'Slow Science': Building scientific concepts in physics in high school

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“Slow Science”. Building Scientific Concepts in Physics in High School

Abstract

In this study, a progressive learning approach to physics, based on Knowledge Building pedagogy, was compared to a content-centered approach in which explanations, experiments, and discussions are centered on the transmission of knowledge. Forty-six students attending the first year of high school participated in this study over a whole school year. Students' knowledge and mastery of physics concepts were assessed through questionnaires containing both open-ended and multiple-choice questions. Overall, the "progressive learning" group outperformed the content-centered group. Results are discussed in relation to the theoretical background and the experimental teacher's diary of classroom activities. The main conclusion achieved by this study is that the teaching of physics should be slow, cyclic and developmentally appropriate for the context.

Keywords: physics, high school, scientific concepts, progressive learning, knowledge building

Physics plays a fundamental role in the formation of the citizen. Indeed, in the Programme for International Students Assessment, science literacy is defined as the scientific knowledge and the use of that knowledge to achieve an aim, and to act as a reflective citizen (OECD, 2006, p. 12). Various studies have underlined the importance of physics to secure future needs for scientific and technological competence (Angell, Guttersrud, Henriksen & Isnes, 2004; Drury & Allen, 2002).

However, students often struggle in this subject, and many strong incorrect beliefs are held regardless of the efforts of teachers and educational professionals. Misconceptions are particularly present in the area of physics, and are considered the first source of difficulties in this subject (Duit & Treagust, 2003; Eryilmaz, 2002; Stewart, Griffin, & Stewart, 2007.

Angell and colleagues (2004) claimed that recently Western countries have multiplied their efforts to develop curricula in physics education in high schools. Scholars have contributed by stating that science education should include knowledge *about* science, besides core scientific knowledge (Sjøberg, 2002). Furthermore, the aims and objectives of the teaching of physics need to be developmentally adequate (Gardner, 2011).

There are several research projects with the goal of improving science education, and most of them are grounded in socio-constructivism. This approach highlights the importance of attributing an active and constructive role to the learner, in an educational context that provides him/her with the tools to do so. Socio-constructivism challenges the dominant approach in schools, the transmission mode, in which the learner is seen as a passive receiver of knowledge transmitted by authoritative sources (teacher, textbook, and the like). The debate between transmission and constructivist approaches has been resolved in favor of the latter. However, two new sets of problems have risen. Firstly, socio-constructivism has been challenged by a few authors (Bereiter, 1994). Secondly, schools still adopt a transmission approach (Barak & Shakhman, 2008; Wells & Mejia Arauz, 2006) or, in the best cases, have internalized only a few aspects of constructivism, an effect defined as "lethal mutation" (Brown, 1992). The next two paragraphs will examine these two issues more in detail.

Reform-based science teaching

Socio-constructivist theories have produced a reforming movement in several educational systems, in particular in the area of sciences. Reformers interested in improving teaching, especially in science, encourage teachers to focus more on inquiry (Mortimer & Scott, 2003; Keys & Bryan, 2001), and student-centered instructional practices (Schneider, Krajcik & Blumenfled, 2005). The change advocated by reform-based movements has been very slow, especially in science teaching (Barak & Shakhman, 2008). Teaching in new ways requires teachers to develop new knowledge and teaching skills (Schneider *et al.*, 2005). In a study exploring physics teachers' beliefs and practices about introducing reform-based instruction in their classrooms, Barak and Shakhman (2008) discussed how teachers often consider reform-based instruction as an idealistic view of education, rather than an actual schooling practice. Also, teachers are not metacognitively competent enough to foster thinking in the classroom.

To create an inquire-based learning environment in science classrooms, teachers need to develop new skills, such as guiding student inquiry and supporting collaboration (Schneider *et al.*, 2005). In this sense, if we want to support teachers in reforming their teaching method, more than taking a look at lists of instructional strategies, it is important to explore examples of teaching approaches clearly inspired by the principles of inquiry and reveal the underlining process. In this sense it is useful to explore Bereiter's (1994) progressive learning approach, and Scardamalia and Bereiter's (2006) Knowledge Building model for two main reasons:

- they are grounded in inquiry and support this process with several other guiding principles;
- their criticism helps to reveal what happens in classrooms where the teacher "thinks" that he or she is implementing a teaching approach inspired by socio-constructivism.

Content-centered and progressive-learning approaches

According to Bereiter (1994) the key for science education is progressive discourse, rather than constructivism. Even when applying socio-constructivist techniques, schools often introduce scientific concepts to the students in an encyclopedic manner (Bigozzi, Vezzani, Tarchi & Fiorentini, 2010; Falsini, 2007; Fiorentini, 2008). In this perspective, science is taught "backwards" (Arons, 1992): teachers propose a scientific fact as a finished truth, a dogma, and explain it theoretically or, in the best cases, demonstrate it in the laboratory, basing it on knowledge of other laws and formulas. Although these methodologies have been proven to be less effective than hands-on inquiry and interactive teaching-learning methods (Coletta & Phillips, 2005), schools, especially high schools, are still relying on this traditional way to convey scientific knowledge (Barrett, 2009). In this regard, Mortimer and Scott (2003) offered an interesting analysis of the problem that schools typically encounter when implementing socio-constructivism in science classrooms. Teachers generally agree that science lessons should be student-centered and active. However, it seems that too much reflection is dominated by the activities to be assigned to students. Thus, socio-constructivism translates in lists of experiments and "things for students to do." This emphasis on practical activities drew attention away from the key feature of science lessons: the way in which classroom talk is orchestrated (Mortimer & Scott, 2003). This situation is particularly true for physics, as this is probably the most tightly guarded of all the sciences (Angell, Guttersrud, Henriksen & Isnes, 2004). Carlone (2003) coined the term "prototypical" physics to describe the traditional practices and beliefs about science that have prevailed for decades. According to her, prototypical physics, envisioned as difficult, hierarchical, and objective, is still reproduced in everyday school practices, often masked as allegedly “reformed” physics. The necessity to “situate” learning in real contexts for the students, and to introduce cooperative learning in school practices is increasingly subject to discussion on the teacher training agenda. However, what teachers intend to do does not necessarily transfer to what they actually carry out in class. As a result, students often describe science curricula as dull, authoritarian, abstract, full of unfamiliar concepts, with little room for enjoyment or interest (Sjøberg, 2002).

This list of issues proves how the idea of constructivism has yet to be fully comprehended in schools. Every teacher of science, physics included, recognizes the value of experimentation and observation, but these two components are not sufficient by themselves (Bereiter, 1994). According to Bereiter (1994), discourse should be attributed a central role in science, and in science education. Data is not a generator of progress *per se*, but it provides evidence that can be critically discussed, and the results of this discourse can eventually lead to progress. Research (and science education) progresses through progressive discourse. The idea that thoughtful discussions by students lead to better learning is not entirely new either. For instance, Mortimer and Scott (2003) discussed the communicative approach in relation to the teaching of science. They identified four different classes of communication, resulting from the interaction between two dimensions: dialogic-authoritative, and interactive-non-interactive. However, what Bereiter proposed is that classroom discussion needs to be seen as part of a larger ongoing discourse, and not just as a preparation to understand facts or as an after-experiment analysis. Research results have, in fact, discouraged teachers from engaging in classroom discussion for its own sake (Wells & Mejia Arauz, 2006). Classroom discourse needs to be progressive (Bereiter, 1994). Hakkarainen (2003) stated that participation in a progressive discourse can be elicited if we facilitate explorative processes, so that students learn to work together to search for new knowledge, to answer new questions, and not just to find answers to pre-existing questions. What is proposed here is that in a progressive-learning approach, the shift is not toward the individual, passively as in the transmission approach or actively as in the constructivist approach, but toward the knowledge building community (Hakkareinen, 2003).

Scardamalia and Bereiter's Knowledge Building model (2006) aims at systematizing the concept of progressive learning in a few principles. This model has been successfully implemented in several classroom sciences (see for instance Chuy, Resendes, Tarchi, Chen, Scardamalia & Bereiter, 2011). In a Knowledge Building Community, each science unit should start from "real ideas and authentic problems", as scientific knowledge should be "pervasive" and start from an attempt to understand the world. In an attempt to "democratize knowledge", students' ideas should be considered as valid as the ideas stated in the textbook or by the teacher. Indeed, every idea can be "improved" upon and science is continuously working to refine the coherence, quality, and utility of scientific ideas. Consequently, "idea diversity" is considered essential to develop advancements in knowledge. To achieve knowledge advancement, students need to individually engage with the knowledge-building process, by elaborating their own ideas and negotiating scientific meaning with other students ("epistemic agency"). On the other side, knowledge building is also a responsibility of the community, as aims and contributes are shared, and fundamentally students are collaborating to advance the collective knowledge, instead of each student working individually and separately. Authoritative sources (e.g. textbooks, but also the Internet, often used to transmit knowledge faster) are not the only source of knowledge, but represent an important reference in order to keep in touch with the state of the art of knowledge in a specific area. However, in a knowledge building community, knowledge is not just shared: through knowledge-building discourse, students continuously refine and transform ideas, in order to achieve the shared aim of advancing knowledge. Lastly, assessment needs to be consistent with such a perspective. Teachers should distribute assessment so that it can be used to have feedback on how the work for knowledge advancement is proceeding. Assessment is embedded in the community practices so that it can transform the practices themselves (Scardamalia & Bereiter, 2006).

From this overview it becomes clear that progressive learning requires a significant change in perspective to be adopted in a classroom. In this regard, Hakkarainen (2003) claimed that knowledge building communities do not emerge spontaneously or in a short period of time, but they need to be deliberately and consistently cultivated (Hakkareinen, 2003).

Research Questions and Hypotheses

From this overview of issues concerning the teaching of physics in high schools, a few important aspects can be derived. The importance of science in general and physics in particular is universally accepted, both to form reflective citizens, and to secure countries' needs for scientific and technological needs. Although several scholars have highlighted the efficacy of implementing socio-constructivist principles in physics-related school practices, teachers find it problematic to apply them and still rely on a transmission approach, in which experiments are used as a way to support teachers' explanations of laws and formula. To tackle these issues, this study aimed at creating an "evidence-based practice", in which physics is promoted by integrating teaching practices – shown through empirical studies to be efficient - that are compatible with the environmental and organizational context. To increase the level of adherence to real-life school contexts, we took into particular consideration the ecological validity in designing the research method. This means addressing ecological validity - methods and materials are close to real-world situations -, more than external validity - extent to which the results of a study can be generalized to other situations. As opposed to internal and external validity, ecological validity is often neglected in experimental studies, as it is not considered to be necessary to the overall validity of a study (Shadish, Cook & Campbell, 2002). As a consequence of this stress on ecological validity: we worked with experienced teachers; we decided to analyze differences among teaching methods that were already existing, rather than training newcomer teachers; and we focused on a whole school year. Two learning approaches were compared. One learning approach was content-centered and mainly based on the pattern “teacher’s oral explanation – students’ individual study of the textbook – assessment”, with a few observations in the laboratory and discussions of experiments mostly conducted by the teacher. In this kind of approach, the teacher follows a set curriculum and is considered, along with the textbook, the most important authoritative source of knowledge. Students are allowed to learn by referring to external abstract knowledge, with aims and objectives clearly defined by the teacher.

The other learning approach can be defined as “progressive learning.” In his discussion on the educational role of scientific discourse, Bereiter (1994) claimed that science learning should be based on progressive discourse, a set of commitments, such as a commitment to expand the body of mutually accepted facts, and work toward an understanding that all participants will appreciate as an advance. This approach required two important shifts: from a teacher-centered class to a knowledge building community, and from concepts to ideas. Instead of transferring knowledge or constructing knowledge according to set paths, the students and teacher work together on ideas with the aim of advancing the community knowledge and creating learning objectives that are developmentally appropriate for the students. In synthesis, the progressive-learning teacher created a syllabus based on students' needs, but addressed each topic flexibly, depending on how the class reacted to it.

In this perspective, each member was given the epistemic agency and accountability to advance knowledge. The classroom proceeded in a progressive spiral of discussions, hypotheses, experiments, refined ideas, constructive use of authoritative sources, and rise-aboves. The teacher’s main role was to make sure that the ideas on which students were working, the physics concepts that were constructed, and experiments were all appropriate for the students’ developmental stage. More importantly, the teacher had to mediate between national curriculum standards and a teaching-learning perspective where the number of objectives for each lab session were limited (as Séré pointed out in 2002) and given the right amount of time to be achieved.

This study contributes to the scientific literature in several ways:

- it explores and describes an inquiry-based and progressive learning teaching approach, and discusses the application of theoretical principles through the teacher's journals;
- it compares a progressive-learning approach to a constructivist one, in which classroom discussion and experimentation are also included;
- it takes an ecological perspective, and analyzes the "actual" implementations of the two approaches, rather than "trained" ones;
- it explores progressive-learning in high school physics, a rather underdeveloped area of research.

The main hypothesis of the present study is that students following a “progressive-learning” approach internalize more physics concepts than students following a “teacher-centered” approach. In a Vygotskyan perspective, students progress in their development by internalizing socially given cognitive tools, which, in turn, change the functions and structures of their minds (Vygotskij, 1973). This hypothesis will be explored by comparing students’ performances in questionnaires on physics concepts, and also by analyzing the progressive-learning teacher's diary. In this way we will be able to answer to two important questions: "what" the differences are, and "why" there are such differences.

Method

Participants

Forty-six grade 9students (19 girls and 27 boys; 14 years old) in a high school in Florence (Italy) participated in the research. Two classes participated: the progressive-learning group (23 students; 12 boys and 11 girls) and the content-centered group (23 students; 15 boys and 8 girls).

Participants were selected on the basis of their teachers. Within the partnership between the Department of Education and Psychology (University of Florence, IT) and the Center of Teachers' Democratic Initiative (Florence, IT), we have selected two teachers with the following criteria: at least 10 years of experience in teaching physics in high school, as this is the minimum number of teaching years indicate by scientific literature to define someone as 'expert' in a field (Ericsson, Charness, Feltovich & Hoffman, 2006); a willingness to participate to the research project for a whole school-year; both teachers working in the same institute, to control for socio-demographic and school environment factors; a clear pedagogical orientation, one grounded in the progressive-learning approach, and one inspired by the constructivist approach, as assessed by preliminary interviews. In particular, we created the interview for the progressive-learning teacher on the basis of the 12 principles of the Knowledge Building model (Scardamalia & Bereiter, 2006). This set of choices was made to ensure that the study had a strong ecological validity: we were interested in what the actual implementations of progressive-learning and constructivist approaches is like in schools.

Measures

The participants were tested twice, at the end of the first semester and at the end of the school year. The authors agreed with the teachers who participated in this study not to insert a pre-test assessment. In fact, the 9th graders (first year of high school in Italy) had never systematically explored physics concepts before entering high school, as this subject is not formally taught before this grade. The study aimed to explore students' learning of core concepts in physics, which can only be acquired through formal learning.

The two groups were compared on the conceptual construction of physics concepts by giving the students a 13-item questionnaire. This questionnaire was given to both groups twice: as an intermediate measure of efficacy (end of the first semester), and as a final measure of efficacy (at the end of the school year). To control for content/face validity we used the panel of experts method: the questionnaire was constructed in collaboration with the two participating teachers, who implemented tasks and items used in past tests to assess 9th-grade concepts (Rattray & Jones, 2007).

Both questionnaires, intermediate and final, included 13 questions: 10 were qualitative questions to explore the knowledge of a concept, and 3 were quantitative, to explore the knowledge of formulae (see Appendix A for examples).

Procedure

The intervention took place during the first year of high school, over a whole school year. After several conversations with the teachers in the school, we selected two physics teachers, and the 9th grades they were teaching, to participate in the study. Both teachers had several years of teaching experience, a great knowledge of the subject and of teaching methodologies. One teacher adopted a progressive-learning approach in her classrooms, whereas the other was content-centered, and implemented both a transmission and a constructivist approach. We selected the two teachers because they were highly representative of the two approaches to teaching physics that we wanted to compare in this study: progressive learning, based on discourse; and what is often considered to be "constructivism" in our classrooms, an approach giving students an active role, but still focused on content. We also decided to select a teacher who already adopted a progressive-learning technique, rather than creating an intervention and randomly assigning teachers and students to the groups, as we believe that such an approach cannot be taught in just a few weeks.

At the time of the study, the students had not yet received a formal teaching of physics, and it was assumed the two groups were equivalent at the beginning in that they had no scientific knowledge on topics of physics.

The two experimental groups shared the same National Curriculum for the teaching of physics in the 9th grade, set by the Ministry of Education in Italy. The groups used the same textbook. It is important to note that the main difference between the two groups lies in the method of teaching, which, consequently, has repercussions on school practices, and use of textbooks. One of the most evident differences lies in the two syllabi. As already said, the two teachers covered all the topics prescribed by the National Curriculum. However, as a consequence of the teaching method, the progressive-learning teacher was able to teach and discuss with the students more sub-topics than the content-centered teacher did. Below we give more details of the main differences.

Progressive-learning group

During the school year, the progressive-learning group studied physics topics through cycles of teacher's lectures and explanations, experiments and discussions. The teacher followed a syllabus, where the main topics were listed. However, the progressive-learning teacher developed each topic in a way that was developmentally appropriate for her class's zone of proximal development (Vygotskij, 1978). Rather than introducing topics as in general developmentally appropriate for the age of the students, as suggested by the national curriculum, the teacher had the chance to explore each student's acquisition process in action and expand it when necessary through classroom discourse. As suggested by Vygotskij, education should act in the space between what the child is capable to achieve on his/her own, and what is capable to achieve in collaboration with more expert ones. Classroom discourse allows to create multiple zones of proximal development (as each student is exposed to other students' perspectives) and allows the teacher to monitor the whole process. In this way, the classes may have followed similar curricula, but the process in which each topic was inquired was very different. The syllabus can be accessed in appendix (appendix B).

The following materials were used to perform experiments in the laboratory or the classroom:

- springs, elastics, chest expanders; dynamometers; goniometer; weights and blocks; "optical lever" (Arons, 1992); adhesive tape and other unstructured material for the study of electrostatics; plastic and glass sticks, supports, electroscope; magnets; unstructured material available in the classroom

The progressive-learning group focused on scientific procedures, observations and misconceptions characterizing the domain of physics. Each topic was addressed through manipulation of objects and/or observation of situations from everyday life. Under the teacher's guidance, mainly based on examples and analogies, the students worked on activities, produced graphs and diagrams, and discussed the topic in class. This approach lead students to be eventually dissatisfied with their conceptions (misconceptions), and made them willing to test and modify them. Teachers usually know what students' misconceptions typically are, and address them explicitly. However, this does not allow students to constructively challenge them, above all because they do not consider them as misconceptions. Just as scientists do, students begin to work towards a revision of their theories once exposed to contradictory evidence. It must be noticed, however, that this study did not focus on students' misconceptions, and future studies should verify this statement. Each lesson referred to the previous one, in order to help students to create the correct links among topics. Definitions of relevant concepts were never given to students by the teacher, but derived from a path that, through the formulation of hypotheses, observation, and justification of phenomena, allowed students to construct operational definitions. The school laboratory was used continuously to allow students to test the concepts constructed in class. Consistently, the students' homework was based on open questions allowing them to express their opinions on concepts of physics. Students' notes, reports, homework, and discussion results were collected in individual timelines, which functioned as study guides.

We will better present the progressive-learning procedure using excerpts from the diary of the teacher on a physics topic: static forces. The topic comprehended a total of 21 school hours. Static forces are a developmentally appropriate concept for 9th graders as it does not interact with other physics concepts, such as movement, acceleration, and the like. In progressive learning, the teacher proposes these topics to students in a sequence so that each physics concept is based on other concepts that have already been internalized by students, as assessed by the teacher through classroom discussions, and students' reports. Differently from other approaches, the program does not follow a set of given steps (such as the chapter of a textbook), but allows student to decide the next steps of the knowledge building concepts. Also, in this approach the grading is mainly based on students' reports, rather than quizzes, which gives the teacher the opportunity to explore students' understanding of class experiences and discussions. This recalls the principle of "symmetrical advancement of knowledge," (Scardamalia & Bereiter, 2004) as opposed to the advancement towards a specific type of knowledge characterizing content-centered approaches. Also, when few students did not seem to understand a concept, the teacher considered it an opportunity to challenge the level of knowledge achieved by their peers, and used the incorrect beliefs to foster classroom discussion or the planning of an experiment. Conversely, in content-centered settings, often the teacher does not want to slow down the other students, and provides students who did not understand a concept individual support: an individual class, or individualized homework.

To begin, the teacher had students manipulate springs, attempting to ground the topic of forces in students' "real ideas and authentic problems" (Scardamalia & Bereiter, 2006). During the discussions, some students used the term "deformation" and the teacher underlined the pertinence of this concept. As there was some debate on the forces in action, the teacher asked students to represent the situation graphically. Below are a few examples of the drawings made by the students (Figure 1):

INSERT FIGURE 1

Figure 1. Students' graphic representations of the forces acting on a spring.

The teacher noticed that the students did not just draw the forces acting on the elastic, but also the one exerted by the elastic itself. Consequently, the teacher realized that the gap between the students' conceptions and her aims was still significant.

One student suggested that a way to exert one only force on the spring is by hanging it on a support. Here we can see the principle of "idea diversity" in action (Scardamalia & Bereiter, 2006). A progressive-learning classroom is good for working with many ideas at the same time and a single students' idea can move the collective work forward to improve ideas (Scardamalia & Bereiter, 2006). So, students hung the spring on the edge of the blackboard, but the teacher made them aware that even an inanimate object can exert a force. At this point, the teacher asked the students to draw the forces in action on the spring and they did not have any difficulty in doing so. However, when asked to draw the forces acting on the object, the students struggled. Thus, the teacher dropped the object to the floor and asked the students to draw the forces in action during the fall: the force was just one, gravity. After this experience, the students did not have any difficulty in drawing the correct diagram for the object attached to the spring. Immediately, a student hypothesized that the spring could be used as a means to measure forces and everyone agreed. The original hypothesis of using deformation as a means to measure was replaced by the hypothesis of measuring length in order to derive the intensity of the force. Then, the class was engaged in associating a quantity, a number, to each spring. Two alternatives were explored: either the number is large when the spring extends easily with a small weight, or the number is large when a heavy weight only causes a small extension. The class discussed the two alternatives and finally decided on the latter. It is important to note that the discussion was never relegated to specific moments, but was a continuous flow or, to use Scardamalia and Bereiter’s words (2006), “pervasive”. The teacher showed the students a few dynamometers, and asked those who had already seen them to remember the meaning of the word: measurer of force. At this stage, the teacher felt the students could be exposed to an authoritative source, as they had the theoretical background clear in their minds, and were able to use it constructively (Scardamalia & Bereiter, 2006).

Content-centered group

In the content-centered group, the teacher applied both transmission and constructivist practices. The syllabus can be accessed in the appendix (appendix C).

The teacher and the textbook were the authoritative sources in class and "contained" all the relevant information to be learned. The disciplinary content was transferred to the students through the teacher’s lectures and explanations, and students’ individual engagement with the textbook. Students studied topics directly in the textbook and solved textbook exercises (students’ homework). The teacher assessed the students’ knowledge through oral and written tests.

At times, the teacher implemented constructivist practices, by having students observe, discuss and reflect in written form. Typically, when the teacher wanted to introduce a new topic, or conclude it, she brought students to the school laboratory, introduced the law and the formula they were going to observe, and conducted the experiment. Afterwards, students discussed their impressions, revealed their misconceptions and reflected if they had changed their conceptions or not. Although aware of the presence of misconceptions, the teacher did not allow students to constructively challenge them. Finally, students were asked to write an essay on what they had observed and learned in class. If possible, the students themselves were able to perform the experiment, while the rest of the procedure remained the same. The following materials were used to perform the experiments in the laboratory or classroom:

- springs; dynamometers; goniometer; weights and blocks; "optical lever" (Arons, 1992); plastic and glass sticks, supports, electroscope; magnets.

An example of an experiment conducted in the laboratory concerned error of measurement. Students had to take several measurements of the same object, and report all the scores. Students compared their scores and noted how they were always different. Students calculated the averages and standard deviation scores and discussed how each measurement should also be reported in indication of the error. Students discussed the implications that this finding had on their day-to-day habits.

Another form of constructivism took place during the teachers' explanations. Oftentimes, the teacher introduced the topic of the lesson, and then asked students what they knew about it, inquiring as to their prior knowledge and raising awareness of their misconceptions. Then, the teacher lectured on the topic, defining the concepts, describing the laws, making examples, and addressing students' prior beliefs and misconceptions. The teacher concluded by asking students if they still were of the same opinion or if some sort of conceptual change had taken place. For instance, forces were a topic that was introduced in class in this way by the teacher. The teacher asked the students which forces are at play when we are standing up and not moving. Then she asked the students how we can measure them. Some forms of misconception arose from this discussion, such as the difference between mass and weight. The teacher explained what the difference was and introduced the formula to calculate forces.

At the end of each unit, students were assessed in class with a written text. The teacher asked conceptual questions, and questions in which students had to apply a formula.

During the school year, participants studied how to measure aspects of real life, and use measurements to describe the world surrounding us through the teacher's lectures and experiments in which small lengths, time and mass were measured. Then, the content-centered group's teacher explained the theory of errors to the students, and how to use mathematical data. Subsequently, the teacher introduced and explained the topics of forces and balance in fluids by discussing the main aspects and laws.

Data Analysis

The students' answers to the intermediate and final versions of the physics questionnaire were coded according to the following system: 2 points for correct answers, 1 point for partially correct answers, 0 points for wrong or missing answers. Two independent raters coded the material. Inter-rater reliability was 86% for the intermediate questionnaire, and 89% for the final one. Each incongruence was discussed and resolved by the two independent raters. The two questionnaires, intermediate and final, reported good reliability scores, with the alpha coefficients being respectively .75 and .89.

The extreme outliers of each variable were identified and eliminated by observing the relative box plots. The normality of each dependent variable's probability distribution was explored: in those cases in which a variable distribution was not similar to a Gauss curve, the appropriate monotonic transformations were applied before carrying out the inferential statistical analysis (Fox, 2008). Differences in students' performances in the intermediate and the final physics questionnaire were compared through two Analyses of Variance (ANOVA).

Results

Post-intervention and Follow-up Tests on Concepts of Physics

To test the research hypotheses, the progressive-learning and content-centered groups were assumed to be equivalent at the beginning of the school year, and were tested twice, at the end of the first semester and at the end of the year. The descriptive analyses are reported in Table 1.

INSERT TABLE 1

The performances of the two groups in the intermediate and final questionnaires were compared through two univariate analyses of variance. The progressive-learning group outperformed the content-centered group both in the intermediate test (7.78±2.24 in Progressive-learning vs. 4.91±3.15 in Content-centered; $F_{1,44}=12.71$, $p<.01$, $\eta^2=.22$), and in the post-test (11.19±3.23 in Progressive-learning vs. 4.64±2.72 in Content-centered; $F_{1,41}=51.94$, $p<.56$, $\eta^2=.56$) (see table 2).

INSERT TABLE 2

Moreover, the progressive-learning group reported a statistically significant change over time, from the intermediate test to the post-test, whereas the content-centered group did not (see Figure 2).

INSERT FIGURE 2

The time x group interaction effect explained 33% of the variance in the dependent variable (Λ=.67; $F_{1,41}$=20.51, p<.01, η^2=.33).

Discussion

The importance of physics in the formation of reflective citizens (OECD, 2006), and the fact that Western countries are concerned that students struggling in physics today will affect and might not secure societies' future needs for scientific and technological competence (Drury & Allen, 2002) demand further analysis of how to support teaching practices related to the subject of physics. In this study, we contributed to the dialogue on science education by exploring a progressive-learning approach and compared it to what schools understand by constructivism.

The progressive-learning group outperformed the content-centered group both in the intermediate test (end of 1st semester) and in the post-test (end of the school year), and showed a significant change in time. The results were remarkable, considering that the independent variable (group) explained from 22% to 56% of the difference in dependent variables. The content-centered group did not improve in time, confirming that "lethal mutations" (Beown, 1992) of constructivism in schools do not produce any effect. The content-centered group was able to understand physics concepts only at a surface level. This data, instead, provided strong support for the efficacy of the progressive-learning group's method in achieving a deep understanding of physics concepts. The most important aspect characterizing the "progressive learning" approach is its range of components. Firstly, usually physics education is learning *about* science, and not just core scientific knowledge (Sjøberg, 2002). Instead, the progressive-learning group's teacher worked with the students as if they were a community of scientists, discussing hypotheses and designing experiments for the advancement of knowledge. In this way, the students were able to increase their epistemological perspective on physics and understand products (concepts) by exploring the process (by testing hypotheses). This approach fostered a fundamental developmental shift in students, from learning physics as a system of true statements, to learning physics as a system of statements that have been, and currently are, supported or challenged by someone (Gardner, 2011). Students learned the difference between "observing" and "interpreting", "reality” and "phenomenology", and learned not to confuse facts that they can observe and their interpretation. It is the difference between saying "objects are charged with electricity and attract each other" and "objects attract each other and so we think they are charged with electricity". Indeed, in science concepts are invented and not discovered, and it is important not to confuse the two levels (Arons, 1992). Physics is a progressive science, where students, just like scientists, should work in order to advance knowledge, test and refine hypotheses, and progressively replace old and invalid theories (Bereiter, 1994).

The advance that this research is attempting to make is twofold. We wanted to put forward the relevance and the impact of a progressive-learning approach in science education in an ecological context. Furthermore, we wanted to compare it to a transmission/constructivist approach, which here we have called the content-centered group, which represents what most schools and teachers understand by constructivism.

Discussion and experiments are often considered the *conditio sine qua non* of a constructivist approach. However, as Bereiter discussed (1994), these two elements are not sufficient. Generally teachers are focused uniquely on the discipline, and use transmission (lecture, textbook) and constructivist (discussion, experiment) means to convey concepts and facts. Rarely are teachers focused on the learners. One element that can be inferred from the description of the progressive-learning group is that the teaching of physics, and science in general, needs to be slow. This does not necessarily mean covering fewer topics than indicated in the National Curriculum. But, sometimes, it means sacrificing the learning of definitions and formulae in the favor of a deep understanding of the concept.

According to this study a key element is "discourse." The students' and teacher's ideas were put on the same level and inserted in a cycle, in which experiments always followed students' socio-cognitive conflict, that is a simultaneous confrontation of different approaches or thinking systems, that takes places during a social interaction (Doise, Mugny & Pérez, 1998). Experiments were designed by them, and used to advance the community (classroom) knowledge Such a progressive discourse can be elicited if students are allowed to explore physics by searching for new knowledge (Hakkareinen, 2003), as opposed to working backwards from principles and concepts (Arons, 1992). Adopting a progressive-learning approach requires several shifts: from concepts to ideas (Bereiter, 1992), from co-construction of meaning to a knowledge building community (Scardamalia & Bereiter, 2006). For instance, teachers often place experiments either at the beginning of a unit, as a hook for the students' interest, or at the end of the lesson, as a conclusion. In this study, the progressive-learning group attempted to insert experiments within the knowledge-building work, sometimes to test a hypothesis, sometimes to observe a formula, and other times to trigger a discussion on a phenomenon. The progressive-learning teacher used experiments for a variety of purposes, and instead of focusing on their frequency, tried to determine when each experiment was developmentally appropriate. More than just internalizing single facts of physics, the teacher helped the students to interpret and construct the meaning of the interconnections existing between physics concepts, by giving them epistemic agency (Scardamalia & Bereiter, 2006) and also making sure that the concepts which investigated would fit into each student's zone of proximal development (Vygotskij, 1978). The teacher continuously monitored their efforts from a developmental perspective, by reflecting on classroom discussions (with the support of personal journal-keeping), and reading students' reports. Although this aspects needs to be backed up by future research, we suggest that the main difference between the two approaches described in this contribution stays in the quantity and use of these teaching tools. Assuming that also content-centered teachers make use of classroom discussions and students' reports, in the progressive-learning approach discussions and reports are used to make the knowledge building discourse pervasive (Scardamalia & Bereiter, 2004). It is a continuous flow. Discussions are always present in class, and by reflecting on them and reading reports, the teacher extends such discourse also outside the class. The progressive-learning teacher reads reports not only with the aim of grading students and assessing their level knowledge, but to determine what is the state of art of the knowledge building process, and where should the class be headed next. The problem is not just whether concepts are developmentally appropriate for students. The problem is that physics teachers should monitor if the direction in which knowledge is advancing is developmentally appropriate for the specific classroom, and whether the concepts that the students are looking into fit the developmental context of the classroom.

The main conclusion achieved by this study is that the teaching of physics should be slow, progressive and developmentally appropriate for the context. Our data indicates that progressive learning is more effective in fostering students' conceptual knowledge of physics than a transmission/constructivist approach, which is what teachers generally apply in their teaching practices when they want to have a constructivist approach. Both approaches implement experiments, observations and discussions; however, the former is focused on ideas, whereas the latter is focused on content.

Furthermore, the comparison between the two syllabi produced an interesting reflection. One of the main objections to "slow science" in general is that continuous use of the laboratory to foster students' literacy in physics eventually leads to an impoverishment of the content covered. Teachers running many experiments and allowing classroom discussion are only able to work on a few concepts. Instead, this study showed a different trend, and demonstrated that progressive learning, mainly based on constructing scientific concepts by testing hypotheses through experiments, allows the teacher and the students to study intertwined concepts in a progression, where a conclusion achieved with an experiment leads to a new hypothesis that needs to be tested, and so on. Both syllabi included the topics that teachers need to cover in the first year high school in Italy, as indicated by the national guidelines of the Ministry of Education. However, the progressive-learning approach allowed the teacher to go more in detail and explore more sub-topics than the content-centered approach. It must be remembered that the topics inserted in a curriculum are indeed conceptually interconnected, and the progressive-learning approach helps the teacher to reveal such a pattern, allowing the students to go back and forward in the program. Instead, approaches centered on the content often treat the topics as separate, in a linear sequence, without remarking the connections between concepts of different units. Although this aspect might confound the data analysis conducted in this study, it is very difficult to control, as it would be unethical to oblige teachers to apply the same identical syllabus. Indeed, both teacher followed the national curriculum, within which each teachers is free to decide teaching and learning practices. Also, it would be extremely artificial to have a progressive learning approach applied only on a specific unit, without exploring the interconnections with other units.

In conclusion, this study contributed to the scientific literature on physics by exploring a teaching approach based on progressive learning. Participants were high school students, a population scarcely studied, especially in the domain of sciences. We compared it to another approach, a constructivist approach and centered on the content, which is how typically socio-constructivism is applied in classrooms (Mortimer & Scott, 2003). We have also supported the explanation of the Knowledge Building principles, the progressive-learning approach implemented in the study, with excerpts from the teacher' journal, in order to provide clear instructional advices to newcomers to this approach. Another original contribution of the study was its ecological perspective, aiming at describing what really happens in classroom, rather than training teacher to use an approach and testing its efficacy on students' competences.

However, this study was affected by a few limitations, which derive from the focus on ecological validity, and represent directions for future research. Firstly, the sample sizes of the two classes were rather small, because of the choice of working for a whole school year with experienced teachers in the two approaches compared in this study. Future research should increase the external validity of our findings, by replicating the study with different teachers and larger samples. Secondly, external and internal validities would be strengthened by future studies exploring what really happened in the classroom during instruction and what other factors might distinguish the two classes (how well each principle was applied, whether there were differences in terms of clarity and structuredness of instruction, and the like). Thirdly, following the advice of the participant teachers, we decided not to pre-test students knowledge of physics concepts, to preserve students’ self-esteem and perception of self-efficacy. We believe in the equivalence of the groups, since none of the students had been formally exposed to physics before the research. Nevertheless, the two groups could have differed in terms of "folk" physics, and misconception, types of knowledge which could have boosted or hindered their formal learning of physics concepts. Including this aspect would have also allowed to analyze the potential of progressive learning to foster a conceptual change in the presence of misconceptions. Future studies should include some measurement of prior knowledge of physics that provides information about student’s conceptions, and at the same time is ethical and ecological. Fourthly, the study compared two different teaching approaches along a whole school year. Consequently, many confounding variables could explain the results we obtained. We decided to adopt an ecological approach in this study, in which materials and measures were as close as possible to a real-life situation. In future, it will be necessary to run an “unpackaging” study, in which other measurements of other context variables (e.g. differences in syllabus, availability of a laboratory, and the like) are included, as they could possibly account for differences between the two groups. Lastly, future studies should explore more in detail the impact that progressive-learning has on students' thinking. For example, it would be interesting to determine how this approach affects students' misconceptions and internalization of physics concepts, with a follow-up study.

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Appendix

A. Examples from each questionnaire.

From the intermediate questionnaire:

Example of a qualitative question.

Three bricks are supported in three different ways: the first one on a marble table, the second one on a wooden table, the third one on an elastic carpet. Are there any forces present?

- *a. yes, in all three cases*
- *b. yes, but only in the third case*
- *c. yes, except for the third case*
- *d. I do not know*

Specify which forces are present: ____

Example of an application of formula.

Two people are on opposite sides of a river and pull a boat with two ropes. The angle between the two ropes is 60°. How much is the total force exerted on the boat if each individual force is 75N?

From the final questionnaire:

Example of a qualitative question.

Some magnets are attached to the door of a fridge, as souvenirs from many travels. Decide which one of these statements correctly describes the situation:

- *a. the metal of the door attracts magnets; there is no reciprocal interaction between magnets*
- *b. the magnets, being small, exert a small attractive force on the door*

c. *the magnets are attracted by the door, attract the door, and can attract or repel each other*

d. *the magnets and the fridge door interact in an attractive way; there is no reciprocal interaction among magnets, which in fact are still.*

Example of an application of formula.

The edge of a copper cube (density= 8.9 g/cm^3) measures 2.0 cm. How much does the cube weigh? Express the result in N. If we hang the cube on a spring with an elastic constant of 125 g/cm, how much does the spring extend?

B. Syllabus followed by the progressive-learning group during the school year

- *Describing the world surrounding us*: Measurements of length (earth's roundness, distance earth-moon and earth-sun; measuring angles in astronomy through construction and use of a height quadrant; measurements of unattainable heights); Eratosthenes's method to measure terrestrial radius
- *Forces*: Recognizing forces in simple situations and graphically representing them; Elastic force (Hooke's law); Weight force, dynamometers, the Newton; Specific weight, measuring volume with a graduated cylinder; Normal weight exerted by a surface; Friction force; Composition of forces: the parallelogram rule; Decomposition of a force along two assigned axes; Determining the resulting force of two or more forces by decomposing the orthogonal components; Decomposing gravity force on an inclined surface; Electrical phenomena (to strengthen the concepts of force as interaction); Electrification by rubbing. Distinguishing electric from non-electric; Repulsion and attraction between electrified bodies; Attraction between a charged and a neutral body (electrical induction); The concept of electric charge and the existence

of only two types of charge; The origin of the adjectives positive and negative; Conductors and insulators; Electroscope.

- *Weight of air and the concept of pressure*: Phenomena that can be interpreted with the horror vacui theory; The functioning of a lift pump; Torricelli’s experiment and interpretation of phenomena through the air weight hypothesis. Modifications to Torricelli's and Pascal's experiments; Definition of pressure, Stevino’s law, use of different units of measurement for pressure; Pascal’s law; Air pump; Elasticity and compressibility of air; Boyle's law; First hypothesis on nature of air, interpretation of pressure, relationship between pressure and density.
- *Temperature and heat*: Fusion and solidification. Constancy of temperature in passages of state; Variation in volumes and density in transitions of state; Calibrating a liquid thermometer; Celsius and Fahrenheit thermometric scales; Propagation of heat, conduction, definition of thermal conduction; Thermal equilibrium; Heat as something transferred (extensive quantity); Definition of calorie, and of specific heat; Dependence of pressure on temperature of transfer of states; Latent heat in transfers of state.
- *Observation and experiments in the laboratory*: Across the topics, the teacher proposed experiments on: scientific notation, order of magnitude, meaningful numbers, experimental uncertainties, random uncertainties (due to instrument sensitivity), absolute and percent uncertainty, propagation of uncertainties in indirect measurements; Measuring lengths with the gauge; Studying elastic deformations: spring (Hooke’s law) and “optical lever”; Simple measurements of force with dynamometers; Measuring angles to verify the parallelogram rule; Characteristics of friction force; Observing phenomena connected to air pressure and Torricelli’s experiments; Torricelli’s vacuum experiment; Air elasticity; verifying Boyle’s law;

Verifying Archimede's law; Fusion and solidification of phenyl salicylate; Calibrating a thermometer; Observations on the propagation of heat; qualitative comparison of the conductivity of several materials; Determining the specific heat of some metals.

- *Other learning tools*: Using resources from websites: Eratosthene's method (www.vialattea.net); Meridian and height quadrant (www.imss.fi.it); Experiments on pneumatics (http://brunelleschi.imss.fi.it/museum/indice.html); From thermoscope to thermometer (http://brunelleschi.imss.fi.it/museum/indice.html).

C. Syllabus followed by the content-centered group during the school year

- *Physics and the measurable reality*: Describing the world: Galileo and the experimental method; Lengths and units of measurement; Other characteristics of bodies: surface area and volume; Scientific notation, order of size, significant numbers; Other characteristics of bodies: mass and density; Experiments: measuring small lengths, measuring time and mass.
- *Theory of errors*: Direct and derived sizes; Experimental errors: sensitivity, random, systematic; Calculating the experimental error, different types of error; Propagation of errors in indirect measurements; Experimental data and mathematical relationships; Constructing and reading a graph.
- *Forces, their vectorial representation and balance*: Definition of vector; Analytic method to sum vectors; Effects of a force and units of measurement; Elastic force: Hooke's law; Gravitational force.
- *Balance in fluids*: Pressure: Pascal's principle; Hydrostatic pressure: Stevino's law; Atmospheric pressure: Torricelli's experiment.

Tables

Table 1

Descriptive analyses

Group		N	Mean	SD
Progressive-learning	Physics_1	23	7.78	2.24
	Physics_2	21	11.19	3.23
Content-centered	Physics_1	23	4.91	3.15
	Physics_2	22	4.64	2.72

Table 2

ANOVA of the progressive-learning and content-centered group's performances in the physics questionnaires

		Sum of squares	df	Mean of squares	F	Sig.	η^2
Physics_1	Between groups	94.70	1	94.70	12.71	.00	.22
	Within groups	327.74	44	7.45			
	Total	422.44	45				
Physics_2	Between groups	461.53	1	461.53	51.94	.00	.56
	Within groups	364.33	41	8.89			
	Total	825.86	42				

Figures

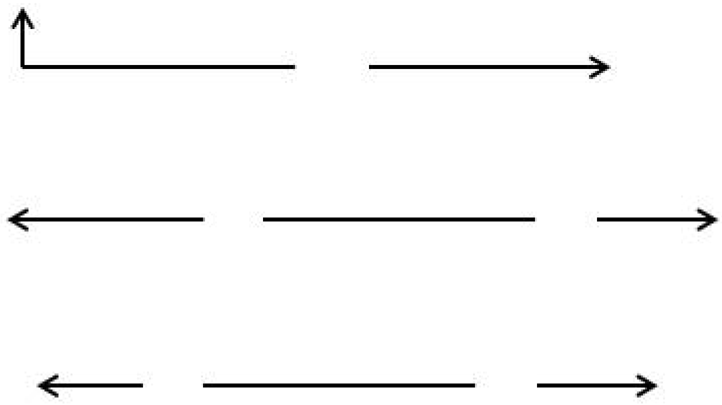

Figure 1. Students' graphic representations of the forces acting on a spring.

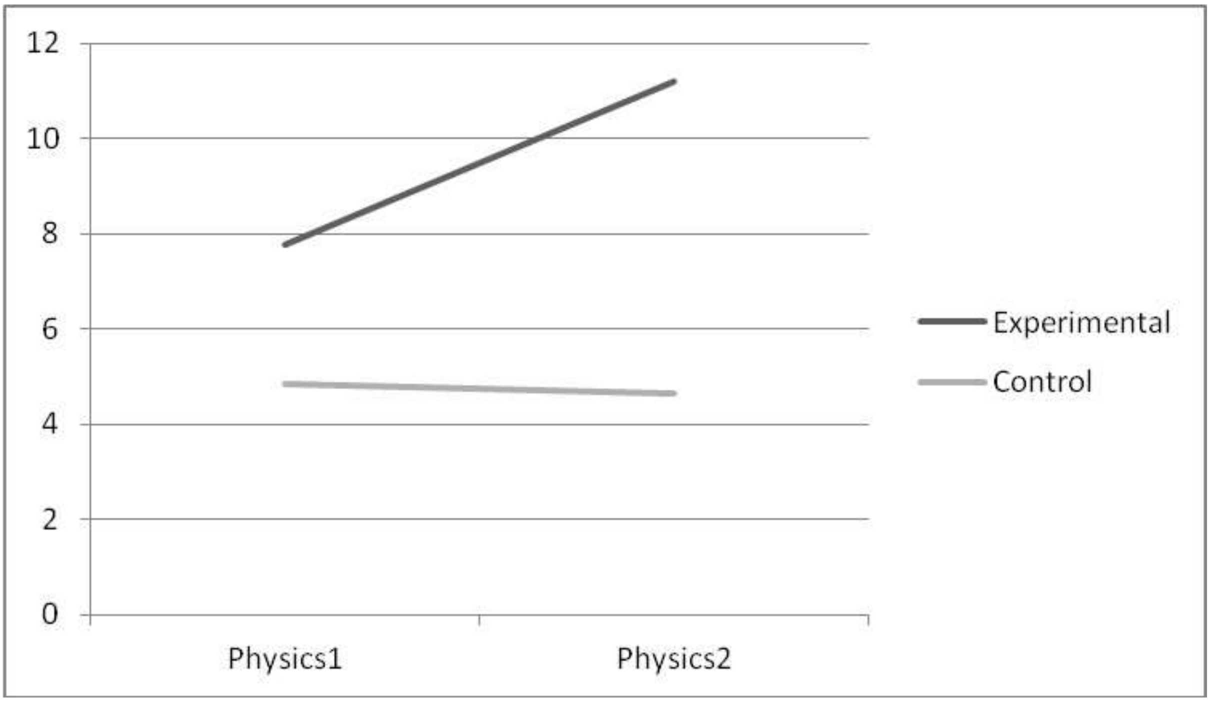

Figure 2. Time X Group interaction in the physics questionnaire.