the norms he met when he studied classical mechanics and the community that can be shaped by the norms of XX century physics. The community that he had experienced in learning classical physics is the realm of determinism, truth, rigor, unique and rigid forms of reasoning. The norms of this community can create tension when you try to overcome the boundaries since they tend to promote closeness, the creation of bubbles, exclusive clubs from which it can be difficult to cross the barriers and develop any nexus of multi-membership.

Indeed, when you try to apply these forms of reasoning out of the physics community, one feels a sense of extraneity. They do not work to accomplish the goals and to respect the norms of other communities. Thus, the acceptance of those norms induces a sense of belonging that tends to shape a strong form of A-identity among the students.

On the other hand, the communities shaped by theories like relativity or quantum physics are very different. For example, relativity can be seen as an example of openness, of how physics breaks down absolutes and worldviews. Relativity and quantum physics leave room to conceive the coexistence of different perspectives, of divergent thinking and can lead to developing the ability to have different points of view. The student tells very explicitly how the norms of a community of practice touch the personal dimension of identity. He describes that he uses inquiry methods he learned from physics to question himself and he also explains how a sense of belonging to a community, saved by socio-scientific norms, can create an A-identity. For this reason he feels strongly the relevance to take care of unpacking the implicit norms that a discipline implicitly imposes and rule out a class dynamics.

Interpretations of *collateral*

The goal of 4.1 was to investigate the proximity of students to the research narrative and collect opinions about the effectiveness of problem formalization.

At the end of chapter 2, the following question was proposed:

> *«what are the thinking tools developed in a* ***collateral*** *way inside the community of practice of a physics class, that forms the outgoing flux of competencies which will be part of the repertoire of the pioneer, living at the nexus of multi-membership?»*

This question aimed to reflect on what knowledge objects and skills can have/maintain value at the nexus. So the focus is on those skills that, by assumption, are those developed in a *collateral way* inside the community. The interview protocol was designed also to investigate it. One question aimed to understanding what came to students' minds when they heard the expression *collateral learning* and whether they considered it effective.

Some students agreed with the definition. For example, S1 said:

> *«Yes I feel very comfortable with this definition and I like it so much since essentially* ***reflects what I see within physics****, this capability to transfer this kind of competencies, as you said while speaking about thermodynamics [...] that gives you the chance to actually see macro and micro and almost indirectly forces you to make your personal links, considerations, to connect these two concepts [...] undoubtedly if I want to end up I must sum up all the pieces, I just cannot build them separately, and by mixing all it develops this openness of thinking...»*

S3 underlined the difference between process and outcome, considering the *collateral learning* as something that happens during the continuous interaction between student and physics objects. Thus if the appropriation of the objects of the repertoire can be considered an outcome, acquiring competencies collaterally from the other side is read as a process, like a process that establishes a network among the knowledge objects.

> *«I agree with you since when I study whatever subject, and specifically physics, I pay attention more to the processes, but the kind of process that makes you create links, starting from one concept and ending to another... a kind of reasoning, so in this sense collateral learning aimed to see not only what is the content of the explanation but also* ***how that sounds in your mind for other things****...»*

The other 5 students express that collateral does not reflect properly the idea of the mechanism that I was suggesting. Two of these explained their position referring to the meaning of collateral in medicine, as something bad and undesirable.

For example S2, said:

> *«Collateral is OK, so I approve it, but it seems...well I associate it mostly to the danger, collateral danger. In this sense collateral appears almost as undesirable but instead to me it is desirable or even necessary.»*

or S4 said:

> *«It's OK but unfortunately collateral may remind something bad, so it could better to focus on the unexpected feature... to say that maybe we can find a word that highlights something that does not depend voluntarily on the subject but it is a spontaneous process...Maybe emergent learning, from physics of complex systems»*

The other students, that express some hesitation toward *collateral learning*, throughout the interview, seemed to attach a different meaning to the expression.

For example S6 exchanged the word collateral with exportable; instead looking at the research narrative it can be seen that collateral is related to what happens inside the class (first scene) whereas exportable is a word linked to what happens in the second scene, when the student takes some of the competencies appropriated in a collateral way, outside the community, toward the nexus.

Resuming, it seems that maybe *collateral* is not the best choice to remind such kind of mechanism of learning; further the probable mis-interpretation that could arise by using such a word (and actually arose in some of the interviews) can condition the reasoning. Indeed what can be considered a drawback encountered in the interviews analysis is that students which understand something different were conditioned in giving subsequent answers, taking the discussion out of the focus.

4.2 Contributions for an answer to RQ2

4.2.1 Collective discussion

This part of the collective discussion was devoted to an initial exploration to the possible directions to address RQ2. From the preliminary results of the collective discussion, the RQ2-a and RQ2-b (section 2.2) were refined. Furthermore, the analysis was the starting point for the design of the interview protocol. The questions that students were asked to answer (Table 3.1, part 3) were:

1. How can be stimulated, within a physics class, a participation for imagination?

2. Among the thinking tools that can be appropriated within a physics course, which ones do you think are more exportable and coordinable with competencies from other communities?

3. Which of the objects of a physics course can be treated as boundary objects?

As regards the first question, the figure 4.5 shows students' answers organized through a thematic analysis.

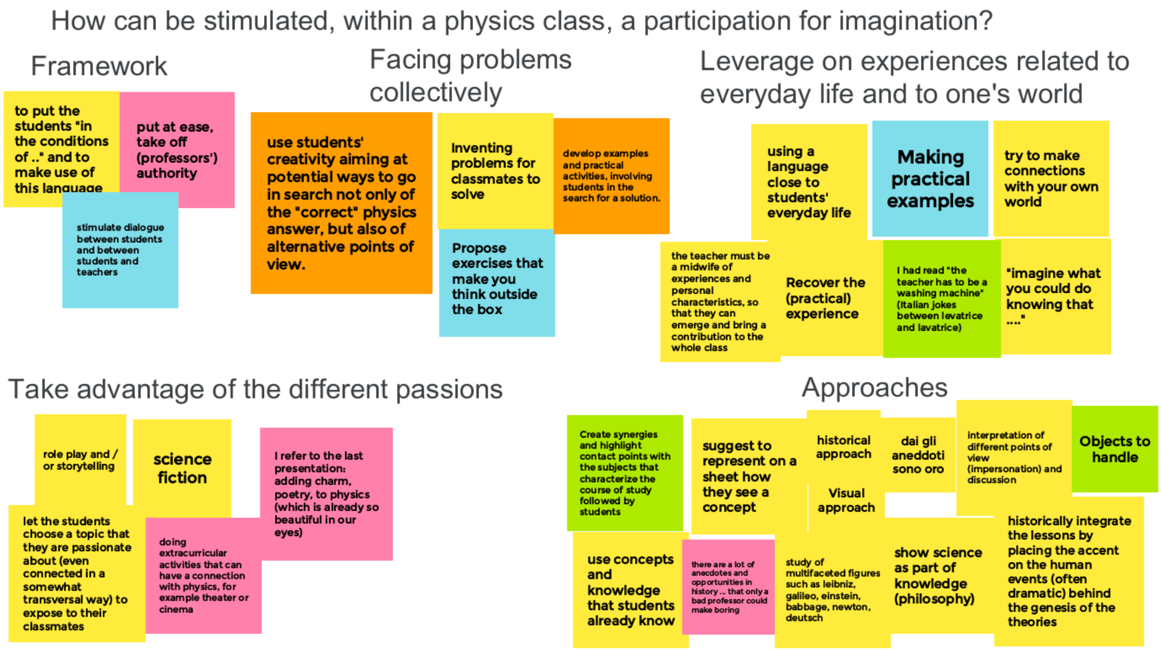

Figure 4.5: First Jamboard question

From the jamboard the first thing we can notice is the diversity of the answers that reflect the different aspects that activate students' imagination.

Five main clusters can be individuated. The first one regards the kind of environment and the role of teacher that can be created to foster a participation for imagination. The environment have to be not authoritarian putting the students at ease and promoting the dialogue between the students and between students and teachers. Given the harmonious and open environment, different are the strategies individuated by the students to activate the participation for imagination. As suggested by the second cluster, a strategy can be to propose exercises that lead to thinking outside the system and exercises/problems to be solved as a collective enterprise, valuing the different points of view, the different ways to solve them. From the third cluster, it emerges the importance of the link with the everyday experiences or with the personal worlds. It can be pursued by the teacher both using a language near to everyday life and sharing personal experiences.

The fourth cluster suggests the importance also of personal passions "outside" the school such as games, science fiction, and so on. It can be pursued for the students for example organizing extra-curricular courses that can mix science and cinema or theatre or letting students choose transversal themes they are passionate about and sharing them with the class. The last cluster provides the different approaches that can be put into play to trigger participation for imagination. Also in this case the diversity of the students emerged clearly: from the importance of the historical approach and anecdotes to the epistemological and philosophical approach to the more experimental one. Two other aspects that emerged need to be underlined:

- to foster the *longitudinality* (Levrini et al., 2015) that is to leverage on the knowledge that the students already knows (putting in coherence)
- to create synergies and a big picture in which disciplines can be rearranged, a picture in which the contact points can be highlighted.

As regards the second question, the jamboard, organized through a thematic analysis, is shown in figure 4.6.

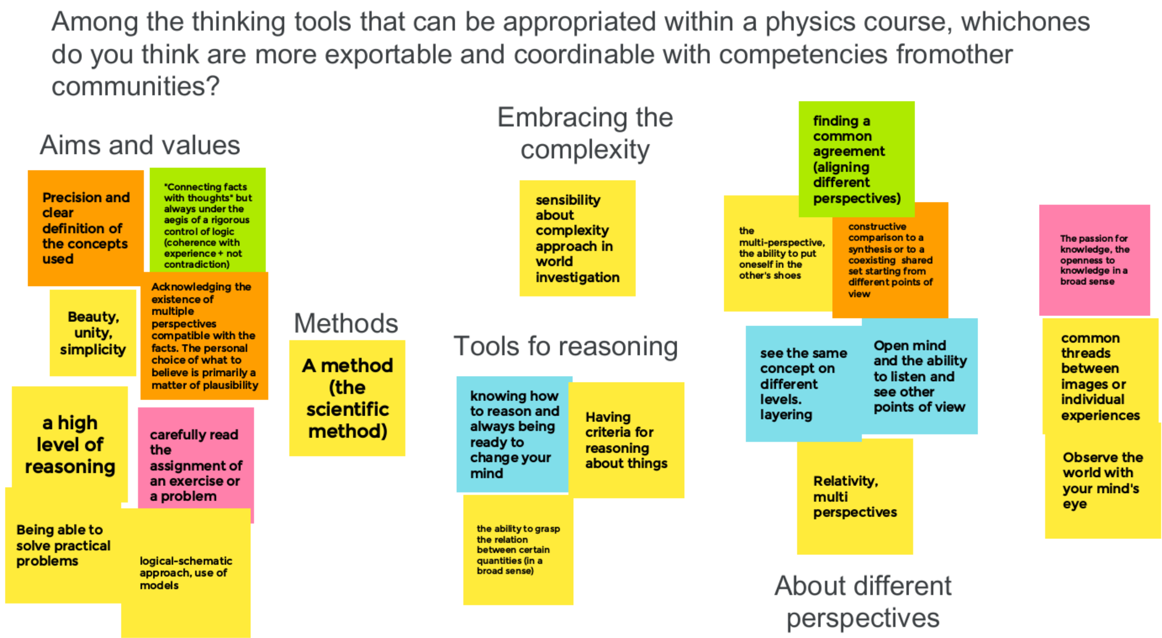

Figure 4.6: Second Jamboard question

The first cluster (on the left) concerns the aims and values of physics that are "exportable" from the physics community to others. Among the values of physics, students pointed out the precision, the definition, and the rigor. Between the aims, the students carry out interpreting and solve real problems and the investigation of the world through the use of models.

The second cluster concerns the methods that can be exported; in this case, the scientific method.

The third cluster is linked to the tools of science that, for these students, provide us with criteria for reasoning and the capacity to look for the dependence between quantities.

The other clusters concern the thinking tools that can be exported (also metaphorically) from physics. Sometimes they also deal with personal attitudes toward the world. So the idea of embracing the complexity, of accepting the coexistence of different perspectives, being able to change perspectives, accepting openness and so on.

The jamboard related to the last question is reported in figure 4.7, organized through a thematic analysis.

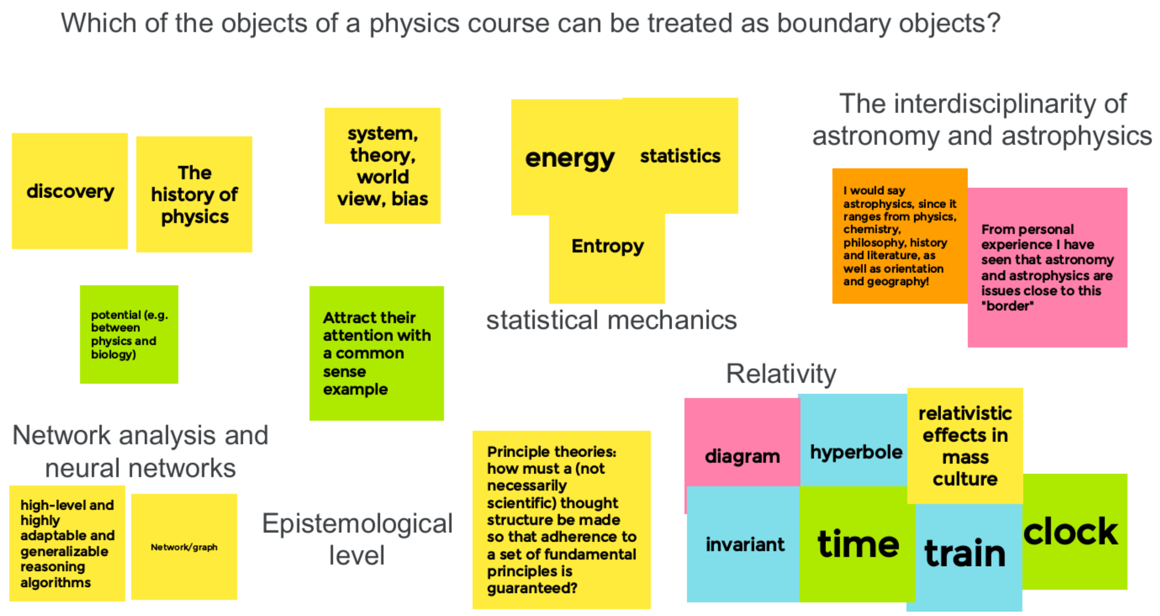

Figure 4.7: Third Jamboard question

Anticipating that many of the students present on the day of the collective discussion had never heard anything about a boundary object before, so many different elements and many different interpretations of boundary objects emerge from figure 4.7.

Some students projected their idea of boundary objects in "boundary context". This is the case of Astronomy and Astrophysics or the History of Physics or Statistics. They are for sure interdisciplinary fields and themes, but they are not boundary objects in the vision of Akkerman and Bakker (Akkerman and Bakker, 2011; Wenger, 1998).

Some students instead provided examples of concepts that can be boundary objects such as the potential (between Physics and Astronomy), the concepts of entropy and energy, the network, the diagram, the hyperbole, the idea of time and invariant, and so on.

Thus, from the analysis of this jamboard it emerges that the students do not have a unique image of boundary objects. Nevertheless a particularly innovative aspect is the idea of a theory of principle as a boundary object. The student indeed highlights how the structure of theories of principles can show a knowledge organization that can be exported out of the physics community.

4.2.2 Interview

In this second subsection, the analysis of the interviews[2] with the aim of contributing to RQ2 is reported. To this purpose, the interviews have been read to point out the data that refer to possible examples of criteria of activation of collateral thinking and examples of physics grounded sources.

The data have been then organized and clustered according to the scheme reported in figure 4.8. The scheme can be read from below upwards. At the basis of the scaffolding, students' main ideas of methods/approaches/environments that could trigger the appropriation of the collateral abilities are reported. Then, in the middle of the structure, there are students' examples of collateral thinking tools developed by the appropriation of Lorentz transformations, and then more general examples taken from other physics topics, methods and so on. Finally two red arrows suggest directions towards two general classes of collateral thinking tools.

Collateral competences activation: criteria

Different ideas of criteria came out from students' interviews that are linked to their personal experiences. In particular, the four particular ideas emerged by the analysis are schematically reported in figure 4.8.

Two students (S3 and S4) stressed the idea that one single topic (object of repertoire), even if it is very dense in meaning, does not trigger anything by itself. For them collateral learning emerges mainly from the interaction between different objects or different models, rather than a single one.

> *«Maybe within a macro-area such as thermodynamics yes there is, but not for single concepts inside the thermodynamics...it is not something which arises with the first or the second principle of thermodynamics, but it arises through the interaction of them [...] this to me triggers these collateral competencies.» (S3)*

[2] for privacy reasons students are relabeled as S1, S2, S3 and so on.

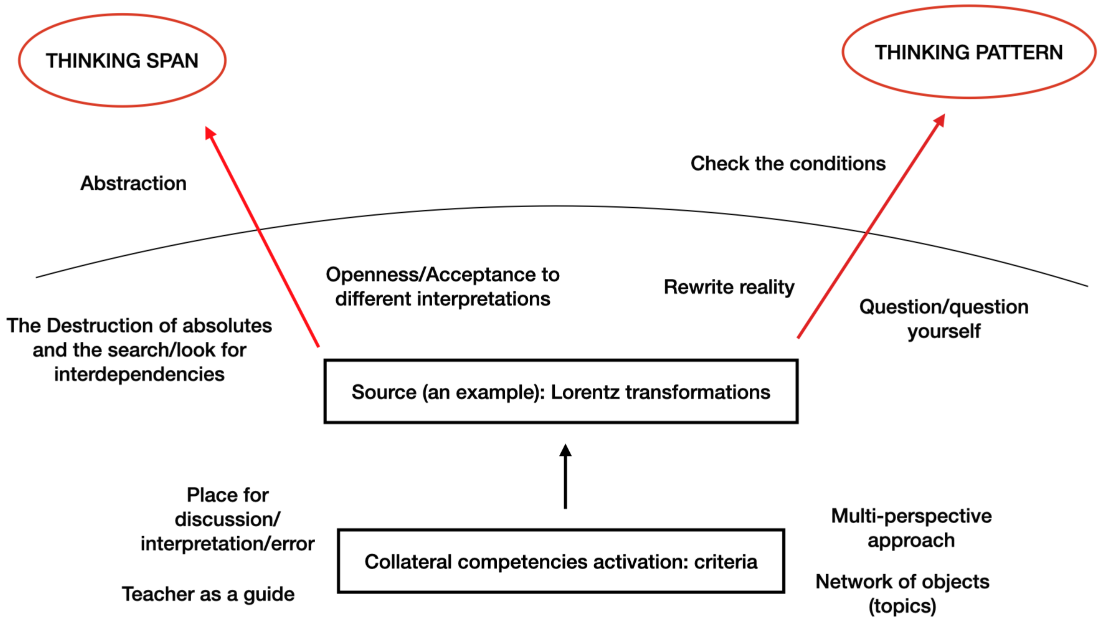

Figure 4.8: Scheme representing the logical structure about collateral thinking tools

> *«These general competencies (create models, select the right pieces of information), they do not come from a single specific model, it is not the matrix formalism, it is not the atomic model, it is not the approach of Minkowski or the one of Einstein... It is a set of theories which together help me to develop the ability to formalize... what is relevant is not the single model.» (S4)*

Another criterion of activation, emerged in particular from S3, is the multi-perspectiveness, that is the idea of approaching a single physics topic from different perspectives (*historical or philosohical*). In the words of S3:

> *«In this sense you can create that (collateral) competence, but because you created a setting on purpose... even with a single object, since you gave these variations on the theme [...] and in my opinion this can be done with several topics in physics because if you know how to stimulate these reasonings exploiting historical or philosophical stuff, thus exploiting something that is not strictly the physics content but rather the setting in which that content was born.»* (S3)

S3, about the historical approach, stressed also the importance of thinking that science is a cultural product made by people and that the progress has also been achieved through scientists' mistakes. This aspect creates an environment in which the students feel *free to make mistakes*. And the *possibility to go wrong* can foster the development of collateral competences. In the student's words:

> *«[about historical approach] it allows you to create an environment within which also the student feels free to make mistakes, to reason, and if he can reason he can create the collateral competence [...] the impossibility to go wrong, even on a theoretical level about reasoning on concepts, because they are told you in the straight order, is that which I think inhibits the chance to develop the ordinary competences, but also the collateral ones.»* (S3)

S1 stressed on the role of the teacher to create spaces that are open to debates and confrontations. In S1 words:

> *«(it is possible to acquire some collateral learning) if there is time and space to set down an interaction, a debate... and the teacher guides the discussion; this to me favors collateral competence improvement.»* (S1)

> *«you have to be brought there, you cannot do it by yourself.»* (S1)

S4 highlighted that the teacher can guide and give all the tools, but there is also the need of an active participation of the students in learning. In the student words:

> *«There is also an active participation of the subject, a desire to try, to strive, and then over time, after that an habit has been established, start to learn in a different way [...] but only by commitment of the student, otherwise there is not (the chance to trigger collateral learning).» (S4)*

> *«I cannot teach you to think; I can give you the instruments to learn to but I cannot do it for you.»(S4)*

Sources (examples): Lorentz transformations

This part is dedicated to the extrapolation of some sources that can induce the development of collateral thinking tools. We decided to start from the Lorentz transformations because all the interviewees knew the subject well and because we wanted them to remain as close as possible to physics. The main students' ideas linked to Lorentz transformations, which can be seen as exportable thinking tools, are:

1. **The Destruction of absolutes and the search/look for interdependencies**

   S2 refers to the destruction of absolutes as an enormous transfer, as a collateral competence that can be transferred outside physics, to be used for analyzing life. Time and space are no longer absolute and independent. In S2 words:

*«Another concept which can be taken out (from the Lorentz transformation) is the destruction of the absolutes, as time and space seen as completely independent but (instead) looking at how one can influence the other; this to me is an enormous **transfer**, through which analyze life too...»*(S2)

The destruction of the absolute allows one to see interdependencies, to look at inner relationships between concepts. And Lorentz transformations are the bridge that let arise the interdependence between classical and special relativity. In S2 words:

*«And being able to see not all as absolute and independent, but having the ability or at least the **intention** to find out how one depends on the other and **see the relationships** that are present... this is a structure that I would personally take out for myself [...] Showing that object (Lorentz equations), is effective if you want to see **interdependencies**, and then you can take (this ability) out.»*(S2)

*«So I think that this is one of the best utilities coming from Lorentz transformations, they are a **bridge** between two separate worlds, the one that you can see and experience through Galileo and the other [...] they bring gusts of what is behind, of (special) relativity... and you can do this only by Lorentz (object).»*(S2)

2. **Openness/Acceptance to different interpretations**

For S4 the Lorentz-dependent thinking tool is the acceptance of the existence of different correct interpretations about the same concepts (in this case relativistic invariant and relativistic effect). In S4 words:

*«Yes for example the **debate**, is very important... before to enroll at physics I used to have a dual perspective about debating, so one that is right and the other that is wrong, I didn't see some intermediate shades. Then, studying for example the Einstein-Minkowski debate about space-time, I realized that things are actually **open to interpretation**; relativistic effects are always there, relativistic invariant is still there, not interpretable, but for what concerns the causes, how to read those relativistic effects, there's plenty of space to talk about.»*(S4)

Also S2 pointed out the same thinking tool of S4 as a general tool provided by physics (i.e. also from wave particle dualism). In S2 words:

«You can apply a concept that you learned through modern physics, it can be for example the wave-particle dualism or a unitary vision of all,

or an approach towards special relativity... you can take these ideas and they give you the input to face different situations and acquire diverse points of view, so it should not necessarily be an inquiry process but it can be also an alternative perspective (the skill).» (S2)

3. **Question/question yourself**

   S1 carried out another thinking tool that is linked to the attitude of *questioning*. This tool emerged from the role of Lorentz transformation in history and on the passage from Galilean to special relativity. So the idea of *questioning* can bring to see a *larger structure*. For S1 the act of questioning is important (*"he cannot say/he cannot stop"*), otherwise there is the risk of losing things, or *missing all the stuff behind*. In S1 words:

   > *«So thinking about Lorentz it is the (competence to)* ***questioning****, questioning yourself too, being able to say "well, what I've been looking at, until now, was not completely correct, it is just one little* ***part of a larger structure****" ; so if one wants to understand SR and Lorentz transformations, for what they are, and to what they lead to, he must necessarily question himself, he cannot say: "OK, so far Galilean relativity worked, I don't care", to say he must realize that he cannot stop there, or better if he stops there he will go ahead anyway, but he will* ***miss all the stuff behind.****»*(S1)

4. **Rewrite reality**

   S6 pointed out as a Lorentz-dependent thinking tool the idea of rewriting reality. Galilean relativity represents an obstacle that has to be overcomed. This can happen also in life, there are moments *in which you won't understand anything of what is going on*. But if one has the experience of studying relativity, he/she has the possibility *to rewrite all your cognitive, conceptual, mental approach and find solutions*. In S6 words:

   > *«If you want just approach special relativity you have to* ***rewrite the entire reality*** *and this ability to rewrite reality is not trivial, neither easy, and when you actually manage to overcome this obstacle, this (ability) is something that necessarily* ***stays on you*** *[...] there will be for sure a moment in your life in which you won't understand anything of what is going on, but having the experience of studying special relativity, and thus (having experiences) of ways in which you can rewrite all your cognitive, conceptual, mental approach [...] maybe will help you to find a solution.»*(S6)

Other sources

In this section we illustrate other cases of physics related collateral thinking tools.

1. **Check the conditions**

   S5 pointed out two important thinking tools related to each other: the *logical reasoning linked to search for data-sources* and the check of the data-sources. In student words:

   > *«Well it reminds me... which is not strictly dependent from physics, but for my case it spread out from there (physics), which is the logical reasoning linked to* ***search for sources****... it is not enough that your reasoning works, it must be grounded on something(S5) [...] to say spend time to look for sources, try to formalize the issue, it is what I do more and more and I feel that this is weighting less and less. Probably because it is something I developed over time... it is not strictly related to one physics topic but I would say is anyway related to the environment in which I grew up (academic). (S5)»*

   > *«for this reason I would say that academic environment, that in my case is Physics environment, helped me to say: "OK, but let's try to formalize what we are saying, let's check if this has foundation, let's check if there are sources, data..." thus being the picky one [...] and* ***I am accustomed to do*** *that, even for little things but also for the most important, such as Covid-19. (S5)»*

2. **Abstraction**

   S4 pointed out another physics collateral thinking tool that is linked to the inability to visualize all the phenomena, so abstraction skills have to be developed.

   > *«Then the fact that you have to face, in physics, with phenomena that you don't understand all the way or visualize in your mind, forces you to develop an* ***abstraction skill****. (S4)»*

By looking at the students' words, and at the single competencies discussed, it seems that they can be referred to two characteristics of the thinking: the **span** and the **pattern** (figure 4.8). Abilities such as *Openness/Acceptance of different interpretations, The Destruction of absolutes and the search/look for interdependencies, Abstraction*, can be seen as qualities of thinking that enlarge its span, its range of action. Abilities such as *Question/question yourself, Rewrite reality, Check the conditions* give to the thinking a pattern of action, as thinking structure that can be "shifted" from a context to another, from a community of practice to another.

This idea can be recognized also in S2 and S6 words.

> *«Inquiry tools, I think this definition is very appropriated...which stands for transfer; thus which you can take it and make it yours in different fields... I would define in this way: a cognitive transfer that you steal from physics...it can be considered a pattern (S2)»*

> *«In my opinion some of the things that I took out from physics community of practice are actually reasoning structures (S5)»*

So their function can be read as a reasoning structure that can be taken out from the original practice. To conclude this set of examples presents what students consider as collateral thinking tools which they personally developed or hope to do, through the study of physics content at school. They are quite different one from each other, but the common basis is that they are features which resonate with physics epistemology. So the idea is that the student, by adding these thinking tools to his own physics-related mindset, can better approach the physics-practice, at an epistemological level. This may be a first step for identity development, and so a first suggestion on practical ways by which to address the general RQ2.

Conclusion

This work is born from a recurrent idea that I have always had in my mind, about the role that education had personally on me. I feel to be a privileged person, since I had the occasion of studying in different places, different schools, universities, research institutes and so on; of course I am aware that what I studied had an impact on what I am as a person, in a way it shaped me as the citizen that I feel I am right now. But there is still an open and unanswered question within myself, related to the precise ways through which this process of modeling has occurred. In particular I cannot answer clearly a question like: *«what was the role of physics in my life as growing as a person?»*; all I can say about this is the role of physics in outlining my academic growth, in the way I figured out my future career; but that is all the story.

There is another question I cannot answer; for example if I wonder, *«would you be the same kind of person, Francesco, if you had studied something else, as for example history, pedagogy and so on? What did the subject you leant give to you, what about the scientific communities that you took part in and the scientific dimensions that you have encountered?»*. All this led me to think in general to what extent and in which sense physics affects students that get in touch with it; as soon as the question shifted to a higher dimension, no longer personal, I noticed the sensation of a huge problem: that actually many students perceive physics as not particularly meaningful for them. Thus I started to think that by facing this issue from a higher perspective maybe I could have found also pieces of answer to my initial personal questions.

Therefore what I did was first to map the general problem into a form that could make sense for the research community. Thus, I carried out a deep study and re-analysis of the STEM literature, with a specific focus on the part concerning the relation between physics and identity, ended with a research narrative. This narrative represents the outcome of a review process and formalizes the problem in terms of theoretical constructs elaborated with the research in STEM and Physics education.

The narrative is mainly centered around the idea of community of practice (Wenger, 1998), but it incorporates the constructs of Discourse & Affinity identity (J. Gee, 2000), practice-linked identity (N. S. Nasir and Hand, 2008), epistemic agency (Stroupe, 2014), socio-scientific norms (Yackel and Cobb, 1996), boundary crossing mechanisms (Akkerman and Bakker, 2011; Wenger, 1998), and appropriation (Levrini, Fantini, Tasquier, Pecori & Levin, 2015).

The narrative has been tested in two empirical studies with physics students attending the course in Physics Education in Bologna. Aims of the studies were: i) to test students' proximity of the problem and the effectiveness of its reformulation in the narrative (RQ1); to collect suggestions, opinions, experiences to turn the narrative into an operational set of suggestions for teaching (RQ2).

The narrative has be considered a first level of answer to the general problem; namely this first step (RQ0) was conceived as a test of the possible reformulation of the issue. Once the answer to RQ0 has been given, I proceeded with the latter two levels of questions. Indeed, starting from a formal problem, it was of interest to measure its urgency, thus how much important is seen by students and if the narrative created describes it properly. This first question has been named RQ1.

The first study concerns a collective discussion (a kind of focus group) held in April with fourty-four students of the course "Physics Education"; the second study regards a set of in-depth interviews carried out in July/August with seven students out of the initial fourty-four. For this purpose an interview protocol has been produced, mainly following the indication of Castillo-Montoya (Castillo-Montoya, 2016).

The results which came out were divided according to their relation with question RQ1 and RQ2. In particular through the analysis of Wooclap and Jamboard material, RQ1 appears to find an encouraging answer among students, but it is my opinion that the most robust answer to RQ1 is represented by two case studies; indeed these two people resonate even unconsciously with the narrative, validating its construction at least for their case. A fine-grained analysis of one of these two students (S2) has been carried out to show the depth, the quality and the richness of thinking that the narrative was able to trigger.

For what concerns RQ2, the analysis brought to gather a set of physics related collateral thinking tools that students reported as meaningful for them, both inside physics community of practice and outside. These data have been placed in a structure divided into activating criteria, Lorentz examples, and general examples.

Given the nature of RQ2, we cannot say that these data actually answered the question, but at least they may represent a contribution for a subsequent follow-up of the inquiry. Indeed I am aware that a lot of elements which form the narrative have not yet been addressed in this work, such as the individuation of possible criteria to characterize the exportability of collateral thinking tools outside physics community of practice. However, this could the first step for an eventual further research.

Appendix A - Protocol

Table 2: Protocol questions

Part one	Part two
Thinking about the words *collateral learning* reminds you something similar to the example presented? If you want we can refine together this definition.	Looking at your experience in physics communities of practice, have you ever felt that that community was more separated and had higher boundaries, in terms of value, relevance, with respect to your other communities?
Do you think that studying physics at school (high school or university) brings some degree of *collateral learning*? If so, could you please give some examples related to physics and try to make a detailed identikit.	Have you ever felt that the tools developed in a collateral way inside physics community of practice were contrasting with other tools coming from diverse personal communities? How did you faced that inconsistencies?
What should look like a kind of learning to be considered *collateral*?	Referring to the figure of pioneer, have you ever felt a pioneer in external communities situations, properly by the use of thinking tools developed through collateral learning in physics? Could you argue on this?
Starting from your experience, maybe related to the course of Didattica della Fisica, could you tell me an object, concept through which you think you realized some kind of *collateral learning*? Could you explain the reason why that particular object is related to that type of learning?	

If we think to Lorentz transformations, how could you map this idea?	
Maybe not all of that you learn in a collateral way can be useful in general, but do you think that some forms of collateral learning, concerning Lorentz or generally in physics, can be used as resources in everyday life? Could you tell you which and why, relating to Lorentz or other? Could you tell if there situations in you life during which you realized you were using these tools (collateral forms), taken from physics?	

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