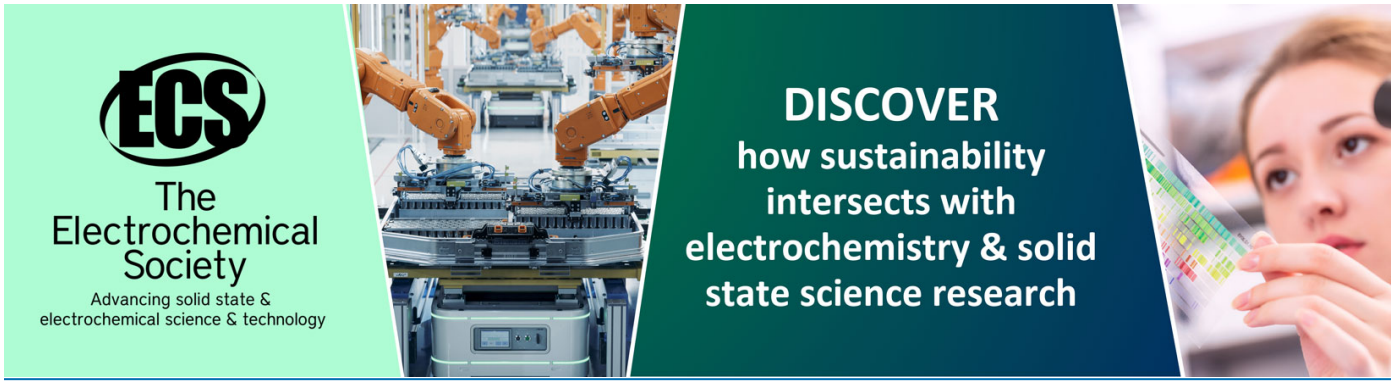
Educational reconstruction of physics of complexity within a creative writing classroom activity



Educational reconstruction of physics of complexity within a creative writing classroom activity

F De Zuani Cassina and O Levrini

Department of Physics and Astronomy "A. Righi", University of Bologna, Alma Mater Studiorum, Bologna, Italy

francesco.dezuani2@unibo.it

Abstract. Disciplinary identity is widely studied in physics (and science) education research. Great attention has been devoted to studying the role of sociocultural factors in students' career choices and persistence, such as students' participation or gender differences. However, few works within the literature have investigated the role of the cognitive-epistemic core of scientific disciplines in identity work. In the first section of the paper we discuss the state of the art about science-identity. Then, we discuss the theoretical frameworks that informed the construction of our idea of *epistemic-personal consonance/dissonance*: the "Reconceptualized FRA to NOS framework" and the "Model of Educational Reconstruction". In section 4 we introduce a qualitative analysis of data collected within a classroom activity held in 2021 and discuss it according to our Research Question. The findings show that students used complex systems epistemology as *scaffolding* for the expression of personal needs; they reconceptualized personal demands by borrowing epistemological structures and practices of complexity as tools to change perspectives about personal issues. The findings of this first dataset call for the need for further data to analyze and enrich the discussion around physics epistemology and identity.

1. Introduction

Issues of accessibility and persistence in the STEM field are more and more crucial problems to be addressed by policymakers and educators. Indeed, few students graduate and pursue STEM careers [1,2] compared to the high demand for STEM occupations. Some reasons can be traced back to the lack of a sense of belonging to scientific disciplines [18] or widespread problems of epistemic injustice in science classrooms [4]. In addition, another challenging issue is the widespread unbalanced representation of women and racialized minorities within STEM master's students as well as the workforce. For these reasons it seems urgent to develop predictors which could help in making previsions about persistence/dropouts in the scientific field and fostering as much as possible accessibility for STEM; in this sense, STEM-identity constructs are often used as predictors in science education research.

One important reference for STEM identity is the framework elaborated by Carlone and Johnson [6]. The authors elaborated three markers (*competence*, *recognition* and *performance*) accounting for tracing science identity work. The feeling of belonging to the science community (which represents the degree of development of science identity) is argued to evolve through iterative proofs of *competence* that are *recognized* by the other members of the community (classmates, colleagues, chiefs, students), and evaluated by *performances*. The work of Hazari and colleagues [9-11] then expanded Carlone and Johnson's framework by adding a fourth marker (*interest*); the authors explored quantitative correlations

among the markers (exploiting multiple regression techniques, structural equation modelling, etc.) to check whether general correlations can be found across diverse settings. One of their main conclusions is that is not possible to generalize claims about the direction and extent of correlation between the markers, in promoting/inhibiting identity construction, without considering and analyzing each context [9,10]. Apart from Hazari, many other scholars have used the construct of Carlone and Johnson as an analytical lens to explore science identity: for example Avraamidou examined the role of *recognition* in the academic life of three women who "*authored multiple identities*" (two of which are of colour and one of them is Muslim), showing different kinds and sources of recognition (or *mis*-recognition) which impacted physics-identity work [5]. Hyater-Adams and colleagues [12] combined Carlone's framework with the framework of "racialized identity" (coming from the work of Nasir in math education) to form a new lens named "Critical Physics Identity"; such lens allows to consider the racial identity and its impact in the subsequent formation of a physics-identity, and so get to know how racial or religious minority communities are marginalized "*to push the field of physics forward into a more inclusive and equitable future*" (Hyater-Adams et al., 2018, p. 17). Elsewhere Fracchiolla and colleagues [13,14] considered the concept of Community of Practice (CoP) in investigating the development of physics identity for graduate students through participation in informal physics programs; they ended up claiming the effectiveness of informal spaces in fostering identity development as shifting participants' positioning from the periphery to the centre of the community of practice.

All the frameworks introduced so far share a socio-cultural conceptualization of identity as a position allowed by authorities within institutions, a trait recognized in the discourse with individuals, and an experience shared in the practice of affinity groups [8]. Nevertheless, other scholars [15-19] interested in the relationship between identity and science have been working by focusing on the effect that disciplinary epistemology can have on identity work. For example, Jaber and Hammer [15] discuss the value of *epistemic affect* and *epistemic motivation* as triggering factors for STEM-identity construction through learning: epistemic emotions "*are experienced in the epistemic work of constructing and critiquing knowledge*", thus an engagement with the specific features of disciplines [16]. In the paper, they show how the feelings experienced within the practice of science and the meta-affect regarding the kind of science experience "*contribute to […] forming a stable disposition with respect to science as a discipline*" (Jaber and Hammer, 2016; p. 33). In their work, the affective dimension is crucial but is driven by a specific form of knowledge encountered by students (in this sense they call for an *epistemic emotion*).

Other scholars focused on the perceived lack of (personal) *relevance* and *authenticity* [17] of school science for students, stressing the cognitive-epistemic point of view for identity work. For example, Levrini and colleagues [18] reconstructed the complexity of physics nature in the classroom by a process of educational reconstruction, highlighting the different positions that the discipline itself presents (for example a macro-perspective or a micro-perspective in thermodynamics), and enhancing an image of physics as personally relevant: this promoted a kind of learning which they named *appropriation*. Appropriation [18,19] is described as "*learning science in a way that is deeply integrated into students' personal construction of their sense of self*" (Levrini et al., 2018); to this effect appropriating scientific contents is connected with the formation of personal identity. The authors conceive the promotion of science identity formation not as promoting practices and norms at the level of institutions, and they neither advocate for students' recognition and acceptance within the disciplinary community (or the classroom); whereas they push for teaching a kind of discipline that can be made open and relevant for students, as they can find their position within it and use it for the construction of personal identity. This objective is shared by both the authors of this paper and it will be supported in the next paragraphs.

2. Theoretical framework construction

In this section we introduce the idea of our theoretical construct, which aims to unpack the nexus between the epistemological aspects of physics and the process of identity work.

Indeed, when speaking about identity, we do not dismiss the importance of relations, roles, rules, and habits experienced by the individual in a disciplinary context; however, we do claim that when

considering the "context" we cannot avoid taking care of disciplinary epistemology and knowledge too. To ground our reflection, we chose two theoretical frameworks: the "Reconceptualized FRA to NOS" model [20] by Erduran and Dagher (2014), and the "Model of Educational Reconstruction" [21] by Duit and colleagues (2012).

The first framework is positioned within the Nature of Science (NoS) research. The authors wanted to construct an image of scientific disciplines which could grasp the commonalities as well as the specificities of disciplines usually considered scientific. The authors made a reconceptualization of the Family Resemblance Approach developed by Irzik and Nola [22], projecting that into the field of NOS. The nature of disciplines is defined through resemblance, in the sense of agreement between observers, contexts, etc; as a neural network "understands" what a cat is by adding all the features that images codified as cat actually contain, the same can be done for defining what a scientific discipline is. This approach is powerful since it is broad and elastic enough to gather specific features that are present across scientific disciplines, without excluding some of them from the list of scientific disciplines. As a summary result, Erduran and Dagher designed a wheel, where the inner core stands for cognitive-epistemic features of scientific disciplines, whereas the outer circle of the wheel stands for their socio-cultural facets; in the cognitive-epistemic features we find *aims and values*, *practices*, *methods and methodologies* and *knowledge,* whereas in the socio-cultural ones we find *social organizations and interactions*, *political power structures* and *financial systems*. The reason why we took this framework as a reference is that allows us to focus mainly on epistemic features of scientific disciplines when thinking about instructional activities.

The second framework is the Model of Educational Reconstruction, elaborated by Duit and colleagues [21] upon the legacy of Didaktik and Bildung, an educational perspective widespread across German-speaking countries since the beginning of the 70s [23]. In the specific, "*Bildung is viewed as a process (which) denotes the formation of the learner as a whole person […]*" while "*Didaktik is based on the notion of Bildung (and) concerns the analytical process of transposing human knowledge like domain-specific knowledge into knowledge for schooling that contributes to the above formation (Bildung) of young people*" (Duit et al, 2012; p.16). Consistently, the authors call for an education where "*science content is not viewed as 'given' but has to undergo certain reconstruction processes […] (and) to be transformed into a content structure for instruction*". Hence the goal is to design instruction activities with two steps: i) examine the features of the context of instruction and collect students' ideas and demands; ii) deepen the study of scientific basics content and highlight epistemological features embedded; then proceed with outlining principles, guidelines and modules for instruction coherent with the local context [21,23]. This process of content reconstruction intends to exploit the depth of contents as the richness of methods, practices and aims implied by them, to construct a local teaching implementation that could be in agreement with students' views, conceptions, perspectives and capabilities.

Taking these two frameworks as our pillars, we introduce the idea of *epistemic-personal consonance/dissonance*: we conceive it as the "local" impact that contents' epistemology may have on students' identity work. Here we name *epistemic-personal consonance/dissonance* the process by which some personal identity issues are sent into consonance (or dissonance) by physics' contents epistemology, as interpreted by Erduran; hence it could happen that some personal issues are supported in their expression by ideas coming from the discipline (consonance), or at the contrary are inhibited by them (dissonance). The research goal is to develop this idea and shape it as an operational lens that could allow tracing the relationship between epistemology and identity. At this point of the research, we still do not have markers, nonetheless, the aim is to develop them through a grounded theory approach [25]. Indeed, the goal is to collect data from several teaching implementations, then analyze each of the datasets, see the kind of connections emerging, compare outcomes between different datasets and through this process develop the markers we are looking for.

Therefore, the role of the previous frameworks as pillars of this reasoning seems essential. The FRA wheel indeed reminds the foundational importance of epistemology in dealing with the nature of disciplines; at the same time the epistemology, especially the one behind some physics contents, is rich

enough to allow a disciplinary reconstruction (MER approach). In this sense, we can consider epistemology a kind of "control variable" and check the impact it could have.

Given this, we need to explore our broad research question: "*What types of disciplinary knowledge and what kind of educational reconstruction leave room for personal-epistemic consonance/dissonance episodes, in physics learning*?".

3. Context and analysis

In this section, we report the first data analysis which contributes to the operationalization of our theoretical idea. The data analysis aims to gather possible links between physics epistemology and identity issues emerging from students' voices/words and check to what extent they can contribute to the development of markers.

To this purpose, we selected a database coming from a project held at an Italian secondary school (grade 9) with 15-year-old students (N=24) in 2021; the aim of the project was to merge the language of physics of complexity with the language of literature (see in the specific De Zuani et al., 2023). The idea behind the choice of such a topic, made by the teachers, is well explained by Jacobson and colleagues: "*the conceptual basis of complex systems ideas reflects a dramatic change in perspective that is increasingly important for students to develop as it opens up new intellectual horizons, new explanatory frameworks, and new methodologies that are becoming of central importance in scientific and professional environments*" (Jacobson and Wilensky, 2006, p. 12). Indeed, complex systems represent a new paradigm that is close to the paradigm dominating the post-modern society, the *risk-society* (Beck, 2000); dealing with complex systems nature can provide students with lenses more useful than the ones provided by the Newtonian paradigm, in order to make sense of a society dominated by risk, uncertainty, chaos, etc. We furthermore claim that addressing such an interdisciplinary topic as the complex systems from the perspective of science, allows to better enhance the change of paradigm that historically happened (indeed complex systems have been initially developed within biology and physics), from linearity to non-linearity, from determinism to emergence.

In the project, the Italian language teacher and the math-physics teacher designed together an extra-curricular course of creative writing. The Italian teacher guided the students to learn the techniques of creative writing, as well as the meaning of narratological constraints, while the math-physics teacher led the students into the physics of complex systems and its basic concepts: definition of complex systems, circular causality, feedback loops, non-deterministic chaos, emergent properties. At the end, the students were divided into groups of four and each group was asked to produce a final "group essay" (a tale). Each essay was required to focus the narrative on an example of a complex system, such as a nest, a flock, or an anthill, and to respect the narratological constraints faced in previous lectures.

The reason why we chose this dataset was that at first reading and after triangulation among three researchers it was agreed that in the essays there were implicit but also explicit references to identity issues, as well as explicit references to some epistemological features of physics of complexity, even if this was not a requirement for the writing of the essays. Given the research objective discussed earlier, we decided to deepen the initial intuition.

Hence a thematic analysis [26, 27] with the software NVivo was conducted. The essays were coded into 38 *codes*; then codes that referred to similar significances were grouped into *themes* (12 themes have been found). In the end the themes were again clustered into two broad *categories* which refer to the RQ (see figure 1 for all the details), following the guidelines elaborated by Braun and Clarke [27]. The objective of thematic analysis is to develop categories that could help illustrate the contents expressed in students' words at the intersection with the research interests expressed by the RQ; in this case, the effort was to read and categorize a fictional text, in which students do not answer questions as if they were interviewed, but they exploit the essay peculiarity and its *space of freedom* (characters' voices) for expressing themselves.

The first category developed ("*The individual with himself and with the group*") includes all the themes related to identity issues. The second category developed ("*Practices and values of the study of complex systems*") includes all the themes related to the epistemology of the physics of complex systems.

Figure 1. The diagram shows the qualitative data analysis process. Codes are displayed on the two sides; in the squared blocks there are the corresponding themes in which they were grouped; at the centre the two categories in which the themes were finally clustered.

These two categories mark the two areas of interest (epistemology and identity) of our study. The study, grounded in the data, has provided nuances of these two categories. For example, the "group connotation" of the identity category comes from data and was not conceived at the beginning; the same holds for the themes that show their adherence to data.

Once the dataset was coded, for each of the six essays the focus was pointed to the themes belonging to the two categories and their interrelations, with special care to the parts of the text where codes belonging to the two categories were spatially close, subsequent or overlapped, given our interest in the kind of links which can emerge between epistemology and identity issues.

4. Findings and discussion

In this section, we first sketch the meanings of the themes related to epistemology and identity, and then we look at some examples of links that emerged. We will ground our discussion on some excerpts taken from students essays[1].

In the essays there are several references to epistemological features of complexity; for example, the students systematically mentioned the role of changing perspectives, an epistemic practice required to manage the many dimensions of complex systems (the micro-dimension of local interactions between agents, the macro-dimension of emergent collective properties, the meso-dimension of the long-range correlations between agents). Connected to this, students reported that the reality "changes" according to the perspective since it is possible to describe a complex system macroscopically, microscopically or mesoscopically, but the descriptions are quite different: "*(it was clear) that things do not have a unique nature, but change according to the eyes, the light under which they are looked at*".

The awareness of the many perspectives is complementary to the awareness of what can be looked at by choosing one perspective or another: looking from inside the system allows paying attention to the single agent and its interactions, whereas looking from outside the system allows seeing the behavior emerging from the interactions of all the agents. Anyway, regardless of the perspective, students report the inability to have total information, since is impossible to locally look at all the agents at the same time, as well as impossible to grasp the whole system since "you will always miss a little part": "*To better understand this phenomenon, I could try to observe a single cell, but from this perspective, I can only see that the bubble will soon be engulfed by another or burst, so we can never predict what will happen. Observing the whole would be a very good perspective, as we can see what external agents are changing the whole. But in doing so, we would lose sight of the elementary unit of the phenomenon, that is, the single bubble, so understanding is impossible; I cannot understand how this reality can exist*" (speaking about a tin full of water and the molecules forming it, essay #4). Thus, dealing with complexity requires courage to accept this inability and question the meaning of "knowing": "*This complexity cannot be fully understood, but one can try to reach a truth very close to it […] (since a complex system) is something that cannot be broken down, or it would lose its very meaning*" (essay #4). The process of understanding within the field of complexity is reported as a reconciliation between perspectives that provide different realities, but which can have a meeting point; is a kind of learning that requires merging two points of view.

As mentioned before, this dataset shows also identity-related elements emerging; in particular, there is a systematic reference to the relationship between the self and a group, such as the family, the peers, and the class. Students report the tension between the need for independence and the safety provided by the community; being alone is risky but allows one to know oneself, whereas the group is commonly a safe place but it inhibits exploring personal individuality and personal future: "*Wow, it would be wonderful to disconnect from everything, to be able to feel free from the group I belong to. […] I would like to have time to pamper myself, to travel, to stop somewhere knowing that I am not in a hurry or have to look after the group. MY group, MY home. […] Would I be capable?*". Though, there are several excerpts in which the group is described as a "place" that rejects individuals (if different), and so is not

[1] The full text of the essays can be provided under request, by contacting the first author of the paper.

always a dimension within which one could be safe. Besides the differences emerges a pattern: the characters of the essays are willing to know themselves and "the others" can sustain or limit this demand.

For what concerns the links emerging between the two poles of the RQ, we present below the analysis of one (due to space constraints) representative excerpt with a dense overlapping of themes belonging to the two categories (Table 1): "*He thought that the birds had opposite views than the sea dwellers who, on the contrary, were forced to look at the world from below. Two opposite perspectives (that were) looking at the same world, both aware of each other's existence but unable to understand each other. He would have loved to have known how to fly, to have the ability to observe the whole thing from above. He often wondered how many things could be captured from that perspective, details that were overlooked by anyone and yet, observed from up there, might seem like something extraordinary. He, a fish, never able to float, destined for existence on the bottom, at that moment only wished he could have been able to twist his nature and know the other half of the world. He remembered when sitting on the bed in his room, he talked about Parmenides, how he argued that "The Being" is and can not "not-be". "The Being" knows that he/she/it exists, but is he/she/it able to know him/her/itself? Or "The Being" is, without knowing him/her/itself? Its existence at that moment was amalgamated with the other thousand unanswered questions, mingled with the nothingness claiming to be so. The complicated interests, but the complex fascinates. The lack of fixed rules, uncertainty and greatness frightens, and only those who are able to peek beyond and control the fear, succeed in coming to terms with the fear, even if never in an absolute way*".

Table 1. Sentences and related themes to which they were labelled. Refer to figure 1 for all the themes and the category they belong to.

Text	Theme
He thought that the birds had opposite views than the sea dwellers who, on the contrary, were forced to look at the world from below. Two opposite perspectives looking at the same world, both aware of each other's existence but unable to understand each other.	- Understanding as reconciliation of two perspectives by approximate view
He would have loved to have known how to fly, to have the ability to observe the whole thing from above.	- Vertical perspective
He often wondered how many things could be captured from that perspective, details that were overlooked by anyone and yet, observed from up there, might seem like something extraordinary.	- Local- global view - Consequences of the process of perspective change
He, a fish, never able to float, destined for existence on the bottom, at that moment only wished he could have been able to twist his nature and know the other half of the world.	- Consequences of the process of perspective change
"The Being" knows that he/she/it exists, but is he/she/it able to know him/her/itself? Or "The Being" is, without knowing him/her/itself? Its existence at that moment was amalgamated with the other thousand unanswered questions, mingled with the nothingness claiming to be so.	- Individual seeking himself outside the group and in the dual relationship
The complicated interests, but the complex fascinates. The lack of fixed rules, uncertainty and greatness frighten, and only those who are able to peek beyond and control the fear, succeed in coming to terms with the fear, even if never in an absolute way.	- Emotions with respect to complexity

The students are dealing with the personal demand of knowing themselves: "*The 'being' knows that he/she/it exists, but is he/she/it able to know him/herself?"*. In front of this demand the "fish", which is looking at the world from its own perspective, "*only wished he could have been able to twist his nature and know the other half of the world*". The narrative is built to show that other views are possible, by borrowing multi-perspectiveness (global and local points of view) from the epistemic practices of physics of complex systems; the bird can see the world from above and, thanks to this alternative, the dichotomy between "the known world" and the "other unknown half" is reframed and problematized. This could be a metaphor for the dichotomy between what is the current state of identity, and the other half of the self, the features of identity still to be developed. This is explicitly reported a few lines after: "*he had to come back to the surface, he had to show himself to the other half of himself*". In other essays, the multi-perspectiveness and the multi-scale focus (the habit of moving back and forth from global to local view) are borrowed again to build a conceptualization of a personal issue. The global scale represents the community and the local one represents the individuals; the internal point of view is used to represent the action of looking while staying inside the group (peers, family), whereas the external point of view means looking through the eyes of someone who does not belong to the group. Through this, the students had the opportunity to rephrase and evaluate the tension, for example, between the need for independence and the fear of leaving the group.

In addition, epistemic emotions have been found in the essays. The reference to complexity epistemology is conscious and is often accompanied by an expression of judgment, showing emotions towards the physics content exposed in class. For example, a sense of fascination for the forms of complexity and properties such as emergent phenomena has been found in more than one essay. On the other side, it appears often a feeling of discomfort and fear towards complexity, due to a lack of complete understanding; even a sense of frustration is expressed by the characters' voices: "*After a while, however, he huffed: he still could not see everything, could not register in his mind every little facet of what he was observing; each time he noticed that he had missed something, an extra leaf, a small hidden branch.*". The thematization (connection with features of complexity) of such emotions contributes to linking personal demands with those scientific contents, enhancing their personal relevance for students.

The excerpts discussed so far show how students used epistemological structures and practices of complex systems as tools to rephrase and restructure identity-related demands; the reference to personal identity demands was not part of the teachers' request but appeared to be an urgent need for teenagers. Looking at the entire dataset, this *scaffolding* action of complex systems emerges quite systematically, as a support in looking forward to identity development moving through ZPD (zone of proximal development).

5. Conclusion

In this paper we initially discussed the state of the art about science and physics identity; then we described our idea of *epistemic-personal consonance/dissonance*, the frameworks upon which it is grounded and the objective of developing markers for an operational lens able to trace the relationship between disciplinary epistemology and identity-related issues. Then we presented a data analysis made on essays written by secondary school students, within an activity whose aim was to present the specific features of physics of complex systems, educationally reconstructed according to the context (15-year-old pupils). From the qualitative analysis systematically emerges the scaffolding role that epistemology had for students: by highlighting the cognitive-epistemic core of the content in class and letting students explore it through creative writing (hence fostering an enlargement of the meaning due to the interdisciplinary approach), it was possible to trigger students' expression of some personal demands related to identity, as in particular the tension between the self and the group, properly because those features were seen as useful instruments to rephrase and reconceptualize such demands. This main outcome has been confirmed through a procedure known in qualitative research as "member checking" (Anfara et al., 2002). Indeed, during a meeting held in the second half of November 2022 with the secondary students who wrote the essays, we resumed the teaching module and presented the analysis

made; in the subsequent discussion the students confirmed that in the essays they were talking about themselves consciously or even unconsciously, even if that was not part of the task.

As they report, "*so in the end we told precisely ourselves inside that cloud* (an example of a complex system they had to describe in their essay). *But it's something we normally do when we talk to each other as well […] so writing about complexity through a cloud that is already a complex structure anyway turned into something simple because we were talking about us*" (student 4). Another student says also: "*So this text also served very much as a dialogue between us, to figure out just how we wanted it to represent us*" (student 1). They recognized and shared with us also the reason for the "group connotation" of identity category: "*(we wrote them) in a period (pandemic) when we had to relate so much to our own personal reality and much less in our relationship with others [...] Personally I thought a lot during those months about the relationship with others and the relationship with myself and I think you can also perceive from the themes the fact that personal identity was a highlight because by not having a relationship with the other the conception of ourselves is amplified and is constantly being questioned*" (student 1). They reported as well about the spontaneity of talking about themselves, implied by the choice of using creative essay workshops as the final part of the activity: "*In my opinion, it was quite spontaneous*" (student 3) or "*when you write it you don't think about it very much. When you write you throw down what is in your head*." (student 4). Another conclusion is that essays were conceived as a "place" with a lot of freedom and students talked about personal questions because of the "safety" embedded in the creative writing experience. As the Italian teacher adds: "*And here is that freedom to be able to talk about us freely because if I have to give a heart to the cloud, the first thing that comes to me is to give my heart, and then put myself as the subject*".

Therefore, we consider the scaffolding action that emerges from data a first example of a possible link between physics epistemology and identity-related issues, and we believe this is the first interesting contribution to our Research Question.

We expect that similar results, with new links, can be found also in other contexts with different scientific topics, provided that the epistemic core of physics is highlighted in its multiple systemic and interactional and process structures are discussed. For these reasons, we are planning other activities that will again exploit the creative writing language, given its effectiveness in allowing the reconceptualization of physics epistemology.

References

[1] Bottia M C, Mickelson R A, Jamil C, Moniz K and Barry L 2021 Factors Associated With College STEM Participation of Racially Minoritized Students: A Synthesis of Research *Review of Educational Research* **91** 614–48
[2] Lockhart M E, Kwok O M, Yoon M and Wong R 2022 An important component to investigating STEM persistence: The development and validation of the science identity (SciID) scale *International Journal of STEM Education* **9** 34
[3] Mostafa T 2019 Why don't more girls choose to pursue a science career? *PISA in Focus* vol 93 (Paris: OECD Publishing)
[4] Stroupe D 2014 Examining Classroom Science Practice Communities: How Teachers and Students Negotiate Epistemic Agency and Learn Science-as-Practice: Examining classroom science practice communities *Science Education* **98** 487–516
[5] Avraamidou L 2021 Identities in/out of physics and the politics of recognition *J Res Sci Teach* **59**
[6] Carlone H and Johnson A C 2007 Understanding the Science Experiences of Successful Women of Color: Science Identity as an Analytic Lens *J Res Sci Teach* **44** 1187-1218
[7] Stroupe D 2022 Naming and disrupting epistemic injustice across curated sites of learning *J. Learn. Sci.* **31** 317–34
[8] Gee J P 2000 Identity as an Analytic Lens for Research in Education *Rev. Res. Educ.* **25**
[9] Hazari Z, Sonnert G, Sadler P M and Shanahan M C 2010 Connecting high school physics experiences, outcome expectations, physics identity, and physics career choice: A gender study *J Res Sci Teach* **47** 978-1003

[10] Hazari Z, Dou R, Sonnert G and Sadler P M 2022 Examining the relationship between informal science experiences and physics identity: Unrealized possibilities *Phys. Rev. Phys. Educ. Res.* **18** 010107
[11] Hazari Z, Lock R, Cass C and Beattie C 2014 Obscuring Power Structures in the Physics Classroom: Implications for Student Engagement and Physics Identity Development *J Res Sci Teach,* **52**
[12] Hyater-Adams S, Fracchiolla C, Finkelstein N and Hinko K 2018 Critical look at physics identity: An operationalized framework for examining race and physics identity *Phys. Rev. Phys. Educ. Res.* **14** 010132
[13] Fracchiolla C, Prefontaine B and Hinko K A 2020 Community of practice approach for understanding identity development within informal physics programs *Phys. Rev. Phys. Educ. Res.* **16**
[14] Prefontaine B, Mullen C, Güven J J, Rispler C, Rethman C, Bergin S D, Hinko K and Fracchiolla C 2021 Informal physics programs as communities of practice: How can programs support university students' identities *Phys. Rev. Phys. Educ. Res.* **17** 020134
[15] Jaber L Z and Hammer D 2016 Engaging in Science: A Feeling for the Discipline *J. Learn. Sci.* **25** 156–202
[16] Davidson S G, Jaber L Z and Southerland S A 2020 Emotions in the doing of science: Exploring epistemic affect in elementary teachers' science research experiences *Science Education* **104** 1008–40
[17] Kapon S 2016 Doing research in school: Physics inquiry in the zone of proximal development: Physics inquiry in the ZPD *J Res Sci Teach* **53** 1172–97
[18] Levrini O, Fantini P, Tasquier G, Pecori B and Levin M 2015 Defining and operationalizing appropriation for science learning *J. Learn. Sci.* **24** 93-136
[19] Levrini O, Levin M, Tasquier G and Fantini P 2019 Orchestration of classroom discussions that foster appropriation *Science Education* **103** 206-35
[20] Erduran S and Dagher Z 2014 *Reconceptualizing the Nature of Science Education: Scientific Knowledge, Practices and Other Family Categories* (Springer Netherlands)
[21] Duit R, Gropengiesser H, Kattmann U, Komorek M and Parchmann I 2012 The Model of Educational Reconstruction – a framework for improving teaching and learning science *Science Education Research and Practice in Europe. Cultural Perspectives in Science Education* (vol 5) ed D Jorde and J Dillon (Rotterdam: SensePublishers) chapter 2 pp 13-37
[22] Irzik G and Nola R 2011 A Family Resemblance Approach to the Nature of Science for Science Education *Science & Education* **20** 591–607
[23] Klafki W 1995 Didactic analysis as the core of preparation of instruction *J. Curric. Stud.* **27** 13–30
[24] De Zuani F, D'Orto E, Fantini P, Tasquier G and Levrini O 2023 Enhancing relevance and authenticity in school science: design of two prototypical activities within the FEDORA project *Frontiers in Education* **8**
[25] Beck U 2000 Risk society revisited: Theory, politics and research programmes *The Risk Society and Beyond: Critical Issues for Social Theory* ed B Adam, U Beck and J van Loon (SAGE Publications Ltd) pp 211
[26] Glaser B G and Strauss A L 1999 *The discovery of grounded theory: Strategies for qualitative research* (New York: Routledge)
[27] Anfara V A, Brown K M and Mangione T L 2002 Qualitative Analysis on Stage: Making the Research Process More Public *Educational Researcher* **31** 28–38
[28] Braun V and Clarke V 2006 Using thematic analysis in psychology *Qualitative Research in Psychology* **3** 77–101