A Longitudinal Approach to Appropriation of Science Ideas: A Study of Students' Trajectories in Thermodynamics

Abstract: This article provides an empirical analysis of data collected during the implementation of a teaching proposal on thermodynamics in a class of 20 students (17 year-olds) of a scientifically-oriented secondary school in Italy. During the activities, each student made evident progress in gaining intellectual autonomy as they took part in the teaching/learning dynamics of the classroom. Although the research had, up to now, an empirical orientation, this paper aims to provide a contribution for advancing theory development in physics education research. The study gives an example of the application of a specific model of teaching/learning (the Model of Longitudinal Development) that acted as "framework for action" in the design of the learning environment as "properly complex territory." The data analysis gives indications for how to develop a theoretical understanding of the concept of "personal learning trajectory" and it provides a basis for exploring the factors that can trigger intellectual autonomy.

1. Introduction

This article focuses on an empirical analysis of data collected during the implementation of a teaching proposal on thermodynamics in a regular 12th grade class in a scientifically-oriented secondary school in Italy.The study is an example of application of a specific model of teaching/learning (the Model of Longitudinal Development, described in Section 2), that acted as "framework for action" (diSessa & Cobb, 2004) in the design of a learning environment as "properly complex territory."

A framework for action is intrinsically and self-consciously heuristic. The purpose of a framework for action is to provide some useful focus and direction for the design of learning environments. However, because frameworks for action may involve multiple, diverse design elements and plans (some of which may have inexplicit underlying assumptions), frameworks for action are not themselves "theories of teaching and learning" that can be tested or falsified. The results of a design that is informed by the heuristic principles of a particular framework for action are iterative in nature, and often involve making explicit and gaining a better understanding of the initial choices made by intuition or guess-work and guided by previous design experiences. This is what happened also in this study: through feedback from our students, we progressively gained a refined awareness of both basic features and the potential of the materials we had designed. In sections 3 and 4, we document this progress by stressing what we had explicitly planned before and during the implementation and what became, to our surprise, evident in the monitoring of the classroom activities.

Although empirical in orientation, this study intents to go beyond purely heuristic findings and aims to provide a contribution to the enterprise of advancing theory development in physics education. The choice of focusing the study on the specific concept of "learning trajectory," known in the research literature of design studies (Confrey, 2006), did indeed allow us to find important hints in the data for developing the research from a more theoretical point of view. In particular, by working on real examples of learning trajectories constructed by the students themselves, the fairly abstract and mainly evocative word "trajectory" seems to gain specific and operatively recognizable properties. These properties appear to be good candidates not only for defining it, but also for potentially including it in a "local theory" (diSessa & Cobb, 2004), aimed at explaining the connections between individual and collective growth and individuating the factors that can trigger intellectual autonomy through the construction of personal learning trajectories.

Section 5 is devoted to implications for future research and stresses the need to point out such theoretical foci of attention on which future studies can be carried out.

2. The Model of Longitudinal Development (as a framework for action)

The Model of Longitudinal Development (MLD) is the main product of the Italian PRIN project *"F21 - Teaching and learning pathways in physics for the 21th century, in both "formal" and "informal" education"* (2004-2007). This project involved nine Italian research groups in physics education and was coordinated at national level by Paolo Guidoni.

MLD is comprised of a set of shared criteria for designing teaching materials that allow the cognitive potential of the pupils to be progressively exploited and tuned to the construction of physics knowledge along the pre-university curriculum (from Kindergarten to upper secondary school) (Guidoni & Levrini, 2008; Levrini et al., 2009).

According to the model, the longitudinal development of physics teaching/learning is schematically seen as a continuous widening of phenomenological evidence correlated to more and more powerful modelling along 3 macro-levels of development:

- Level one (K-8) - phenomenological "appropriation" of common life experience;

- Level two (grades 9-10, the first two years of upper secondary school) - re-arrangement of phenomenologies into pre-theory structures (nets of physical concepts);
- Level three (grades 11-13, the last three years of upper secondary school) - re-arrangement of the previously acquired knowledge in terms of physical theories, up to the basic concepts and formal insights of "modern" physics.

The structure of physical knowledge as discipline (i.e. its organization in terms of theories roughly corresponding to the traditional "chapters" in which physics is usually taught) is not taken in the model as the basis on which the whole long-term curriculum can be organized. Rather, the disciplinary structure of physical knowledge is considered to be a high cultural goal to which students will be progressively and consciously guided in the last years of upper secondary school.

In this study, MLD acted as framework for action. The experiment on teaching/learning thermodynamics, described in the next section, concerns the level Level 3 (L_3) and has been designed according to the following criteria, assumed within MLD as general orienting principles for the design of the experiment:

a. *The role of productive complexities in a physics reconstruction for all students (physics as culture).* The teaching/learning process is assumed to be meaningful if it tunes, in a productive way, three very complex systems: Real world, physics and cognitive dynamics. Because of the involved forms of complexities, hyper-simplified instructional descriptions and explanations, by making the material seem easy, can dangerously distort the learning process as well as the content. On the contrary, once useless complications are avoided, forms of unavoidable complexities can be exploited as productive for creating learning environments rich enough to enable each student to exploit his/her potential and to follow the route more congenial to his/her cognitive style and/or cultural interest. In the proposal on thermodynamics described below, the two main sources of productive complexities considered are: (1) The comparison between different approaches to the same content (a multi-perspective approach) and (2) the plurality of the dimensions tuned in the proposal (a multi-dimensional proposal). Such forms of complexities have been investigated by our research team for several years, in particular in studies about teaching/learning modern physics (special relativity and quantum physics) (see, for example, Levrini et al., 2008).
b. *The distinction between classroom corridors and students' individual trajectories.* The two terms "corridor" and "trajectory" are taken from the work of Confrey (2006) who asserts the necessity for research to develop teaching paths in actual classrooms in collaboration with researcher-teachers in order to reach two kind of goals: i) To provide teachers "of guidance (…) to organize corridors (…) as intellectual spaces through which students progress" realizing "a particular conceptual trajectory through the corridor", "with variations among students", and ii) To allow the researchers to identify the invariants inside the different paths and to use them in "the articulation of domain-specific guidance illuminating conceptual corridors" and in "engineering and identifying multiple means for constructing" corridors that can be successfully navigated in different ways by different classes.

In short, according to the MLD, the criteria used for designing the teaching materials and strategies are strongly oriented by the aim of fostering the creation of the learning environment as a *properly complex territory*, that is:

- able to outline a wide, coherent perspective where productive complexities are exploited (*corridor*);
- suitable to be "navigated" by the students along different *trajectories* according to different cognitive styles and/or cultural interests.

3. The study

The context

The study concerns a teaching/learning experiment carried out during regular activities within a class of a science-oriented secondary school (Liceo Scientifico "A. Einstein") in Rimini, Italy. The class, composed of twenty 17-year-old students (9 girls; 11 boys), was attending the 4th year of upper secondary school (12th grade) and had studied physics from the first year (9th grade). Following the MLD, during the first two years (Level L_2), the teacher (PF, one the authors) carried out activities strongly focused on the problem of guiding students to construct pre-theory structures (nets of physical concepts) suitable to manage classes of phenomenologies (concerning motion, heating, light and vision, waves). The re-arrangement of the acquired knowledge in terms of physical theories (L_3) was the general aim of the activities carried out from the third year (11th grade). Before the teaching of thermodynamics as a theory, the curriculum had covered classical mechanics and special relativity. The thermodynamics corridor implemented in class was designed by a research group made up of researchers in PER, experienced teachers and undergraduate students.

According to the MLD criteria, the design of the thermodynamics corridor was characterized by the following basic choices:

- to present the same contents from different approaches. In this case, the two approaches were the macroscopic and microscopic ones, treated consistently as two different models, that can be compared by confronting the complementary explanations the two models give of the same phenomenology;

- to develop a critical-epistemological reflection on the peculiarities of the two approaches through specific activities (a questionnaire where students were asked to analyze and discuss excerpts of epistemological texts on the distinction between the two approaches, submitted at the beginning of the thermodynamics study; two collective discussions about the questionnaire performed at the beginning and at the end of the whole work);
- to emphasize the comparison of thermodynamics with the theories previously studied (classical mechanics and special relativity), so as to support learning as a continuous process of refining, re-investing, revising the models and the formal structures already acquired by looking at what was already known from new and more powerful perspectives.

The previous experiences of the group in designing teaching materials of modern physics (Levrini 2002) have provided interesting results about both students' understanding of the physical concepts (Levrini & diSessa, 2008), and the development of students' intellectual autonomy in properly complex territories (Levrini et al. 2008).

Following the research results of many years of investigation about teaching/learning modern physics, the design of the thermodynamics proposal was explicitly shaped by the following two research-based assumptions:

1) A multi-perspective approach can foster deep understanding of the physics concepts.
   In particular, the model of coordination class of learning and conceptual change (diSessa & Sherin, 1998), used as theoretical framework for analyzing a complex classroom episode, provided a theory-based explanation of *why* explicitly exposing, managing, and relating multiple classes of projections of a physical concept (the concept of proper time in special relativity), also elicited by the comparison between the geometrical and operational approach to special relativity, seems to be a good instructional technique to work around documented difficulties in conceptual change (in special relativity) (Levrini & diSessa, 2008);
2) The multiple dimensions (phenomenological, formal, conceptual, metacognitive) tuned by the analysis of historical-epistemological debates on the interpretation of the formalism of modern physics can foster the creation of a complex learning environment where the students are stimulated to reflect on the intricacies of the opinions and their personal involvement with them.
   A heuristic study on the implementation of a teaching proposal on quantum physics enabled us to point out that the multi-dimensional learning environment fostered students' intellectual autonomy by encouraging them to generate the questions that puzzled them and find out explicitly productive answers by themselves (Levrini et al., 2008).

The main methodological feature that distinguishes the research on thermodynamics is the focus on student's individual trajectories. The pieces of evidence about students' trajectories collected in our previous studies on different topics mainly came from classroom discussions and therefore the elements of intellectual autonomy emerged from the occasional individual contributions. In this study the aim of pursuing the individual trajectory was clear from the beginning and specific activities and instruments were designed for this purpose.

Aims, data sources and methodology

The study here presented focuses on a selection of the data we collected during the whole experiment on teaching/learning thermodynamics. We focus on the transcripts of the individual semi-structured interviews that were conducted at the end of the whole work. The interviews were specifically performed for addressing some research questions that had arisen from the previous study on quantum physics: Are the properly complex territories defined above really suitable to be navigated by the students along their own learning trajectories in an explicit and conscious way? If so, is it possible to point out what identifies an individual trajectory with respect to the classroom corridor? What features of corridors, teaching strategies and/or collective activities can trigger the construction of personal trajectories?

The first two questions will be answered fairly precisely by means of the data analyzed so far, whilst as far as the third question is concerned, the study will provide a preliminary answer in terms of hypotheses about the possible factors that enabled students to construct their own trajectories.

Out of the 20 students of the class, in order to avoid interfering too much with the regular classroom activities, 10 students (5 boys and 5 girls) have been selected for interviews so as to represent students' variety as far as motivation to study physics, special interest in thermodynamics, contribution to classroom discussions, level of performance in regular physics tasks are concerned.

The interview protocol included:

- general questions like: *What did you find more and less interesting in the work you did on thermodynamics? Why? What did you find easier and what more difficult?*
- specific questions addressed to the individual student for clarifying something he/she had said during the classroom activities, like: *During the last discussion in class you mentioned the existence of an interesting relation between thermodynamics and the theories you previously studied (like mechanics). Would you mind telling us more about this?*

The interviews have been conducted by a masters student (GT) in the presence of a researcher (OL) and another masters student (MS). They have been audio-recorded and transcribed. In the first step of the heuristic study, we decided to select 5 out of the 10 interviews so as to analyze a reduced amount of data and to make the search for criteria to analyze the whole set of data easier (Glaser & Strauss, 1967). The analysis of the 5 interviews produced 5 profiles that are illustrated in the next sections. The analysis allowed us to better define the nature of the trajectories that characterize each student's way of navigating the classroom corridor.

Results

Confrey's distinction between "corridors" and "trajectories" is strongly evocative in pointing out the different roles of the teacher and the students in the teaching/learning episodes. In the design phase of the study on thermodynamics, the distinction was taken as a synthetic way to emphasize the need both of assuring an active role to the students in constructing their own learning trajectories, and of dedicating research and teaching efforts in designing learning environments (corridors) able to foster a resonance between the growth of the individual intellectual autonomy and the collective classroom progression.

A major research product of the construction of the students' profiles was the tentative redefinition of the concept of trajectory that appears to enable us both to extract deeper information from data and to contribute to the development of a theoretical frame of analysis.

At the present level of the analysis, in order to share and discuss with other researchers the results of our attempt at better defining the concept of trajectory, we think it useful to report the 5 profiles reconstructed from the interviews with the students. For this purpose we also include whole original sentences from the students' protocols so as to respect to the extent possible, the students' style of argumentation.

Michele: Actuality of real life and curiosity for "how things work"

Michele, at the end of his interview, summarizes very clearly his position: "*I like Physics because it explains <u>how reality works</u>, so to say, I'm very curious about <u>how objects work</u> and natural events…*".

Next year Michele will start Engineering at the university. His interests are already precise. The topics that were most impressive for him were the definition of temperature and the kinetic theory of gases that "*better explains the causes, that is what temperature is, the very word, whereas in the macro* [approach] *we study the effects without being able to give a satisfactory explanation of the word*", but even more the Carnot Cycle: "*real life is there, let's say, these processes, the engines working through these cycles, therefore I was more interested in connecting it to real life than in knowing exactly what it is*".

He had previously been highly interested in classical mechanics, getting very good marks on it: *"we were looking for causes there"* as he said, it was a *"framework"* for understanding *"things of the real world"*, like engines, he was very keen on. While studying thermodynamics he was very quick in dealing with formal steps for expressing ideal gas laws at microscopic level and in studying heat engines. His out-of-school interests and his personal objectives have driven also his school-work that gives him satisfaction.

Also because of his very precise motivation, Michele played an important role in the classroom dynamics by taking a very clear position both in favour of the microscopic approach to the first law and in favour of the macroscopic approach to the second law: He became a stable and respected reference, often opposed to Matteo's position.

In spite of his precise preferences, Michele expressed his interest in the whole teaching path, because "the two ways led to reality" and gave an example of how "scientists work":

"*It seemed to me very interesting for understanding…. these two different ways to manage to arrive to principles, to how reality was investigated. It was very interesting to me also for understanding how scientists work, how Einstein, Poincaré worked…"*

Matteo: The pleasure of speculating and the search for approaching science from a "humanistic" point of view

The sentence that better summarizes Matteo's position is: "*I take for granted that <u>it is fundamental to speculate on reality and life</u>, because when you see phenomena and you get formulas out of that, then you have nothing, no foundation on which to stand. […] I believe that in order to find a way to understand a method to reach a reality […] it is fundamental to build a basis and <u>to speculate on how theories are found</u>, how concepts are elaborated. These concepts will certainly last longer than some formula."*

Matteo appears to like neither the formal elements of physics, "*too abstract*", nor the science claim to arrive at the truth: "*In my opinion Physics should not aim at truth, it should only […] be useful for mankind […]. To try to believe it possible to find in phenomena the foundation of truth is, I believe, an assumption out of the physics domain*".

The main point of his argument is that, in doing science, "human" and "far from reality" frameworks are projected on the world: *[…] <u>the sciences seem to me mainly human constructions</u>, I mean the way man has to investigate nature, to try to explain, may be without understanding that we cannot explain nature because we* *are human, we can only explain by the means we have… [and these] in my opinion are not powerful enough to catch the laws of nature… they are all human constructions that seem to me very inaccurate*".

Matteo played a role in the discussions similar to that of Michele, taking very precise and opposite positions to Michele's ones by criticizing the kinetic theory of gases and the microscopic approach in general: "*yes, the approach I prefer, you may already know, is the macroscopic one, because it stops at observing what happens and does not try to investigate reality, does not aim to understanding how these things happen from the inside, like the microscopic theory does by probing the bodies and finding some particles that move the same way… strange things*".

His opinion of science takes a positive turn when Matteo judges the epistemological activities carried out in the classroom. The topic he particularly enjoyed was the concept of irreversibility connected to the time arrow: "*yes, it is exactly this about entropy, where it develops a way of looking at the world which is a little less naive, because we see that the world is becoming, that some things that happen cannot be transformed… taken back to how they were: people get older, the table falls over, the cup breaks… cannot be put together again and here is a key concept to manage to accept even somehow reality, trying to explain everything following the path we went with these laws of mechanics, which is an odd idea, because mechanics laws are reversible and therefore there is no reason for a time line and for the time to go ahead; this may be a too philosophical way of looking at reality, because this way of refusing the becoming of being, of wishing to explain everything, the fact we understand that something cannot be explained, that there is this time advancing, this becoming that cannot be reduced to a being, may be this is something I enjoyed, I mean I enjoyed it*".

Lorenzo: The pursuit of a unified consistent view of physics

Lorenzo makes his position explicit by saying: "*One can see that everything is resumed, it is <u>not divided in topics</u> each with its own laws, instead everything can be<u> connected, </u><u>unified</u>; the argument becomes <u>wider</u>, <u>more uniform</u>*".

Lorenzo appreciated the macroscopic construction of the ideal gas equation because of its unifying nature: "*It was rather quick, with those three laws [Boyle's and Gay Lussac's ones] we quickly arrived to the ideal gas law"* and its link to mechanics ("*trying to explain again temperature by referring to particle dynamics*). He confirms his position when talking about the comparison of the two approaches: "*that in the end I managed to understand which elements I prefer of one and of the other… I preferred one for some features and the other for some others, in the end I managed to make everything uniform, therefore I understood the whole argument rather clearly, thanks to these two ways*".

"Understanding" means, for Lorenzo, "connecting", "unify in a general framework". His focus of attention is the systematic pursuit of consistency: to solve contradictions, to get rid of spurious elements, by bringing everything back to the simplest possible framework (in his opinion mechanics is the simplest theory).

Lorenzo admitted to have met serious difficulties in completing the questionnaire at the beginning of the teaching path: the key was lacking for giving a unified structure to the lot of information contained in the excerpts. The comparison between the two different approaches proved very satisfactory to his needs: "*…when I read it again (the questionnaire) […] I immediately associated microscopic thermodynamics to the constructive type of theory, at once did it come to me….. and I read them (the excerpts) in an altogether different way, … and it was all clearer than the first time, I managed to connect and realized immediately that something had changed… […] and I felt satisfied… because I had then only to read… whereas the first time it had been hard, it took the whole afternoon, I had to read it many times, many passages were obscure….*".

He concludes by saying: "*[…] I noticed a big difference between reading it at the beginning and at the end, I mean that hadn't I read it at the beginning I might not realize all the work we have done*".

Lorenzo played indeed a fundamental role in the final discussion about the questionnaire: his need for consistency was a basic support to reflection and an incentive toward pointing out "contradictions" of the overall reasoning (the "jarring notes").

Chiara B.: "Understanding as seeing" and the systematic effort of widening "one's own views" looking for and testing "new points of view"

In the final discussion on the questionnaire Chiara said: "*We have analyzed thermodynamics from both perspectives, <u>looking</u> at differences and similarities, I mean we have two different <u>points of view</u> ... it may be more complete to try to analyze a phenomenon, or whatever is around us, from two different <u>points of view</u> rather than from one and therefore this teaching path widens what we've done. It widened <u>my view</u>*".

"To understand", for Chiara, means "to see". Her interview is full of this metaphor. The comparison between the two approaches, the two "points of view", as she says, takes a more general, social and cultural meaning. In learning physics, the comparison has been very interesting because it gave various opportunities to "play" between the real and the ideal and to use her metaphor of "seeing": from empirical observation of reality to the investigation through the microscopic approach, of what can only be seen with the "mind's eyes".

"*Talking of the concept of temperature... one* [approach] *is more tangible, more real, because you see it with a thermometer, you measure, you say «yes, there is a change in temperature, I see it, I understand it», but* *also the microscopic one is useful [...] The particle movement, for instance, I cannot see it in a thermometer, only going to the micro can I see this movement*".

Therefore the microscopic approach has been useful from a personal point of view: "*Not so much for better understanding the macro, that I found easier, but because it gave me a different point of view*".

Her attitude towards physics comes out also when she speaks about irreversibility. In the following sentence Chiara expresses her surprise in finding also in the concepts of irreversibility the overturn of reality that allows physics to go beyond appearance: "*[I liked] entropy because it was interesting this business of irreversibility and reversibility of phenomena, ... I told to myself «what a strange thing: phenomena are irreversible, there is a before and an after, but I take them for reversible and also here I make another ideal model, I consider them through other processes», I mean.... it's some kind of overturn always in physics and that's what I like...*"

Chiara plays an important role in both classroom discussions on the questionnaire because of her passion for "*seeing other people's points of view*", for "*widening one's own view and avoiding getting fixed on some issues*".

Chiara C.: Focus on details and search for "not obvious details that are taken for granted"

"*I like physics because I sometimes happen to ask myself... I mean I am rather curious about how things happen*". What Chiara seems to like the best of physics is that "obvious things are not taken for granted".

Of the thermodynamics corridor she enjoyed everything "*that made me notice something I had not noticed before*", like the meaning of measuring an apparently obvious quantity like temperature or the fact that "*a true theory is the one, like thermodynamics, that manages to give the same results from both approaches* [... I believe that] *a theory that really works is the one that manages to compare the two ways that can be verified*".

Chiara pays attention to the smallest details that she keeps under control to be sure that the constructed model of reality is not too idealized or unfounded. "*In the microscopic I liked and disliked at the same time this business of the model of a discrete gas, ideal, rarefied...*". What she dislikes of the model is the idea of "perfection" that appears to give a too ideal and simplified image of reality, neglecting too many details. What she likes is "*to be able to think to a model we can make experiments on and to create such a perfect model that everybody would be able to imagine a thing like that*".

Once she has been reassured that the model is rooted in reality, she can appreciate it for making her notice details she had not noticed before: "*I liked the macro best because it made me think of things that I took for granted, whereas I liked the microscopic because there is this model that makes you think, because if you focus on all the passages to arrive to the final law, we had to take into account a lot of things*".

Chiara played an important role in classroom dynamics because of her attention to details that, when recognized by all students, became catalysts of the discussions.

The idiosyncratic nature of the way each student reacted to the teaching proposal is evident from the excerpts as well as his/her ability to move within thermodynamics showing confidence and competence on the topic (appropriation).

What features of the profiles allow us to say that they constructed their own trajectories within the classroom corridor?

Looking again at the profiles in order to answer to this question we identified a set of criteria that we implicitly used in tracing the profiles and that could be used as an explicit tool for re-analyzing the whole set of data in terms of students' trajectories:

- the line of thought is *explicit* in the words of the student;
- the line of thought is *consistent* across the whole interview;
- the specific approach to disciplinary knowledge is *not occasional* (it can be traced back to the student reaction in various classroom activities);
- the arguments are *on-task*, referring to selected aspects already present in the classroom corridor;
- the keywords, around which the student constructs her/his arguments, reveal personal engagement, by being *genuine* and *emotion-laden*.

4. Final reflections and implications for research

The heuristic study here presented started from a "framework for action" (diSessa & Cobb, 2004) that we developed according to the MLD produced within the Italian project F21. Such a framework oriented us in designing and managing the learning environment as properly complex territory. As far as the research questions are concerned, the study presented here shows that the learning environment really proved to be able to foster students' intellectual autonomy. More specifically, the profiles outlined from 5 interviews allowed us to point out specific features that characterize the individual trajectories with respect to the classroom corridor. In this sense the results, although preliminary, represent an advancement in knowledge on design studies. The results moreover illuminate some foci of attention for analyzing the data and they point out the need for programmatic and iterative investigations over time along different directions:

1. *Re-shaping the framework for action in more detail* and designing future experiments on teaching/learning thermodynamics as "successive iterations that can play a role similar to systematic variation in experiment" (Confrey, 2006). At present, two new experiments are planned: Experiments where the same corridor and the same tasks are proposed to 17-year-old students by different teachers in a different school. This will be the opportunity for testing the effects that the new awareness about students trajectories can have: Their existence can indeed encourage teachers to foster their construction by the students but it can also affect the deeply genuine character of the trajectories described here. In any case, we expect the comparison of these variations of the same experiment to provide new hints for studying the classroom dynamics by cutting the process on the joint that lies between corridors' and trajectories' features.
2. *Analyzing trajectories within the more general problem of conceptual change* and, more precisely, within the problem of *a longitudinal approach to "appropriation" of science ideas*. Meaningful learning of a topic requires, in a quite obvious way, a long-term process of appropriation. By appropriation we mean the process leading to enter a topic deeply – and extensively – enough to see that topic in a personal version. In other studies about appropriation, concerning teachers coping with innovative research proposals (De Ambrosis & Levrini, submitted), it has been pointed out to what extent an appropriation process, that requires one to find one's own point of view, is a problematic task because of the complex dynamics of finding criteria for coherence between (critical) details and a global perspective (Viennot et al., 2005). The students' trajectories described above seem to have all the features of an appropriation process, because of the personal, genuine, character as well as the coherence they have in situating contents details in a global framework sensible to them. The specific point of how, why and under what conditions the construction of personal trajectories is connected to deep understanding (conceptual change) deserves future research studies, both on the data examined in this study (by strictly crossing the personal trajectories and the contents comprehension), and on other data where, for example, the personal trajectories seem to distort the learning of a concept and where the process of appropriation and/or conceptual changes seem to be problematic and/or unsuccessful.
3. *Individuating the factors that can trigger intellectual autonomy* by the construction of personal learning trajectories. A study on "personal excursions"[1], in spite of their different features with respect to students' trajectories, inspired us in the search for those factors that can made the trajectories' construction possible (Azevedo, 2006). In agreement with Azevedo, we think that such factors need not to be identified at a too general level: They have indeed "to operate at a level of specificity that allows for a satisfactory explanation of the dynamics patterns characteristic of personal excursions [personal trajectories, in our case]". Following his suggestions, we think that, as a preliminary answer to the third research question ("What features of corridors, teaching strategies and/or collective activities can trigger the construction of personal trajectories?"), the following factors can be identified:
   - *the specific feature of the content reconstruction* that, by means of the comparison between two different approaches (macro and micro), is able to create a collective dynamics where students are involved with different roles (as partisans, opponents, moderators, disrupters, facilitators, …). Such a dynamics seems to have a productive power in making each student to find her/his more congenial path and progressively to test and refine it.
   - *the features of the activities specifically addressed to activate an epistemological meta-discussion* of the peculiarities of the two approaches. Although unusual, unfamiliar and demanding, the design of such activities has been always carried out in such a way that students could find themselves in their "regime of competence" (diSessa, 2000, quoted in Azevedo, 2006): Activities where they could approach the new epistemological language by applying it to physics domains previously studied.
   - *the choice of the teacher*, made explicit to the students, *to evaluate* their performance in the epistemological activities, by taking into account not "what they wrote or said in specific", but *their level of involvement*, the *coherence of their thinking* and the *contribution they are able to give in the collective discussions*.

All these factors deserve further studies specifically addressed to improve our theoretical understanding of students' trajectories. So far they seem to suggest that students' trajectories are stimulated and become evident in contexts where the whole teaching proposal is systematically developed and managed by the teacher through actions directed to move the learning problems from a plan where only "right-wrong", "yes-no", "bad-good" answers are possible, to a plan where the problems themselves, although respecting the shared disciplinary knowledge, admit an analysis in terms of critical evaluation of different possible, consistent, "points of view".

Endnotes

(1) Personal excursions are defined by Azevedo as self-initiated, self-directed, self-motivated and relatively long-term activities, belonging to a student's trajectory but task-off with respect to the classroom corridor. They represent "key events whereby students connect, in a deep and personal way, to the subject matter and overarching goals [of the unit proposed to them]" (Azevedo, 2006).

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