Chapter 1
General Talk Papers
Considering Physics Knowledge as a Culture – an Approach to Physics Curriculum Matching Interests and Needs of Contemporary Learners

Igal Galili
The Amos de Shalit Science Teaching Centre, The Hebrew University of Jerusalem

There are very few, if at all, new things in this world. Therefore, the agenda of a person is to find a new, fresh interpretation of those familiar.

Giorgio Morandi
Italian Artist

Abstract
Common physics curricula present the subject of physics as a scientific discipline - clearly and univocally. This presentation usually leaves in shade several aspects of this knowledge which are especially important for the contemporary culture in a wider sense. Those emphasize plurality and polyphonic discourse taking place in physics as a living body producing knowledge in the process of construction, debate and refutation in the ongoing practice and across the time. In structuring physics curriculum we suggest to emphasize its basing on a few fundamental theories which comprise a conceptual dialogue, specify the difference among them as well as their commonality (family resemblance). This goal can be reached through structuring the contents of each theory according to triadic affiliation: nucleus, body, and periphery. Such approach may frame the inclusion of history and philosophy of science in school curriculum and create cultural content knowledge (CCK) in students. CCK creates appropriate space for meaningful learning leaving the options of preferable interest to its certain area by different individuals, provides options of emphasis on particular area of knowledge, yet within the big picture of physics. We have applied this approach within the European project HIPST in creating special units – historical excurses presenting conceptual discourses regarding several physics concepts that we illustrate here.

Keywords
CCK-cultural content knowledge in physics education, physics discourse, structure of physics curriculum, discipline-culture, nucleus, body knowledge, periphery knowledge, cognitive preference of the learners, structure of scientific revolution, structure of individual conceptual change.

1. Introduction
Back in the 60s, Josef Schwab, one of the founders of science education research, determined this area as comprised of four thematic commonplaces: subject matter, teachers, students, and environment (Schwab, 1962). Establishing motivation of this study, we first observe and very briefly mention characteristic features of the obtained understanding of each of the commonplaces.

With regard to the commonplace of students, it is common to adopt the perspective of constructivism which states the establishment of individual knowledge in the extended developmental process of interaction of the personal cognition with various external factors (e.g. Duit & Treagust, 2003). It is understood that in the process of learning students ubiquitously produce alternative to scientific conceptions either totally different and/or of hybrid nature (e.g. Vosniadou & Brewer, 1992; Galili et al., 1993). Students are extremely prolific such conceptions and the studies documenting those are extremely numerous (e.g., Viennot, 1979; Driver & Erikson, 1983; Driver et al. 1985; Duit, 2003). Constructivist teaching suggests taking into account this plurality by addressing it this or other way in instruction in order to overcome them as barriers to the understanding of scientific contents.

With regard to the commonplace of teachers, their ability to address the plurality of different conceptions of students and recognize their cognitive preferences (e.g. Tamir, 1985) establish, in view of Schulman (1986),
a special kind of knowledge required in teaching science – Pedagogical Content Knowledge (PCK).

Teachers serve as mediators of the collective, socially possessed knowledge in the complex process of knowledge assimilation. Clearly, this process is much beyond a mere transmission.

With regard to the commonplace of environment, the great variety of suggested forms of supporting effective learning is also extremely wide. This veracity reflects the variety of populations, social contexts of learning, curricula and levels of instruction (e.g. Fraser et al. 2014). Introduction of computer tutorials, simulations, intelligent databases caused a flood of variations of changing traditional classroom environment.

So far one may observe significant conceptual variety with respect to each of the three considered commonplaces of science education. This is not what we may say regarding the fourth commonplace, the commonplace of subject matter. Normally, the curriculum of physics presents what is called disciplinary curriculum (Tseitlin & Galili, 2005). It usually contains topics, concepts and conceptions unfolding to the learner in a traditional sequence and accompanied with extensive solving of standard problems. In applying this approach, such essential features as structure of physics knowledge, its hierarchy, interrelationship between the components, reduction to a few fundamental theories, concept construction often remain in shade of intensive practicing of physics knowledge application and its utilization in problem solving. In such teaching physics, one of the major epistemological issues – the conceptual discourse regarding the construction of physics knowledge, as we possess and consume it now, is not always addressed.

In our study, we considered the way to reveal the conceptual discourse in educational context. We framed this discourse in the triadic structure of knowledge which we previously suggested to represent the relationship among the fundamental theories of physics. Within this framework, we see physics knowledge as a culture (Tseitlin & Galili, 2005), naming such knowledge cultural content knowledge (CCK). We have suggested two ways to accrete such knowledge in educational process. Firstly, we will mention the produced series of historical excurses to the discourse regarding physical concepts, such as motion and weight (Galili, 2011). Secondly, we suggested and tried to apply a summative lecture as a delayed organiser of knowledge, following regular learning (Levrini et al, 2014) as a new format of teaching seeking CCK. In the following, we will briefly present the rationale of the CCK approach and illustrate how it emerges in physics discourse.

2. Physics knowledge as a culture

Physics knowledge is comprised of a few fundamental theories (Heisenberg, 1958; Weizsäcker, 1985; Bunge, 1967). Each such theory establishes an inclusive cluster of numerous elements – principles, concepts, conceptions, models, experiments, explained phenomena, etc., which are coherent with certain conceptual framework and can be represented using dual codification as shown in the diagram of Fig. 1a. It possesses two areas of knowledge elements. The first area – nucleus – includes basic principles and the second one – body – incorporates numerous applications in the form of elements mentioned above comprising the normal knowledge of the theory. This structure represents a disciplinary curriculum which draws on certain theory, such as classical mechanics.

What makes this structure representing a cultural knowledge is the adding of the third type of knowledge elements – the periphery (Fig. 1b). This area includes conceptions, problems, phenomena which are inconsistent, contradict or unexplained by the considered nucleus. These elements may suggest alternative accounts for the same subjects that were already explained and as such belong to the body. The unsolved problems of the periphery challenge the particular theory, its nucleus. This structure may represent a discipline-culture curriculum which observes the relationship of different physical theories.¹

![Figure 1](https://via.placeholder.com/150)

**Figure 1.** (a) The structure of a fundamental theory or a disciplinary course. (b) The structure representing the cultural knowledge of a theory or a discipline-culture teaching.

¹ The triadic codification was applied by Lakatos in 1978 (to depict Scientific Research Program of a fundamental theory. In that use, however, the meaning of the components (the contents of the areas of the triadic diagram), as well as their labels, will be different.
One, thus, faces a choice in the construction of physics curriculum: disciplinary versus culture-disciplinary. The latter presumes making explicit the basic tenets of each theory in comparison with other possible theoretical accounts. Thus, within the cultural knowledge perspective the classical mechanics is not a special case of the relativistic mechanics because the nuclei of both theories are essentially different and contradict each other (time, space, interaction, speed of light, conservation laws, etc.) (Fig. 2). Similarly, one can address the relationship between quantum mechanics and classical mechanics: classical mechanics is not a special case of quantum mechanics.

Figure 2. Discipline-culture structure of two fundamental theories.

This perspective refines the meaning of *incommensurability* of different scientific paradigms often ascribed to different scientific paradigms (Kuhn, 1962/1970). The overlaying bodies of knowledge may depict treating the same problem by different approaches and so shows, in a sense, the *commensurability* of different physical theories. At the same time, the nucleus of each theory is in the periphery of the other showing essential contradiction. This approach allows visualizing the polyphony of physical theories in their accounting for the reality by family-like theories. This picture represents the reality of numerous materials produced by research activities of the normal science.

Let me add why this perspective is termed *cultural*. The term culture is frequently used in a very wide span of meaning. This because, speaking generally, it represents all possible products of human society (Tylor, 1920). Other researchers name by culture separate clusters of human products which distinguish among different areas of human activities such as Art, Science, Literature (Hofstede, 1991). Within the culture of science, one may focus on human behaviour in doing science (Latour, 1987) or on the specific perception of science in light of local culture by a specific ethnic group (Aikenhead, 1997, Aikenhead & Jegede, 1999).

There is, however, a different perspective of one considering the knowledge of physics itself. One may see that physics knowledge presents a discourse, which interprets (beyond describing) reality, is selective in adoption ideas, conceptions, standards of verification and method of inquiry in accounting for the reality, establishes rules and performs experiments. Physics has its values, ethos and ethics. All these imply that the physics knowledge, by itself, presents a culture (Lotman, 2001). Of two possible types of culture – the culture of rules and the culture of texts – physics presents a culture of rules. Our focus in this study, however, is on the content knowledge and the conceptual discourse which makes physics knowledge cultural. So, in our use, culture implies explicit addressing of this discourse.

3. Implications of considering physics as a culture

As mentioned, the cultural content knowledge (CCK) presumes making explicit the conceptual dialogue of science, addressing the conceptual variety in the account for certain subject. One can illustrate this aspect by considering the fragment of a regular school curriculum presenting the "world organization". Usually, it focuses on heliocentric world view as overcoming the geocentric one adopted in the past. Its emergence is often termed Copernican revolution. Within the cultural approach, a teacher would present a picture of the continuous debate from the beginning of physics between the geocentric view – a part of Aristotelean physics – and the alternative views suggested by Pythagoreans prior to Aristotle and by Aristarchus immediately after Aristotle. So placing Aristotle in the nucleus (Fig. 3), one mentions other views of the periphery. One proceeds to the Hellenistic science in which the geocentric view was essentially strengthened by its fundamental elaboration by Ptolemy in his *Almagest* placed in the body of geocentric theory. In the following the teacher may emphasize the non-stopping contributions developing and correcting the geocentric conception by Muslim scholars (Alhazen and Al-Tusi) and criticizing it during the medieval period, those by Buridan, Oresme and Nicolas of Cusa eventually arriving to the modern time. Then, the hybrid view of Tycho Brahe appeared as a strong challenge of the central idea from the periphery. Finally, the wave of critiques started from Copernicus, Kepler and Galileo caused a breakthrough – radical conceptual change of the Copernican revolution. All the process may be framed and visualized by the exchange of elements between the nucleus and periphery in the triadic structure (Fig. 3).
Figure 3. Discipline-culture structure of the geocentric theory of the world order. Arrows show the exchange of knowledge elements between the nucleus and periphery representing the radical conceptual change during the scientific revolution.

The cultural perspective on this subject would include mentioning the more advanced views which upgraded the picture as held in our days and considers by physicists as the correct one. The theory of modern astrophysics left the "helio-centric" perspective in favour of the concept of expanding universe without unique centre, the view that introduces freedom of the choice of an observer depicting the world in his frame of reference.

3.1 Individual conceptual change

The suggested triadic structure can be applied to visualize the individual conceptual change in the process of learning science. The process of exchange between the nucleus and periphery is the conceptual change. We have depicted the conceptual change in the collective knowledge of science (Fig. 3), but if one put the initial conception of the learner in the nucleus and the physics conception taught in the periphery, a parallel process emerges with regard to personal knowledge. Moreover, Posner and colleagues (1982) specified the conditions for such change (dissatisfaction with the old knowledge together with plausibility, intelligent and productive nature of the new conception). These conditions apparently imitate the conceptual change in science. This similarity might indicate certain relevance of recapitulation as a developmental phenomenon introduced to educational psychology in early twentieth century (Kofka, 1925). One may observe certain similarity of onto- and phylogenies of knowledge, limited but existed. Further use of this similarity for promoting the individual conceptual change could be through involving learning materials involving historical conceptual change in the subject matter taught (Galili & Hazan, 2000b). Whether or not the initial view and the educational goal are similar, the important fact is that the educational conceptual change presents the important change of knowledge status. Using the three world idea of Popper (1978), one may say that the educational conceptual change is, in a way, a transition from the World 2 of individual conceptions to the World 3 of physical theories.

The impact of the social environment on the individual learning is very significant. Vigotsky (1994) stated it as process of enculturation. Following intensive research, we also know much more about the features of individual conceptual change (Vosniadou, 2007; Duit & Treagust, 2003; Limon, 2001). The naïve knowledge is stated to be based on basic self-explanatory patterns of spontaneous reasoning rooted in personal experience (Schemata – in Piaget, 1972; and p-prims – in diSessa, 1993). The context dependent patterns of reasoning were suggested by Minstrell (1992) as facets-of-knowledge. Combining the two levels of context independent with context dependent patterns of reasoning, one may obtain a two-level structure of scheme-facets (e.g. Galili & Lavrik, 1998, Stein & Galili, 2014). The latter included also the impact of teaching. We might then depict the conceptual change of students in science by a diagram showing the consolidation of the knowledge in specific area possessing triadic structure (Fig. 4). I may represent learning in a whole domain (mechanics, optics) or concept (weight, image). Even in the best case of successful learning the original conceptions of students do not disappear but preserved in memory and can reappear when students are challenged with a novel problem (Galili & Bar, 1992). This preservation might be depicted by placing the initial conceptions in the periphery of the resultant knowledge.
3.2. Students' cognitive preferences

The triadic structure of knowledge may be applied to refine and classify students' perceptions of physics instruction and attitude to physics. In our empirical study (Levrini et al., 2014), we observed students with various interests towards physics knowledge as might be expressed in Figure 5. Though one may not ascribe hierarchy to the variety of interests in general sense, we do ascribe importance to the awareness of students' different attitudes to physics instruction in a regular class. Indeed, very often the students who show the skills and interest to the body-knowledge – problem solving, modelling, application of the newly acquired knowledge for practical goals are usually most supported by teachers and different institutions known for their support to students. We may call them "pragmatists" or "practitioners" (Fig. 5). This is in contrast with those who show an interest only to the great design, major laws and principles of physics (the nuclei of physics theories) which empower them to understand conceptual explanations of the natural phenomena, technological and social applications of science. These students – "philosophers" in Fig. 5 – are often perceived as not serious enough learners of physics, rather "dreamers" or "humanitarians". There are still the rest, the students who are interested in the controversial aspects of the learned knowledge, the limited justification of the basic decisions, "why this principles, laws, not other possible ones?" These students might disturb the regular flow of instruction, impede the process of practicing the new knowledge in standard problem solving. Yet, though sometimes annoying and disturbing, it is these students that may produce future researchers and creators of the new knowledge. Therefore, we may call them "revolutionists".

All together, the existence of this variety among the students' interests in physics denounces and replaces the dichotomy of students (and people in general) stated by C.P. Snow (1961) and known as two-culture vision of society with respect to science: "physicists" and "poets", good and bad students of physics class. This
inference possesses far reaching implications with regard to the leaning materials for physics learners. Those materials have to speak at least in three epistemic dimensions. Not less important is the inference of necessity of physics education research to address the students' population in its cognitive variety. Neglecting this reality definitely causes missing fundamental features in physics teaching-learning reality. Quite in parallel, one may observe similar distribution of interests in the course of history, in the kind of contributions of different physicists to the construction of physics knowledge. The names of those who contributed to the nucleus of the constructed theories (theory of relativity, quantum theory, astrophysics etc.) are usually better known to the wide public. This activity was praised by Karl Popper who emphasised the role of fundamentals in each physical theory (its nucleus).

Other numerous physicists made an extensive contribution by solving great variety of sophisticated problems, explaining phenomena and experiments, producing various devices drawing on the principles of the basic theories. This great body of knowledge was termed "normal knowledge" and it was praised by the philosopher of science Thomas Kuhn (1962/1970) as comprising the majority of activities in physics at each period of history between scientific revolutions.

There were other contribution too. Those included interpretations which were in odds with the particular nucleus and challenged its claims. For example, some physicists suggested alternative to the commonly adopted Copenhagen interpretation (Schrodinger, de-Broglie, Einstein, Bohm). These contributions essentially motivated the growth of understanding and the progress of the quantum theory. It was the debate of Einstein with Bohr (Bohr, 1949/1959) and the suggested experiment by Einstein-Podolsky-Rosen (1935) which was expected to show incompleteness of the quantum theory. It, however, resulted in the discovery of breaking locality in the micro-world, preserving causality despite instantaneous correlation between entangled particles. Paul Feyerabend (1975) – a philosopher of science – emphasized the key role of such elements of knowledge that went against the norm of the reigning paradigm in order to reach revolutionary change in the adopted scientific knowledge. This claim points to the importance of the periphery of knowledge and praised this type of physics activity.

4. The ways of dissemination of CCK
We have developed two channels to implement the approach of providing cultural content knowledge to the students and teachers at high school level of physics instruction. In the following we briefly describe the approach of historical excurses. Another approach of summative lecture (delayed organiser of knowledge) is described in another publication (Levrini et al. 2014).

Historical excurse is special genre of learning material which recovers the conceptual discourse which produced physics knowledge of a particular concept of physics. Such learning unit recovers in major features the synchronic and diachronic debate that took place in physics in the course of history. We call them excurses in contrast to other close format used by our colleagues who considered historical cases. We have prepared several such excurses (Galili, 2011) and briefly illustrate some of them here.

4.1 Motion
The excurse to the concept of motion included the voices of two basic pre-Newtonian accounts for motion, that by the Hellenic theory of Aristotle and that developed by the Hellenistic and medieval scholars, Hiparchus, Philoponus, Buridan, Oresme, and the scholars of Merton school on Oxford. Their major arguments were depicted in the debate that ultimately brought to the establishment of the Newtonian concept of motion in classical mechanics. The meaning of the new theory was discussed in comparison with other views and the approaches which converged to the Newtonian theory through approach made by Galileo and Descartes. The revived discourse placed to the fore the content of the nucleus of Newtonian revolution: the new understanding of motion as a natural state of natural objects as opposed to the previous understanding as a process objects go through from one state to another. The major change in the nucleus of the new theory of motion was, thus, the replacement of the rest-motion opposition with the rest-uniform motion equivalence (relativity principle of Galileo) (Fig. 6).

The approach of this excurse ascribed a special importance to the First Newton's Law as the most fundamental principle of classical mechanics. This is in contrast to the teaching which does not reserve to it more importance that being only a special case of the second law. It is the latter that is usually in the focus of teaching mechanics at schools. The excurse mentioned how inaccurate translations of the law from Latin
to English performed after Newton caused the impoverishing the deep meaning Newton put to that law\(^2\) (Galili & Tseitlin, 2003).

Figure 6. Symbolic representation of the Newtonian revolution with regard to the concept of motion.

The relevance of the historical development of understanding of motion was argued by certain similarity of the historical conceptions to frequently shown students' conceptions (e.g. McCloskey, 1983a,b; Halloun & Hesteness, 1985).

4.2 Weight
We have dedicated a special excursus to the historical discourse regarding the concept of weight. As a matter of fact, this concept, which is a subject of learning through all levels of physics curricula, is taught differently by different teachers in different countries. In the US the textbooks split between the two options. One defines weight as the gravitational force (e.g. Sears & Zemansky, 1982; Young & Friedman, 2012) and the other defines weight as the force causing weighing results (e.g. Hewitt, 2006; Knight, 2013). This dichotomy in weight definition implies different accounts and explanations of physical situations such as weightlessness and so on. The excursus depicted the major steps in the unfolding of conceptual discourse through the history of weight concept (Galili, 2001). In a simplified way this long history could be represented in the diagram of Figure 7.

The two ways to teach weight split the community of physics educators, and textbook authors in each camp continue teaching in the way considered by them to be the correct one ignoring the other view. This is an interesting feature of this situation that no textbook presents both options and compare them. In a sense, this is a "disciplinary" approach to teaching which contrasts with the "cultural" one. The excursus to weight conceptual history tries to bring a discourse to the fore regardless the decision taken. We believe that awareness of the historical discourse, the arguments launched by physicists and philosophers of science together with researches in physics education might change the situation to better for the students who widely hold numerous misconceptions regarding weight and weightlessness. Several studies in physics education reported about these problems of students (Galili & Kaplan, 1996; Galili & Lehavi, 2003; Stein & Galili, 2014).

\(^2\) The latest translation of Principia by B.C. Cohen and A. Whitman published in 1999 corrected the translation but, of course, could not correct the impact of the previous publications (Newton, 1999).
4.3 Optical Image

Another excursion addressed the optical image concept. It depicted the major steps of the history of this concept and included several accounts for this phenomenon as were adopted in the course of physics progress. In a regular course, optical image is elaborated within the ray theory of light (geometrical optics). Many studies report about numerous alternative conceptions shown by students with respect to vision, image creation, transfer and observation of images (e.g. Guesne, 1985; Galili & Hazan, 2000a,b). It appears that the history of physics knows practically all of the ideas that contemporary students show as misconceptions and which are debated among scholars at different times and living in different countries. The misconceptions: holistic image transfer to the observer (Atomists in Hellenic Science), Active vision by flux and vision rays (Pythagoreans in Hellenic science, Euclid and Ptolemy in Hellenistic science, Al-Kindi – in Arabic science), the image due to mapping of each point of the object to the point of its image by a single light ray (Alhazen in Arabic Science) (Fig. 8). This discourse spread over the time of more than 2000 years and ultimately produced the account as suggested by Kepler in the 17th century and learned at our schools (Lindberg, 1976). The validity of this parallelism, whether or not one adopts the idea of historical recapitulation, is provided by the constructivist account of learning and the inferences regarding the type of teaching required in order to overcome the misconceptions. Drawing on cognitive resonance between the mental models held by the students and the historical conceptions the historical discourse exposed the argumentation of each of the accounts, not only the correct one. This is considered to be the appropriate way towards establishing by students' cultural content knowledge – CCK – with regard to optical image.

Addressing optical image allows frequent involvement of artistic images from history of art and science in the presentation – a feature that possesses additional appealing power for those many our students who are sensitive to visual presentation of scientific statements and especially by means of the artistic images (Galili, 2013).
Figure 8. Schematic representation of the major accounts for optical image concept as appeared in the course of history of science.

5. Discussion and concluding remarks

We may now summarise our perspective on physics knowledge as a subject of learning. Cultural knowledge framework provides a big picture of physics required by those who want to get its holistic view and to perceive its ideology. The big structure of physics as comprised of a few fundamental theories provides meaning to the scientific knowledge as a cluster of a few different rational accounts for reality arranged in several coherent conceptual systems. Actually, it is this feature that provides an individual with a chance to make sense of myriads of knowledge elements (facts, models, problems, conceptions…). Lacking the big picture often frustrates especially young novices who do not see an end to the new knowledge elements which they continuously try to assimilate, to cover more and more. Dealing solely with modelling – an extremely important tool of physics – they indeed might get an impression of endless work: the more we learn the more we know and the more we can proceed with modelling new situations. It is thus important to point to a different perspective by which physicists do cover the whole body of physics, not in details, but in essence. They know the limits of validity of several fundamental physics theories and know their periphery – the difference between their paradigms and something about the open problems. Even if it might be possible (as physicists believe) to reduce all knowledge to one theory of everything, people will not abandon mechanics, thermodynamics, electrodynamics, quantum theory as separate theories with rather clear areas of applicability. Facing a problem a physicist first of all identifies the theory appropriate to apply and starts to "dig" for the solution by creating and applying appropriate model. So, modelling and models are incorporated in the structure of a fundamental theory as its important content (Fig. 9).

Figure 9. Models may appear in all areas of knowledge structure of the theory. This scheme shows theory-model relationship in terms of culture-discipline structure.
The common reservation against the inclusion of periphery to the scope of physics teaching is that such introduction would bring unnecessary complexity, causing much confusion to students whose knowledge is fragile and immature. Besides the role of periphery as making physics contents interesting, dynamic and adequately representing the real physics (which "should be made simple but not too simple" – Einstein) and besides the claim of relevance of wrong (in contemporary perspective) historical ideas as causing cognitive resonance in the learner who possesses similar to the historical conception (Monk & Osborne, 1997, Galili & Hazan, 2000b), it is important to mention the substantial claim made by educational psychologists (Marton et al, 2004) who insisted on the necessity of creating a space of learning which should include the concept to be learned together with its conceptual variation. Meaningful learning, within this perspective, presents a process of discerning the goal concept while contrasting it against its alternatives. This way, through continuous comparison, our cognition works. Thus, the periphery plays, it emphasises the essence of the concept to be learned. In a way, it spotlights the "critical details" (Viennot, 2003) of the considered physical concept.

Finally, regarding the role of history and philosophy of science (HPS), we mention that CCK clarifies the rationale of using such knowledge in creating the relevant periphery and required space of learning. One thus arrives to a special perspective within which two types of HPS materials may be distinguished. One type includes elements which are correct (verified with type) knowledge. They may include, for example, Archimedes' laws of levers and buoyancy, Eratosthenes' measuring of Earth's radius, and Levenhook's invention of microscope. Using these elements together with stories and anecdotes of social and behaviouristic nature are known as interesting and amusing. At the same time, one cannot ascribe to them being essential for the learners of physics.

There are, however, elements of other nature too. They represent the incorrect knowledge of physics, alternative theoretical views and concepts. They might contribute to the periphery of the knowledge we try to mediate to the students. Such are the Aristotelian conceptions of motion or vision, medieval concept of impetus, caloric theory of heat and others. They present building blocks in the process of educational reconstruction of the considered subject matter (Duit et al., 2005). In the construction of our excurses these are relevant and essential. Their inclusion would be considered as an important innovation of physics curriculum.

We may conclude with stating that our belief is that cultural representation of physics knowledge reveals to the learners its conceptual meaning better than disciplinary one and as such, it is required especially for the prospective teachers and researchers. This change may lead to strengthening as aspect of teaching rather than instruction and of training – rather than learning, an important reward in humanistic perspective. Acquaintance of the learners with the relevant scientific discourse performs their enculturation to the culture of physics replacing the low efficient indoctrination of the formal knowledge. This aspect seems to us of central importance. The famous semiotician Umberto Eco once wrote that "The beauty of the universe is manifested not only in the unity of varieties but also in the variety in the unity". CCK approach applies this perspective to the physics knowledge aiming to replace the enormous pressure of understanding exerted on the modern learner of physics with much more preferable pleasure of understanding.

References


Affiliation and address information
Igal Galili
The Amos de Shalit Science Teaching Centre
Faculty of Mathematics and Natural Sciences
The Hebrew University of Jerusalem
Givat Ram Campus
91904 Jerusalem, Israel
e-mail: igal.galili@mail.huji.ac.il
How Can the Learning of Physics Support the Construction of Students’ Personal Identities?

Olivia Levrini
Department of Physics and Astronomy, Alma Mater Studiorum – University of Bologna, Italy

Abstract
In public perception, the humanities (history, philosophy, art, and literature) still have a privileged role as subjects that can encourage students to develop their personal orientations and aesthetics. In contrast, physics and mathematics are school subjects that have been shown to put off many young people because of the strong image of authority they still maintain in which there is no place for arguments and personal views. In this paper, the following questions are considered: How can the learning of physics content support students in constructing their personal identities? Conversely, How does the search for a personal self-narrative influence students’ approaches to learning disciplinary content? The extended body of work I describe in this paper is based on a design experience on the topic of thermodynamics in a secondary school physics class (grade 12). This case is notable for investigating the previous questions since the students in this class came to appropriate, or make their own, the discourse of thermodynamics. That is, their conceptual understanding and disciplinary engagement were accomplished by a reflexive process of populating scientific discourse with personal intentions, purposes and tastes. With respect to this case, I will discuss possible connections between the specific model of educational reconstruction we used to design the teaching materials and the type of productive learning that sits at the nexus of disciplinary engagement and identity and that we have come to refer to as “appropriation.”

Keywords
Identity, Model of Education Reconstruction, Appropriation, Thermodynamics.

1. Introduction: Identity in STEM education
In this paper I will discuss a problematic issue that the study of science at school should, in my opinion, deal with: how can the teaching of sciences result in making learning a transformative personal experience that actually impacts the construction of individuals’ personal identities? Usually it is the humanities (history, philosophy, art, and literature) that have the privileged role as pre-university subjects to encourage students to develop their identities, personal orientations and aesthetics. But, what about physics? Can learning physics support students in the construction of their personal identities? If so, how? The word identity will be used here in the sense that Sfard and Prusak and the sociologist Giddens (1991) give to the term: identities as stories, as opposed to something given and that can be expressed through stories; identities as narratives of the self which are constantly created and re-created in dialogical interactions between people (Sfard & Prusak 2009).

Students’ identity has been widely investigated within STEM education, (e.g., Gee, 2001; Sfard & Prusak, 2005) and, in particular, there is significant interest in how students’ identities affect learning (e.g. Sfard & Prusak, 2005; Nasir & Hand, 2008; Cobb, Gresalfi & Hodge, 2009). However, the inverse question of how learning disciplinary content affects the formation of students’ identities is still little explored. It is this direction – from the learning of a scientific discipline to the construction of identity – that attracted our attention.

In order to provide a contribution towards answering the top level questions mentioned at the beginning, the paper will refer to an extended design experience on the topic of thermodynamics in a secondary school physics class (grade 12), where students came to use the words of physics for developing their own identity, i.e., their narratives of self. The design, implementation and analysis of the experience was a real collaborative effort and involved the teacher, Paola Fantini, and other scholars in math and physics education, Mariana Levin, Barbara Pecori, Giulia Tasquier. For all of us what came out in the class was somehow a surprise, a phenomenon that we did not foresee in advance and it required a long process of
analysis to be interpreted. In order to present what happened, I need to describe briefly the research framework and the context of the experience.

This paper is articulated in three parts: a) the background on the study, including the research framework, the teaching materials on thermodynamics, and the class context; b) the description of what happened in the class and in what sense we can say that physics had an impact on the development of students’ identities, and c) a first-level interpretation aimed at understanding why that happened.

2. Background on the study: the research framework, the teaching materials and the context of implementation

This study has a long story. It started in late ’90’s when the research group in Physics Education in Bologna, led by Nella Grimellini Tomasini, and several other Italian research groups devoted their research attention to the design of teaching materials relevant from a cultural point of view (e.g., Busini & Tarsitani 1996; Grimellini Tomasini, 2004; Levrini, Bertozzi, Gagliardi, Grimellini-Tomasini, Pecori, Tasquier & Galli, 2014a). To anticipate the end of the story, years of collaboration with teachers and plenty of classroom implementations led us to observe that something very special regularly happened in the classes. A “special atmosphere” was perceivable. Thus, in the last ten years, our research work of instructional design was progressively enriched by methodological concerns regarding the issue of how to capture what we perceive “in the air” and to explain it theoretically.

As I already mentioned, the story of the instructional design started in late ’90. Early milestones were the Model of Educational Reconstruction (MER) that we encountered in the 1996 NARST conference, and an UNESCO report about “The reasons of students’ disaffection toward Science & Technology” that Sjøberg presented in the 2001 ESERA conference.

MER became a pillar of our theoretical framework mainly for the image of physics that it gave back within Science Education. Also in this research domain, the necessity of problematizing the stereotyped image of physics as an unquestionable monolithic body of knowledge was stressed. MER, on the contrary, stressed to what extent science and physics, like every cultural product, were “plastic” and mouldable according to many different aims, among which are educational ones (Kattmann, Duit, Gropengießer & Komorék, 1996).

For us, the idea of educational reconstruction attained a special meaning after the presentation of the UNESCO report by Sjøberg in Tessaloniki, where he said: “A key aspect in the lives of young is the search for meaning and relevance. They like areas where their voice is taken seriously, where their views count. Science and mathematics have an image of authority, at least as school subjects. Answers are either right or wrong. There is no place for arguments and personal views. […] The lack of personal meaning and the image of eternal truth and correct answers put off more young people today than before.” (Sjøberg, 2001)

Sjøberg, in stressing the problem of the relevance, was, in our opinion, shifting the main problem for Physics Education from making physics easier and easier to widening and enriching the perspectives. In the light of these milestones, the construction of the materials was oriented toward reaching the goal of making physics simple enough to be intelligible but not so simple to loose its relevance. In the wake of Levy-Leblond, trivialization became the killer of the sense, the “New Medusa” to be avoided as much as possible: “More then the complexity of the original concepts of science, it is, on the contrary, their trivialization […] that, as soon as the concepts reach non-specialized public, exerts a real spell that petrifies them” (Levy-Leblond, 2006).

In order to design new materials able to avoid concepts’ petrification, we searched for forms of productive complexity to be elevated to the rank of design principles, namely principles that could orient us in producing materials enable to encourage secondary students both to attach a cultural value to physics and to find their “place for arguments and personal views” (Sjøberg). The forms of productive complexity that became the design principles in our MER are what we called multi-perspectiveness, multi-dimensionality and longitudinality. These principles were applied to design materials for teaching relativity, quantum physics (Levrini & Fantini, 2013) and thermodynamics (Levrini, Fantini, Tasquier, Pecori & Levin, 2014b).

In the case of thermodynamics, which is the focus of this paper, multi-perspectiveness means that the same content is analyzed from two different perspectives: macroscopic and microscopic. The expected impact of multi-perspectiveness was to enable students to address the documented learning difficulties related to the confusion between macroscopic and microscopic aspects (e.g. Kautz et al., 2005) and, more in general, to improve their conceptual understanding by guiding them to try out the same concepts across multiple

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1 The terms culture and cultural are used by us with a similar meaning to which Igal Galili gives to them and that he describes in his contribution to this volume and that is illustrated in Levrini et al, 2014a.
contexts and definitions (Levrini & diSessa, 2008).

In our materials and during their implementation in class, the macroscopic and microscopic approaches were analyzed and compared also for their philosophical-epistemological peculiarities. This is what is meant by the principle of multi-dimensionality. Operationally, multidimensionality was introduced through specific activities: i) individual analysis of epistemological texts where different authors (Einstein, Poincaré and Drago) discuss their own criteria for distinguishing and comparing the two approaches, and ii) collective discussions where students were encouraged to confront their analyses in order to build a shared classroom epistemological vocabulary. The choice of multi-dimensionality was mainly motivated by the intention of making the learning environment inclusive and “psychologically safe” (Nasir, Rosebery, Warren & Lee, 2006). As Nasir and colleagues argue, inclusiveness is fostered when the epistemological structure of the discipline is made visible and challenge the authoritative and exclusive image of science in which a unique point of view is legitimate (and possible).

Finally, longitudinality means that thermodynamics was not simply introduced as a separate chapter of physics, but as a lens for looking “back” toward theories already studied by the students (optics, mechanics, relativity) and looking “forward” toward new theories (quantum physics). Operationally, longitudinally was implemented by focusing on modeling and by progressively guiding the students to look back toward mechanics and become acquainted with the analogical meaning of physical models of objects (like point-mass or ideal fluid) when they are “borrowed” from mechanics and used in contexts like thermodynamics.

In the case of the study reported in this paper, the materials on thermodynamics were implemented in a class of 20 students (17 year olds) of a scientifically-oriented secondary school in Rimini, Italy. The implementation took about 25 school-periods and the teacher, Paola Fantini, was involved also in the design and, then, in the analysis of the data.

It was in this context that during the implementation of the thermodynamics path something that positively surprised us happened. Students not only showed to be able to cope with the documented difficulties in understanding the basic concepts of thermodynamics and felt the learning environment “psychologically safe,” as we hoped. They also, instead of that “schoolish” language that students usually use by borrowing expressions from the teacher or the textbooks, appeared to make sense of the material in personal ways and used, in their speech, idiosyncratic words and utterances. It was for interpreting such a phenomenon that we designed and realised the study presented in the next section.

3. What happened in the class

To interpret the phenomenon that we perceive in the classroom, we searched for an inspirational word and, at a suggestion of Paolo Guidoni, we focused on the term appropriation. Appropriation is not far from Vygotsky’s internalization, but, at least in Italian, it is a common word used in teaching and, because of that, it sounds semantically richer than the “technical” internalization. In particular, appropriation was chosen for the following meanings that can be attached to it: i) appropriation indicates a process broader than learning and involves cognition, affect, emotion and social behaviour, ii) to appropriate means “to make something mine” and, hence, it includes the idea that the accountability of the appropriation process is situated with the students, iii) appropriation has the same etymological meaning of authenticity. Autos in ancient Greek and proper in Latin have the same meaning: “of one’s own”.

Within the literature, the description of appropriation that we prefer comes from Bakhtin, who wrote: “It [a word] becomes ‘one’s own’ only when the speaker populates it with his own intentions, his own accent, when he appropriates the word, adapting it to his own semantic and expressive intention. Prior to this moment of appropriation, the word […] exists in other people’s mouths, in other people’s contexts, serving other people’s intentions: it is from there that one must take the word, and make it one’s own.” (Bakhtin, 1981, pp.293-4)

That is a very evocative description but we needed something different for interpreting our phenomenon: a more operational construct that could help us understand if students’ discourse revealed whether they did appropriate thermodynamics words. Thus, we worked on our data to bootstrap our definition from them. In a recent paper the whole process of data analysis is described in detail (Levrini et al, 2014b). Here I simply report the main results so as to argue why we can infer that the learning of physics can become a vehicle of identity construction.

The study was realized on the transcripts of eight individual semi-structured interviews that were conducted at the end of the period of data collection. Five interviews were used as core data corpus from which we built our first draft definition. The other three interviews, the most complicated and subtle ones, were used both as contrastive cases (they appeared cases of non-appropriation) and cases to check if our definition was an
effective operational tool to acknowledge appropriation (its application led as to discover that only one case out of the three was a real case of non-appropriation). The overall analysis resulted in the identification of five discursive markers for deciding whether students made progress in learning not only the disciplinary content of the teaching/learning path, but also in making the material relevant in a personal sense. In particular, the analysis led us to argue that appropriation can be operationally recognized when students’ discourse about a scientific term/utterance is:

A. developed around a set of words or expressions repeated several times and linked together so as to express an personal, authentic, idiosyncratic “signature” idea with respect to physics (thermodynamics, in this case);
B. disciplinarity-grounded i.e. the signature idea was used by the student as a tool for selecting pieces of disciplinary knowledge;
C. thick i.e. the signature idea involved a metacognitive dimension (what learning physics meant for the student) and an epistemological one (what image of physics made sense to the student);
D. non-incidental, i.e. the signature idea was expressed in several activities throughout the students’ classroom experience, not just in one interaction;
E. carrier of social relationships, i.e. the signature idea positioned the student within the class community (the “engineer”, the “philosopher”, the “mediator”…)

To exemplify the markers I will consider the case of Matteo. His interview developed around the philosophical words “being” and “becoming” that he repeated several times. From this evidence we could recognized, as idiosyncratic “signature” idea, the philosophical distinction between “being” and “becoming”. The signature idea is grounded in the discipline in the sense that, in the case of Matteo, it helped him to make sense of thermodynamics concepts themselves. Indeed, when he was interviewed about the concept of temperature, Matteo focused his attention on the distinction between delta T (temperature gradient) and T (temperature), because he saw, in this distinction, the philosophical difference between becoming (change) and being (a state). In particular, in the law of calorirometry (Q=mcΔT), Matteo saw an expression of becoming: “there is a change [because of ΔT] that means everything is not stable and everything is not being, there is something that changes.” In the Ideal Gas Law (PV=nRT) he instead saw an expression of being: “[There is] absolute temperature T, that doesn’t change. There is not A [difference in temperature], there is not the change…. ” Already in the other classroom activities, Matteo showed a strong interest in philosophy and his learning of physics was strongly inflected by his orientation to philosophy. In this sense the signature idea was non-incidental and expression of an epistemological positioning within physics (thick) and a personal positioning – “the philosopher” – within the class (carrier of social relationship).

Matteo, like the other students who appropriate the words and utterances of thermodynamics, didn’t repeat the definition of temperature provided by the teacher or textbook. Instead, he gave back what was meaningful in his personal sense. Specifically, he focused his attention on pieces of knowledge related to temperature and reassembled them according to their idiosyncratic “signature” idea. In the words of Bakhtin, Matteo, in selecting and reassembling pieces of knowledge, populated a disciplinarily grounded, i.e. the signature idea was used by the student as a tool for selecting pieces of disciplinary knowledge;

disciplinary knowledge;

in this case) ;

express an

development around a set of words or expressions repeated several times and linked together so as to express an personal, authentic, idiosyncratic “signature” idea with respect to physics (thermodynamics, in this case);

B. disciplinarity-grounded i.e. the signature idea was used by the student as a tool for selecting pieces of disciplinary knowledge;

C. thick i.e. the signature idea involved a metacognitive dimension (what learning physics meant for the student) and an epistemological one (what image of physics made sense to the student);

D. non-incidental, i.e. the signature idea was expressed in several activities throughout the students’ classroom experience, not just in one interaction;

E. carrier of social relationships, i.e. the signature idea positioned the student within the class community (the “engineer”, the “philosopher”, the “mediator”…)
we selected two contrasting lessons – one in which the teacher characterized the dynamic more in terms of “pulling the rope” (Lesson A) and one in which the lesson was more emblematic of what she meant by “letting it go” (Lesson B). The two lessons occurred at the end of the teaching/learning path, after approximately 20 hours of instruction on thermodynamics.

Lesson A was a *synthetic collective discussion* about the major aspects of the macroscopic approach to the second law of thermodynamics. The lesson included topics that were very close to the disciplinary content the students had been explicitly studying. In this lesson, the teacher directed questions at single students who were responsible to provide answers. An example of a question in Lesson A was “Matteo, how are ideal engines connected with Kelvin’s statement? What is the formal expression of the efficiency for an ideal engine?”

Lesson B was an *open and reflective discussion* on points related to epistemological texts (authored by Einstein and others) on methodological distinctions between macroscopic and microscopic approaches to building theories (e.g., Einstein’s distinction between “constructive” theories and “theories of principles”). This lesson was a specific moment where the design principles became explicit and oriented the classroom activities. Here, indeed, *multi-dimensionality* (an epistemological reflection) was applied to analyse multiple perspectives with a *longitudinal* glance. The discussion was articulated in three different moments, corresponding to three collective tasks introduced by the teacher through specific questions:

1) Requirement of verbalizing one’s own view about possible criteria for distinguishing and comparing the macroscopic and microscopic perspectives. This requirement was formalized by the following question that opened the discussion: *We arrived at the end of our path of Thermodynamics and you have reflected about these macro and micro approaches. So, now we are asking you (all) to express your own point of view, in a calm way, calm but express it. What difference do you see, now, between the two approaches?*

2) Requirement of interpreting other (authoritative) positions about the difference between the two approaches and searching for inner and longitudinal consistency. The teacher asked: *Why did Einstein include Special Relativity among the theories of principles and classical mechanics among the constructive theories? Are your criteria for distinguishing between theories of principles and constructive theories consistent with such a claim of Einstein?*

3) Requirement of positioning with respect to other possible views expressed by the classmates. This requirement was formalized by the teacher through this question: *What perspective do you prefer? Which one is, in your opinion, more effective to reach the core of a phenomenon? We had the impression that, in the class, there are different positions on this issue.*

In order to investigate how pulling the rope and letting it go appeared in terms of data, “bird’s eye maps” of the lessons were created by recording who was speaking and for how long (in 2 second increments). In figure 1 and 2, segments of the two lessons are reported.

![Figure 1. A segment of the interactional pattern in lesson A.](image-url)
The maps point out some structural elements that characterize the different interaction patterns: the role of teacher in driving the lesson (very evident in lesson A); the moments of silence (absent in lesson A and more and more present in lesson B); the length of continuous bars of the students (very short in lesson A and longer in lesson B); the student-student interaction (absent in lesson A and present in lesson B).

In order to analyse if and how “pulling the rope and letting it go” fostered appropriation, we focused our attention on three focal students who were in different places with respect to the process of appropriation. The detailed analysis is reported in other works (Fantini 2014; Fantini, Levin, Levrini & Tasquier, pre-print).

Here, I will focus on Matteo so as to illustrate the following results we achieved.

a) “Pulling the rope”, when analyzed at the level of the individual focal students, emerged as an articulated form of revoicing (O’Connor & Michaels, 1992) that the teacher enacted in order to: i) encourage a better positioning of the single student with respect to physics by fixing inaccurate points, ii) reinforce a disciplinary concept so as to enable reasoning to proceed, iii) emotionally support the student, iv) give the student credibility in front of the class.

In table 1, the teacher’s interaction with Matteo in Lesson A (Fig. 1) is reported and teacher’s revoicing is commented. For Matteo, the action of revoicing was particularly relevant since, in class discussions, he frequently tried to evade the more technical and formal aspects of physics and, for this reason, he was not considered a disciplinary reference in the eyes of his classmates. Despite this, and because of his ability to master philosophical arguments, he had a recognized intellectual position in the classroom community but, for the teacher, Matteo was a student who constantly needed to be kept close to the discipline.

<table>
<thead>
<tr>
<th>Turn</th>
<th>Transcript</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Teacher: We have seen that from here [from the second law] come thermal machines and that the efficiency…</td>
<td>The teacher does not need to pose an explicit question. She suspends her voice to check where Matteo is, expecting him to pick up the thread.</td>
</tr>
<tr>
<td>2</td>
<td>Matteo: The efficiency in a cycle can not be greater than 1, but… However, this is also in an ideal cycle.</td>
<td>Matteo understands and picks up the thread of reasoning.</td>
</tr>
<tr>
<td>3</td>
<td>Teacher: Good. It cannot be… We are considering an ideal cycle, an ideal, reversible cycle as Carnot did. So?</td>
<td>The teacher revoices Matteo’s contribution following confirmation that his reasoning is correct. (“Good. It cannot be…), but it can be more accurate.</td>
</tr>
<tr>
<td>4</td>
<td>Matteo: It must necessarily be smaller than 1.</td>
<td>Matteo understands and immediately fixes the imprecision.</td>
</tr>
<tr>
<td>5</td>
<td>Teacher: Exactly. Smaller than 1, not higher and not even equal.</td>
<td>The teacher’s re-voicing here serves the purpose of underlining and reinforcing the student’s contribution</td>
</tr>
</tbody>
</table>
b) In the context of the discussion of the epistemological questionnaire, “letting the rope go” emerged, at individual level, as an articulated participation framework that encouraged different types of students to take part in the discussion. The first moment – requirement of verbalizing – encouraged mainly the participation of self-confident students, while the second moment was a collective puzzlement and all the students were asked to contribute to a collective brainstorming. Here intuitive, creative or deep thinkers students felt particularly comfortable. The third moment – requirement of positioning with respect to the classmates – invited the students, like Matteo, who like debates and who found confrontation of ideas as a useful way to express his own ideas.

The combination of “pulling the rope” and “letting it go” provided all the conditions that we pointed out as relevant for appropriation, corresponding to our five markers. “Pulling the rope” enabled students to find their positioning with respect to the discipline (Marker B) and to the class (Marker E). “Letting the role go” allowed students to nurture their talent in seeking out and defending a personal point of view, among a range of possibilities (Markers A, C, D).

5. Conclusions
In the paper I went through a long process of research that progressively led us to enrich our focus on instructional design with learning sciences concerns. In particular, through an overview of our research program and results I tried to show in what sense we say that, in properly complex classroom environments, learning of and in a science discipline becomes a way for students to construct their personal narratives and in what sense appropriation stays in the nexus between productive disciplinary engagement and identity construction. As a last remark, probably not all the students had fun in this work. For some of them it was also dramatic, since a strong personal involvement touches deep issues. In any case, I feel comfortable in saying that most of them, if not all, felt they were studying something important and worthwhile: learning physics was, for the class and for the single students, a transformative experience.

Acknowledgement
I wish to thank all the colleagues who have been working on this project since the late ’90s (Nella Grimellini Tomasini, Paola Fantini, Paolo Guidoni, Mariana Levin, Barbara Pecori, Giulia Tasquier) and the other colleagues of the research group of Bologna (Eugenio Bertozzi, Laura Branchetti, Marta Gagliardi). A special thanks to Rosa Maria Sperandeo, Claudio Fazio and to the GIREP President, Marisa Michelini, for inviting me to give a talk at this Conference.
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Affiliation and address information
Olivia Levrini
Department of Physics and Astronomy
Alma Mater Studiorum – University of Bologna
Research-Based Interactive Simulations to Support Quantum Mechanics Learning and Teaching

Antje Kohnle
School of Physics and Astronomy, University of St Andrews, UK

Abstract
Quantum mechanics holds a fascination for many students, but its mathematical complexity can present a major barrier. Traditional approaches to introductory quantum mechanics have been found to decrease student interest. Topics which enthuse students such as quantum information are often only covered in advanced courses. The QuVis Quantum Mechanics Visualization project (www.st-andrews.ac.uk/physics/quvis) aims to overcome these issues through the development and evaluation of interactive simulations with accompanying activities for the learning and teaching of quantum mechanics. Simulations support model-building by reducing complexity, focusing on fundamental ideas and making the invisible visible. They promote engaged exploration, sense-making and linking of multiple representations, and include high levels of interactivity and direct feedback. Some simulations allow students to collect data to see how quantum-mechanical quantities are determined experimentally. Through text explanations, simulations aim to be self-contained instructional tools. Simulations are research-based, and evaluation with students informs all stages of the development process. Simulations and activities are iteratively refined using individual student observation sessions, where students freely explore a simulation and then work on the associated activity, as well as in-class trials using student surveys, pre- and post-tests and student responses to activities. A recent collection of QuVis simulations is embedded in the UK Institute of Physics Quantum Physics website (quantumphysics.iop.org), which consists of freely available resources for an introductory course in quantum mechanics starting from two-level systems. This approach immediately immerses students in quantum phenomena that have no classical analogue, using simpler mathematical tools that allow a greater focus on conceptual understanding. It allows from the start a discussion of interpretative aspects of quantum mechanics and quantum information theory. This article gives an overview of the QuVis resource and describes the development and iterative refinement process based on student feedback.

Keywords
Quantum mechanics, computer simulations, conceptual understanding.

1. Introduction
Quantum mechanics holds a fascination for many students, but learning quantum mechanics is difficult. The counterintuitive behaviour of quantum systems often disagrees with our classical ideas, leading to student difficulties that arise when classical thinking is applied to quantum systems (see e.g. Singh 2001, Cataloglu 2002, Wittmann 2005, Baily 2010 and Zhu 2012). Quantum phenomena typically cannot be observed directly and are far-removed from everyday experience. Complicated mathematics including calculus, complex numbers and differential equations are required to describe even simple phenomena. Linked to this, instruction often focuses on particularly simple abstract and idealized systems that are mathematically tractable but may not help learners make real-world connections to quantum phenomena. Research-based interactive simulations can address these challenges of quantum mechanics instruction and support quantum mechanics learning and teaching. Simulations can help students develop mental models by reducing complexity, focusing on fundamental ideas and making the invisible visible (Adams 2008a, Adams 2008b, McKagan, 2008). Through high levels of interactivity coupled with direct feedback, they can promote engaged exploration, sense-making and linking of multiple representations (Clark 2011). Through careful interaction design and accompanying activities, students can be guided towards the learning goals (Podolefsky 2010). Simulations can visualize complicated time-dependent behaviour such as the motion of wave packets that help build physical intuition but may be too complex for students to calculate themselves (Belloni 2006). Simulations can allow students to collect data to see how quantum-mechanical quantities are
determined experimentally. Simulations can help build physical intuition by allowing students to compare and contrast classical and quantum behaviour under the same experimental conditions (Kohnle 2014). They can challenge students’ classical ideas by allowing them to assess whether they can explain experimental outcomes.

The QuVis Quantum Mechanics Visualization project aims to support the learning and teaching of quantum mechanics through the development and evaluation of interactive simulations with accompanying activities. This article gives an overview of the QuVis simulations and describes the research-based development process that aims to optimize simulations and accompanying activities in terms of clarity, ease-of-use, promoting exploration, sense-making and linking of multiple representations. It gives examples of features of the simulations that are aligned with previous work on developing effective educational simulations. It gives examples illustrating how student feedback from individual student interviews and in-class trials was used to optimize the resources. Finally, it summarizes future plans.

2. Overview of the QuVis interactive simulations

The QuVis Quantum Mechanics Visualization Project (www.st-andrews.ac.uk/physics/quvis) develops interactive simulations for the learning and teaching of quantum mechanics concepts (Kohnle, 2010 and Kohnle, 2012). The QuVis website now includes over 90 research-based interactive simulations. Simulations are research-based, with student feedback informing all stages of the development process. Simulations are freely available for use online or download. Simulations cover a wide range of quantum mechanics topics, ranging from the introductory to the more advanced undergraduate level. Simulations include many topics not covered in other multimedia collections. Some of the QuVis simulations make topics typically covered at the advanced level (entanglement, hidden variables, quantum cryptography) accessible to introductory level students. The majority of simulations include an accompanying activity available for download from the website. Full solutions to these activities are available on the website, but password-protected for instructor access only. Instructors who wish to obtain the password for the solutions are asked to email the author.

The QuVis website groups the simulations into four collections: simulations for physics students, for physical chemistry students studying introductory quantum mechanics, simulations to support a new introductory quantum mechanics curriculum based on two-level systems and a recently-launched collection of HTML5 simulations that run on both desktop computers and tablet-based devices. The previous three collections were coded in Adobe Flash.

The “QuVis simulations for physics” collection includes mostly older simulations developed in 2009 to 2011, with 50 simulations in total available. The majority of simulations are aimed at the intermediate level and focus on wave mechanics and angular momentum. A smaller number of simulations are aimed at the introductory level (e.g. probabilistic analysis of classical systems, the photoelectric effect, the Bohr atom) and the more advanced level (e.g. the density matrix, spin clusters and spin chains).

The “QuVis simulations for physical chemistry” collection includes 18 simulations that are less mathematical compared with the physics collection, and include text explanations tailored to chemistry students. Topics of the simulations link to Atkins’ “Physical Chemistry” textbook, with most simulations developed so far focusing on basic quantum theory. A number of simulations were adapted from the physics collection, others were newly developed specifically for physical chemistry students.

The “New Quantum Curriculum sims” collection consists of 17 simulations with accompanying activities that were developed in 2012 to 2013 as part of the UK Institute of Physics (IOP) Quantum Physics resources (Kohnle 2014). These simulations are available both on the IOP website quantumphysics.iop.org and on the QuVis website. The IOP resources were developed as a national UK project. They include around 80 short articles centred on questions with multiple paths through the material. Articles were authored by researchers in quantum information theory and foundations of quantum mechanics. Problem sets, simulations and activities are embedded into the articles. Resources provide material for a full course in introductory quantum theory focusing on two-level systems. Examples of such systems are a spin ½ particle, a two-level atom with a ground state and a single excited state, and a single photon in an interferometer with two possible paths. Developing quantum theory using two-level systems has a number of advantages (Michelini 2000, Scarani 2010, Beck 2012, Kohnle 2014 and Malgieri 2014). It allows from the start a focus on experiments that have no classical explanation. It allows from the start a focus on interpretive aspects of quantum mechanics and quantum information technology. It is also mathematically less challenging, requiring only basic algebra versus differential equations and calculus for the more traditional wave mechanics approach. The IOP resources are freely available but require registration. The simulations cover the topics of linear
algebra, fundamental quantum mechanics concepts, single photon interference, the Bloch sphere representation, entanglement, local hidden variables and quantum information.

The recently launched collection of HTML5 simulations includes a revised layout optimized for both desktop computer and touchscreen use. Controls are more widely spaced, and the active area around each control has been increased for ease-of-use on smaller touchscreen devices. Graphics and displayed quantities are mostly positioned at the top of the window and controls mostly at the bottom, in order to reduce hand obscuration of feedback on touchscreens. Simulations in this collection include both recoded simulations from other collections as well as newly developed simulations. Older simulations from the physics collection are being revised in terms of layout and graphics prior to the recoding. For the New Quantum Curriculum simulations, revisions from in-class trials are being incorporated where needed prior to recoding.

3. Overview of the research-based development process

Figure 1 depicts the stages of the QuVis simulation development and refinement process. Ideas for simulations come from lecturing and tutoring experience and the literature on student difficulties in quantum mechanics.

![Figure 1. Overview of the simulation development process.](image)

The development process starts by defining learning goals for a simulation. Learning goals inform the development of the simulation, activity and assessment instruments used to evaluate effectiveness. The learning goals are typically limited to a single concept per simulation (e.g. degeneracy of states or single photon interference). This reduces complexity and allows the simulation to focus on key ideas, reducing cognitive load. It also allows the simulation to lead students towards the learning goals through the interaction design, e.g. the number and types of controls, their ranges and layout. The initial design considers the literature on interaction design (Saffer 2010), research into student difficulties and research into what makes a good visualization (López 2013 and Chen 2014).

After initial drafting, simulations are coded by undergraduate physics students. These students often have suggestions for revisions to layout or content based on aspects they find confusing or non-intuitive. Thus, student input already informs the development phase. During the coding, the layout is iteratively revised based on experience interacting with draft versions.

Once the simulation is fully coded, it is refined using student feedback from the appropriate level, first in individual student observation sessions and then using in-class trials (Kohnle 2013). Figure 2 shows the research methods used in these trials and their primary focus.

In the individual student volunteer sessions, students first interact freely with a simulation until they feel they are finished. The free exploration phase makes it possible to assess the implicit scaffolding, e.g. whether students are guided through the interaction design towards the learning goals. Students are asked to think out loud during this process, and to describe what they are making sense of and what they are finding confusing. After freely exploring the simulation, students work on the accompanying activity. This makes it possible to assess whether questions are unambiguous and whether the simulation and the activity provide sufficient
scaffolding for students to successfully complete the questions. During this process, the only interventions made are to remind students to articulate their thoughts, and to probe further when a student states they are confused and unable to make progress. If this latter situation arises, the student is first asked whether they can find anything in the simulation itself to help them overcome their difficulties. If not, further questions aim to discern how the student could overcome their difficulty, e.g. through an additional control in the simulation, additional information or rephrasing of text. The aim of posing these questions is to find patterns in student difficulties and ways to overcome them.

Directly after working with the simulation, students then complete survey questions on their experience of using the simulation. Survey questions ask about clarity of graphics, displayed quantities, texts and the activity, ease-of-use, perceived usefulness in enhancing understanding and how enjoyable students found working with the simulation. Students are asked to make comments on points found confusing and suggestions for improvement. These observation sessions are typically two hours in duration, with mostly two and sometimes three simulations used.

Figure 2. Overview of research methods used in the development and evaluation process and their primary focus.

The observation sessions are audiorecorded and use screen capture. Observers take notes during the sessions, and write detailed session notes with impressions after the sessions. These individual sessions typically lead to revisions to interface and content, which are incorporated into all simulations wherever relevant. Especially for more substantial revisions, a second round of observation sessions is carried out to assess the impact of revisions. This typically leads to a second round of more minor revisions. Observation sessions are also used to investigate the effect of different visualizations on student understanding, e.g. the visualization of the photon superposition state on student understanding of quantum superposition.

While the observation sessions give in-depth information on students’ interactions and perceptions and make it possible to ask questions to explore possible changes to the simulation and the activity, they are carried out with only a relatively small number of students that have volunteered for this activity. Thus, issues identified may not be representative, and generalization of outcomes raises issues of validity.

Once revisions from observation sessions are incorporated, in-class trials are used to evaluate simulations with a larger number of students. For the in-class trials, a range of methods are used to evaluate the simulations and accompanying activities (see Figure 2), with a subset of these methods used for each of the trials. Directly after working with a simulation, students complete the same survey questions as in the observation sessions on perceived clarity of different elements, ease-of-use, perceived usefulness in improving understanding, points found confusing and suggestions for improvement. For in-class trials that use simulations in computer classroom sessions, students are observed during these sessions. Google Analytics is used to monitor usage of individual controls, e.g. to determine the fraction of students in a class that used a particular control and the average number of times a control was used. Thus, it is possible to assess whether students find and use all the controls and the frequency of control use. Students’ responses to the activity questions are marked as correct or incorrect to assess whether any questions are on average not answered well. Activity questions not answered well point to issues with the simulation and/or the activity. For simulations with in-built challenges, it is possible to assess student success in completing these challenges, which form part of the activity problems. For a subset of simulations, short pre- and post-tests have been developed that students complete prior to and after working with a simulation. These pre- and post-tests assess learning gains through working with a simulation. The pre- and post-tests are mostly in multiple choice format, but also ask students to explain their reasoning and to rate their confidence in their
answer. This makes it possible to verify that students choosing the correct answer have come to their answer using correct reasoning. Finally, a small number of comparative studies have been carried out. These studies have investigated student learning with two groups of students using somewhat different versions of a simulation, compared students’ interactions with a simulation with one group using the simulation to learn a new concept, the other using the simulation to consolidate the concept, and compared use of a simulation with a pencil-and-paper activity. These comparative studies can evaluate the effectiveness of simulations compared with other instructional strategies, and assess the effectiveness of using simulations in different settings or with different visualizations.

Data collected from the evaluation studies include student responses to survey questions, activities, pre-tests and post-tests. Data analysis uses a combination of quantitative and qualitative techniques. Free-text survey responses are grouped according to common themes and patterns in student responses. For the activity, pre-test and post-test responses, student answers are marked as correct or incorrect to assess the fraction of students with correct responses, and incorrect responses are grouped into common ideas. Some of the in-class trials point to further revisions needed, which are typically minor compared with revisions from the observation sessions. All simulations and activities are revised based on evaluation outcomes wherever appropriate.

For the 17 simulations in the “New Quantum curriculum sims” collection, in total 42 hours of observation sessions were carried out with 19 student volunteers, 17 of which were from the introductory level. Much of the content of the simulations was new to these students. In-class trials have so far been carried out with 9 of these simulations, 5 at the introductory level and 4 at the advanced undergraduate level.

4. Aspects of simulations and activities that make them useful for learning

Figure 3 shows student perceptions of the usefulness of QuVis simulations in improving their understanding for an introductory quantum physics course (using 5 simulations in total) and an intermediate-level quantum mechanics course (using 17 simulations in total). This data is from end-of-course surveys conducted at the University of St Andrews in the 2013/14 academic year. Figure 3 shows that students across both levels find the simulations useful for their learning. Our experience is that these positive results are only possible due to our iterative development and refinement process informed by student feedback.

![Figure 3](image)

Figure 3. Student responses to an end-of-course question “How useful for learning quantum physics have you found the simulations used in the course?” for two course at the University of St Andrews in the 2013/14 academic year.

This section describes how aspects of the simulations are aligned with previous work on developing effective educational multimedia resources. Examples are given of student feedback from individual student interviews and in-class trials, and how this feedback was used to optimize the simulations and accompanying activities.

5. Implicit scaffolding using interaction design principles

Simulation controls that are difficult to master or non-intuitive lead to a focus on the control and user frustration instead of a focus on the content (Adams 2008a and Podolefsky 2010). Limiting the number of controls and complexity of simulations and avoiding extraneous material not directly linked to the key learning goals are important to enhance learning (Podolefsky 2010 and Clark 2011). The QuVis simulations are designed according to principles of interaction design and refined using outcomes from our evaluation studies.
These points are illustrated using the *Interferometer experiments with photons, particles and waves* simulation (Figure 4). This simulation aims to help students develop an understanding of single photon interference by allowing students to compare and contrast the behaviour of classical particles, electromagnetic waves and single photons when passing through the same experimental setup. Students can insert a single beamsplitter or build an interferometer, and for waves and photons insert a phase shifter to vary the relative phase between the two arms. The simulation depicts single photons and the photon superposition state in order to help students develop a productive mental model of single photon interference. This simulation was trialed in five individual student observation sessions and used in introductory courses in 2013 and 2014, with somewhat different photon visualizations used in each of the in-class trials.

The QuVis simulations have a similar look-and-feel, so that students recognize the same interactive features and experimental apparatus across simulations. For example, the design of the optical components and detectors in the *Interferometer experiments with photons, particles and waves* simulation is consistent across all single photon simulations. Simulations use interactive controls such as sliders, radio buttons and tick boxes that are familiar to students. The layout is similar across all simulations, with displayed quantities and controls clearly separated from the graphics or experimental apparatus.

**Figure 4.** A screenshot of the *Interferometer experiments with photons, particles and waves* simulation, which allows students to compare and contrast the behaviour of single photons, particles and waves under the same experimental conditions.

The QuVis simulations make use of the fact that in the Western world controls are typically explored from top to bottom and left to right (Saffer 2010). This behaviour is also seen in the observation sessions. Thus, features students should find early on are placed at the top and left. Input states that can be chosen via radio buttons are ordered to progress from simpler to more complex states from top to bottom. In Figure 4, the order of the input controls helps scaffold students’ exploration to first set up experiments with classical particles and electromagnetic waves before exploring the single photon case. Thus, the order of controls helps students to activate prior knowledge before exploring a new situation. Grouping of controls using panels makes use of the fact that adjacent controls are perceived to be related (Saffer 2010).
outcomes to be opposite, and to link the mathematical and graphical representations of the correlation coefficient.

8. Optimizing simulation activities

Strongly guided activities can inhibit students’ exploration and reduce interaction with a simulation in terms of the number of controls used and total exploration time (Adams 2008c). Studies have shown that getting students to freely explore a simulation before working on an activity can encourage exploration and sense-making (Moore 2013).

The QuVis simulation activities aim to scaffold students’ exploration by progressing from simpler to more complex situations. They ask students to compare and contrast classical and quantum behaviour, make sense of their observations, calculate displayed quantities and make connections between multiple representations. Adding questions that explicitly ask students to compare their calculations with their observations in the simulation helps them make connections between mathematical and visual representations (Kohnle 2013).

For the “New Quantum curriculum sims” collection, all activities start with a question asking students to have a play with the simulation for a few minutes, getting to understand the controls and displays, and to note down a few things about the controls and displayed quantities they have found out. Success on the activity as a whole was investigated depending on whether or not students have completed this question. This analysis used student responses to the *Quantum key distribution with entangled spin ½ particles* (quantum cryptography) simulation used in an introductory quantum physics course taken by students in their first or second year at the University of St Andrews. The activity was given as an online homework assignment, and did not form part of the course assessment. There were 79 students in the class, and 65 of them completed the assignment. Students had not encountered quantum cryptography in class, and thus they were learning new material using the simulation.

Student responses to each of the activity questions were marked as correct, partially correct, incorrect or unanswered. The activity consisted of 8 questions in total. The analysis compared the distribution of fully correct responses to questions 2 to 8 (so excluding question 1 asking students to freely explore the simulation and note down things they have found out) for those students that had completed question 1 (N=52) with those that had not answered this question 1 (N=13). Students that had not completed question 1 had completed the other questions, excepting three students who did not complete the final question of the activity. On average, students completing question 1 had 5.2 other questions correct, students not completing question 1 had 4.1 other questions correct. Thus, there is a difference in the mean number of questions answered correctly, with on average greater success on the rest of the activity for those students that had answered question 1. An independent t-test showed that the difference in questions answered correctly is statistically significant between the two groups ($t=2.634$, $df=63$, $p=0.011$, two-tailed). The mean difference of 0.93 is of medium size as measured by Cohen’s $d=0.63$ (the mean difference divided by the average standard deviation).

This result only demonstrates a correlation, not a causal relationship, between answering question 1 and success on the rest of the activity, and this only for a single study. Further studies are planned to assess the impact of asking students to first explore a simulation freely on sense-making and success in achieving the learning goals.

9. Conclusions and Outlook

Research-based interactive simulations can address challenges of quantum mechanics instruction through user agency, implicit scaffolding, feedback on actions allowing trial-and-error exploration and the use of multiple representations. An iterative development process informed by student feedback from individual sessions and in-class trials is key to developing educationally effective resources. Initial evidence from observation sessions and in-class trials shows that QuVis simulations are helping students learn quantum mechanics topics, including topics such as entanglement and hidden variables at the introductory level that are more commonly discussed at the advanced level. Further evaluation studies at multiple institutions are planned to ensure simulations are useful to students from a wide range of backgrounds.

Current work aims to extend the QuVisHTML5 collection, both in terms of redesigning and recoding old simulations, as well as developing new simulations. Future development will include amongst other topics more simulations on quantum information processing and single photon experiments, as well as a larger collection of simulations suitable for the school level. Future work will aim to make simulations more engaging by including game-like elements aligned with learning goals. Future development will also include...
more open and exploratory activities, including intrinsically collaborative activities that require students to bring together their individual contributions.

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References


**Affiliation and address information**

Antje Kohnle
School of Physics and Astronomy
University of St Andrews
North Haugh
St Andrews, KY16 9SS, United Kingdom
email: ak81@st-andrews.ac.uk
Supporting Teachers Use and Assessment of Inquiry Based Science Education in Classroom Practice

Eilish McLoughlin, Odilla Finlayson
Centre for the Advancement of Science and Mathematics Teaching and Learning (CASTeL), Dublin City University, Ireland

Abstract
Inquiry-Based Science Education (IBSE) has been the focus of many national and international programmes and projects in recent years as Inquiry based teaching methods have been suggested as a way to encourage and motivate students in science. The pan-European ESTABLISH [1] (2010-2014) FP7-funded project has developed a framework for teacher education in IBSE that has been adopted across eleven European countries. The national teacher education programmes (TEPs) implemented different models depending on their own educational and cultural contexts but all incorporated the suite of 18 IBSE teaching and learning materials (Units) which had been collated and developed by the consortium partners for this purpose. The implementation of the ESTABLISH TEPs with pre-service and in-service teachers has been shown to have a positive impact on the participating teacher's attitudes and understanding of IBSE, as well as their integration into classroom practice. However, for many students and teachers, assessment drives the activities in a classroom. Moreover, if something is assessed, then it is more highly valued, by teachers and students alike; hence, if the competencies and skills that are developed in IBSE remain un-assessed, then the development of these skills and competencies will always be secondary to recall and routine problem solving. The pan-European FP7-funded project SAILS [2] (2012-2015) was focused on addressing this issue by providing TEPs to support teachers in using IBSE as well as implementing appropriate assessment strategies to assess the skills and competencies that are developed through inquiry. This paper will outline the concept and rationale of these two projects and will highlight the need for supporting teachers not just to use IBSE but also be confident and competent in assessing student learning in the IBSE classroom.

1. Introduction
Education and training have been central to the Lisbon agenda for growth and jobs and again take primary focus supporting the “smart growth” priority of the growth strategy for 2010-2020 [3]. More than ever, Europe’s success in global competition is dependent on effective partnerships between business and academia to ensure that education delivers “high-level and highly valued skills”, as presented in the 2010 EC Working document on the European 2020 Flagship Initiative [4]. In addition, the European Framework for Key Competencies for Lifelong Learning [5] identifies and defines the following eight key competences necessary for personal fulfilment, active citizenship, social inclusion and employability in a knowledge society and recommends that initial education and training should support their development:

• Communication in the mother tongue;
• Communication in foreign languages;
• Mathematical competence and basic competences in science and technology;
• Digital competence;
• Learning to learn;
• Social and civic competences;
• Sense of initiative and entrepreneurship;
• Cultural awareness and expression.
Employers have also stated that they need a workforce fully equipped with skills beyond the basics of reading, writing and arithmetic to grow their businesses, including:

- Critical thinking and problem solving: the ability to make decisions, solve problems and take action as appropriate.
- Effective communication: the ability to synthesize and transmit ideas in both written and oral formats.
- Collaboration: the ability to work effectively with others, including those from diverse groups and with opposing points of view.
- Creativity and innovation: the ability to see what’s not there and make something happen [6]

However, many employers have identified that “high school graduates were ‘deficient’ in problem solving and critical thinking” [7]. In addition to the above, there has been a recent trend across the EU towards competence-based teaching and learning and a learning outcome approach [8], resulting in significant changes occurring at school curricula level in traditional subject areas such as science. These curricula are now being treated in more engaging cross-curricular ways, with greater emphasis being placed on developing skills and positive attitudes towards science alongside knowledge and with increased use of “real-life” applications to provide appealing learning contexts.

2. Inquiry Based Science Education

Crucial to the development of key competencies in young people is their engagement in the education process. Methodologies such as inquiry-based science education (IBSE) have been highlighted as having the potential to increase student engagement in science at primary and second level and provide such development opportunities [9, 10]. Recommendations from these international reports identify the need for “engaging curricula to tackle the issue of out-of-date and irrelevant contexts and to enable teachers to develop their knowledge and pedagogical skills”.

The global network of science academies [11] also supports the reform of science education on a global scale by encouraging hands-on inquiry-based learning (IBSE), especially in primary and secondary schools – where they define IBSE as comprising of “experiences that enable students to develop an understanding about the scientific aspects of the world around through the development and use inquiry skills.” In their 2006 Working Group on the International Collaboration in the Evaluation of IBSE programs report [12] they discuss IBSE in practice and conclude that, while there is no single model of IBSE, there are recognised features of the classroom activities that indicate IBSE is taking place, such as students will be:

- “engaged in observation and, where possible, handling and manipulating real objects;
- pursuing questions which they have identified as their own even if introduced by the teacher;
- taking part in planning investigations with appropriate controls to answer specific questions;
- using and developing skills of gathering data directly by observation or measurement and by using secondary sources;
- using and developing skills of organising and interpreting data, reasoning, proposing explanations, making predictions based on what they think or find out;
- working collaboratively with others, communicating their own ideas and considering others’ ideas;
- expressing themselves using appropriate scientific terms and representations in writing and talk;
- engaging in lively public discussions in defence of their work and explanations;
- applying their learning in real-life contexts;
- reflecting self-critically about the processes and outcomes of their inquiries.”

The European Commission, having identified IBSE as a desirable methodology to implement in classrooms across Europe to engage young people in science and mathematics and develop skills and competencies to cope with the challenges for a changing world, have funded a number of projects in IBSE such as ESTABLISH and SAILS to supports teachers in adopting an IBSE methodology in their classrooms.
3. Supporting teachers in using IBSE

The overall objective of the ESTABLISH project was to facilitate and implement an inquiry-based approach to science education for second level students (age 12-18 years). To do this the ESTABLISH project was focused on creating authentic learning environments for science education by bringing together and involving all the key communities in second level science education, including science teachers and educators, the scientific and industrial communities, the young people and their parents, the policy makers responsible for science curriculum and assessment and the science education research community. This collaboration has informed the development of educational programmes for both in-service and pre-service teachers (ESTABLISH Teacher Education Programmes) as well as the project’s IBSE teaching and learning materials (ESTABLISH Units). To achieve the project’s aims ESTABLISH adopted the definition of inquiry as the “intentional process of diagnosing problems, critiquing experiments, and distinguishing alternative, planning investigations, research conjectures, searching for information, constructing models, debating with peers, and forming coherent arguments” [13]. The ESTABLISH consortium members collaborated with local actors to develop and pilot IBSE teaching and learning materials and developed 18 substantial IBSE teaching and learning units that encompass an extensive range of science activities that have been proven to be suitable for using in inquiry teaching and learning across the participating eleven countries (Ireland, Germany, Sweden, Cyprus, Czech Republic, Poland, Slovakia, Malta, Netherlands, Estonia and Italy). A list of the topics and disciplines of these 18 units is given in Table 1.

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<th>Physics</th>
<th>Chemistry</th>
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<td>Sound</td>
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<td>Light</td>
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Over 1300 in-service teachers from across the eleven participating countries participated in ESTABLISH TEPs with a further ~ 650 pre-service teachers involved in workshops as part of their initial teacher education. An important outcome of the project has been the development of a framework for IBSE Teacher Education Programmes (TEPs) which provides a flexible and comparable description of TEPs which cater for in-service and pre-service teacher education delivered by face-to-face and online strategies across a variety of cultural, educational and disciplinary contexts. Key results from the project show that following the TEPs, the in-service teachers have increased their understanding of inquiry and their understanding of the roles of teacher and student in an inquiry classroom, with the biggest increase by those who classify themselves as beginners in IBSE.

4. Supporting teachers in assessing IBSE

The SAILS - Strategies for Assessment of Inquiry-based Learning in Science - project (2012-2015) was funded by EU 7th Framework Programme to support teachers in adopting inquiry-based science education (IBSE) at the secondary level. The SAILS project has three main objectives: (1) to enhance existing IBSE teaching and learning materials by incorporating inquiry assessment strategies and frameworks; (2) to partner with teachers to identify and implement assessment strategies and frameworks to evaluate key IBSE skills and competences in the classroom; and (3) to provide teacher education programmes in IBSE and promote a self-sustaining model to encourage teachers to share experiences and practice of inquiry approaches to teaching, learning and assessment - by supporting a community of practice. The project consortium consists of fourteen partner organisations, including universities, small companies and a multi-national organisation, from across twelve European countries (Belgium, Denmark, Germany, Greece, Hungary, Ireland, Poland, Portugal, Slovakia, Sweden, Turkey and the United Kingdom).
The SAILS project also adopted the approach that inquiry was defined as the “intentional process of diagnosing problems, critiquing experiments, and distinguishing alternatives, planning investigations, researching conjectures, searching for information, constructing models, debating with peers, and forming coherent arguments” [13]. Thus it requires more of the learner than simply commanding and recalling scientific knowledge. The main focus of the SAILS project was to equip teachers across Europe with assessment strategies to evaluate a number of key IBSE skills and competencies developed in the classroom, when an IBSE methodology is adopted.

SAILS adopted the approach of extending existing IBSE curricula and Teacher Education (TE) programmes, to motivate and support IBSE practitioners in the classroom, and in addition, to develop a systematic approach to the assessment of IBSE skills, as depicted in the SAILS model in Figure 1.

![Figure 1. The role of curriculum, teacher education and assessment in the improved model of IBSE advocated by SAILS.](image)

A key aspect of the SAILS project involved the selection of appropriate teaching and learning materials that were good examples of inquiry. These materials were then critiqued to identify the main inquiry skill(s) that could be developed through these activities. It is clear that development of inquiry skills is a process that occurs over time and so it was necessary to develop materials to encompass a range of inquiry skills. Additionally, opportunities for collaborative group work and classroom dialogue were identified. These materials were further developed to present models and materials for the assessment of the inquiry skills. Three different areas for assessment were identified, namely assessment of conceptual knowledge; assessment of reasoning processes and assessment of inquiry skills. Informed by expertise within the group, and literature, opportunities for assessment were identified in the activities; however, it was clear that teachers could not trial all aspects of these suggestions. Draft Units were prepared that presented the inquiry approach and offered a selection of opportunities for assessment of the inquiry skills, along with criteria proposed for that assessment. Pilot teachers whom were experienced in IBSE were selected in each country to trial these draft units in their classrooms. The teachers recorded their experiences in the form of Case Studies which outlined the practice of the assessment, the criteria used in the assessment and their planned follow up as a consequence of that assessment. The evaluation of the draft units and case studies was based on trialling inquiry and assessment materials in at least three different countries. The final stage of the project involved collating and presenting the final inquiry and assessment materials developed in 20 Sails Units, as listed in Table 2. This overall approach adopted by project has also led to the development of the SAILS Framework for Assessment of Inquiry Skills, which is a very useful resource for both teachers and teacher educators.
In parallel to this process, the SAILS partners have developed national Teacher Education Programmes (TEPs), with both in-service and pre-service teachers, that offers education in IBSE methodologies and the assessment of IBSE practices. These programmes have been developed over a three stage design and implementation process so that the final TEPs that have been implemented in each country, in accordance with the SAILS Framework for TEPs, integrate the assessment of IBSE within teacher education in inquiry methodologies. The final impact of the SAILS TEPs on teachers will be collated at reported at the end of the project and made available through the project website.

5. Conclusions

To tackle this global challenge of encouraging and supporting teachers to implement an inquiry approach in the classroom requires a wholesome approach to teacher education that also addresses teachers confident and competent in assessing inquiry skills and competencies. The collaborative efforts of the ESTABLISH project have led to the development of appropriate TEPs in IBSE, for both in-service and pre-service teachers, that include context-rich learning environments for IBSE. The outcomes of the SAILS project is to further the impact of the ESTABLISH and other such IBSE projects, by extending the resources of these projects to include appropriate assessment strategies for IBSE. The core objective in the development of these materials is to prepare appropriate materials for use in TEPs with in-service and pre-service teachers. A key outcome of the SAILS project is the development of effective models for the implementation of TEPs for inquiry with integrated assessment which have been informed by trialling with several teacher cohort groups in each country. Further details on both of the impact and resources that are freely available from these two EU funded projects can be found on the ESTABLISH [1] and SAILS [2] project websites.

The continuous and collaborative engagement of researchers, educators and teachers in these two projects over a five year period, has resulted in increased national and international discussion on the importance of assessment of inquiry practice. However, further research needs to be carried out to carefully examine how best to support all science teachers in implementing IBSE and assessment of IBSE skills and competencies effectively in their classrooms.

Acknowledgements

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Table 2. List of SAILS IBSE and Assessment Units

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<td>Electricity</td>
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References

Affiliation and address information
Eilish McLoughlin
Centre for the Advancement of Science and Mathematics Teaching and Learning (CASTeL), Dublin City University, Ireland
Email: eilish.mcloughlin@dcu.ie
Potentially Meaningful Teaching Units (PMTUS) in Physics Education

Marco Antonio Moreira  
_instituto de Física, Federal University of Rio Grande do Sul (UFRGS), Brazil._

Abstract  
The construction of a didactic sequence is proposed here based on learning theories, specially the meaningful learning one. Assuming that there is no teaching without learning, and that teaching is a means while learning is the goal, a sequence is proposed as a Potentially Meaningful Teaching Unit (PMTU). Steps for its construction are suggested, and examples are given.

Keywords: meaningful learning; potentially meaningful teaching units; physics education.

1. Introduction: The classical model of teaching and learning  
Teachers in school, it does not matter whether at elementary, high school or college level, present students knowledge they are supposed to master. Students copy such knowledge chunks as a kind of information to be learnt by heart, reproduced in evaluative situations, and quickly forgotten afterwards. This represents the classic model of teaching and learning, which is grounded in the teacher’s narrative and in the student’s rote learning. Learning theories suggest different approaches, as well as research findings of basic research on teaching. However, neither the theories nor these findings reach the classrooms. It is not the case here to blame educational psychologists, educators, researchers, teachers, and students, however, it is a fact that the narrative model is accepted by everybody – students, teachers, parents, and society in general – as “the model” for teaching and that rote learning is “the learning model”. Actually, as far as practice goes, it is an enormous loss of time.

2. A different model  
This paper intends to contribute to change, at least partially, this situation by proposing the construction of Potentially Meaningful Teaching Units, which constitute theoretically based teaching and learning sequences aiming at meaningful learning – not rote/mechanical learning – and favoring applied research on teaching, that one directed to real classroom practices. Because meanings are in the persons (e.g., scientists, teachers, students) not in the things (e.g., instructional materials). For instance, there are no meaningful books or meaningful classes. But they might be potentially meaningful provided that they are logically well organized and that the learners have adequate previous knowledge.

3. To grasp the meanings  
In a teaching and learning situation students must grasp the meanings accepted in the context of the subject matter. In a physics class, for example, the teacher presents meanings accepted in physics for concepts, propositions, procedures, and the student must grasp those meanings.

3.1 The grasping of meanings: a model  
D.B. Gowin (1981) proposes a model for teaching episodes that seems to fit quite well what has been presented in the last paragraph. His model, from a meaningful learning perspective, can be represented as suggested in Figure 1. In this model, the teacher, who already masters those meanings that are accepted in the context of the subject matter, introduces these meanings to the students with potentially meaningful curriculum materials. This presentation, however, does not imply that the teacher narrates such contents. Quite the contrary, it implies that he/she brings about these meanings to the students by using various strategies so that students are led to perceive their relevance and eventually they come to display an intentionality to grasp and internalize the grasped meanings.
Student’s intentionality
The student, in turn, should get back to the teacher the meanings he/she is grasping in reference to the knowledge conveyed by the educative materials of the curriculum. This type of student’s attitude depends on his/her predisposition, on his/her intentionality to learn. In turn, this will depend on the students’ perception of the relevance of the new knowledge, and on making sense of the learning tasks.
The aim of such interaction that involves teacher, student, and educative curriculum materials is the sharing of meanings. Until this goal is not achieved, until the student does not grasp the meanings as they are accepted in the context of the subject matter, and until he/she does not share them with the teacher, we cannot say that teaching has occurred. Teaching happens when students grasp meanings.

Figure 1. A schematic representation for the grasping of meanings in a teaching episode (adapted from Gowin, 1981)

4. Teaching episode
A teaching episode takes place when the student grasps the meanings the teacher intends him/her to grasp, which are those the community of users has already accepted for the specific context of a given teaching subject matter (Gowin, 1981). If there is no grasp of meanings, there is no teaching.

5. Student-centered teaching
Student-centered teaching is the one in which the teacher works as a mediator, and it is characterized by students who express themselves a lot while the teacher speaks just when needed. Letting students talk implies the use of strategies that favor interaction, discussion, negotiation of meanings among themselves, oral presentation of the product of their collaborative activities to the whole classroom, openness to criticism, and expression of their thoughts and suggestions concerning their peers’ activities.
The student has to be active, instead of passive. He/she should learn how to interpret and to negotiate meanings. He/she must learn to be critical as well as to take critical responses to his/her work. Receiving a-critically the telling of the “good teacher” does not lead to critical meaningful learning, or to relevant learning; it does not guide students to learning how to learn.

6. Collaborative activities
Student-centered teaching implies not only a dialogic relationship, socially interactionist, between student and teacher, but also a student-to-student interaction. Teaching, then, has to be organized in such a way as to provide situations that students in small groups can solve collaboratively. It might be a project, a classic problem (exemplar), an open-ended problem, a concept map on a given topic, a Vee diagram on a research article, a lab practice, a critical analysis of a literary text, a dramatization. There are many possibilities, but it is important that in these activities the students cooperate, disagree, discuss, and look for a consensus.
The outcome of these collaborative activities should be presented to the whole classroom. In that occasion, members of the small groups submit their work to the criticisms of the other groups. This seems absolutely necessary. Criticism and argumentation are important. Self-awareness is important as well. What generally
results from this is that the group that has presented its work usually modifies its presentation. However, we have to consider that this kind of activity does not integrate the script of what means being a student, which has been developed by the students along many years of schooling. At start, students might show some resistance to small group collaborative activities, so that we should be patient and introduce them little by little.

7. Dialogue
When those meanings the students have externalized are not the ones the teacher intended them to grasp, which are those accepted in the context of the subject matter, the teacher should present them once more in a different way, so that students come to externalize them again. Dialogue, social interaction, and negotiation and sharing of meanings must be favored. In any educative event there should be some form of dialogue. Teachers cannot stay on and on speaking to themselves, or telling, while the student just listens and takes notes, or daydreams, or even takes a nap.

8. Social interaction & language
Well-known authors, such as Lev Vygotsky (1988) and Paulo Freire (1987, 1996) have emphasized the need for social interaction. The role of language here is crucial for this dialogue to happen. Neil Postman (1969), for example, points out that language is implied in any of our attempts to perceive reality (p. 99).

9. The role of the teacher
The learning situations proposed to the students should be developed and solved in a collaborative mode, and they have to be relevant, as well as to make sense for these students. It is precisely here that the role of the teacher is essential: it is the teacher that has to carefully select these situations. Furthermore, the teacher is the important mediator of the intense social interaction that results from these activities in a real classroom and/or in a virtual learning environment. A student-centered teaching does not mean that the role of the teacher is understated. When the teacher does not play the role of narrator anymore, it does not indicate that there has been any decrease whatsoever in his/her relevance. On the contrary, as a mediator and organizer of learning situations that are student-centered, he/she becomes far more important than as a mere narrator.

10. The behaviorist evaluation.
Even when teachers and methodologies are constructivist, evaluation procedures, in general, end up having a behaviorist bias: students, parents, principals, lawyers want teachers to have objective written records – proofs – that show whether the student “knows” or “does not know” a given content or topic. As a matter of fact, that is just assessment, measurement, not evaluation. Evaluation is more than just measuring how many “right answers” the student is able to give.

11. Constructing potentially meaningful teaching units - pmtus

11.1 Goal
Such a constructing process aims at developing potentially meaningful teaching units to facilitate the occurrence of meaningful learning of specific declarative and/or procedural knowledge topics.

11.2 Philosophy
Teaching can only happens when learning occurs, and learning has to be meaningful; teaching is the means and meaningful learning is the end to be reached; teaching materials that aim at this type of learning have to be potentially meaningful.

11.3 Theoretical framework

11.4 Principles
• Prior knowledge is the variable that most influences meaningful learning (Ausubel).
• Thoughts, feelings, and actions are integrated in the learner, and this integration is positive and constructive, when learning is meaningful (Novak).

• It is the learner’s responsibility to decide to meaningfully learn a given knowledge chunk (Ausubel; Gowin).

• Advance organizers display/show relatedness between new knowledge and prior knowledge (Ausubel; Moreira).

• Problem-situations add meaning to new knowledge (Vergnaud) and they should be developed to arise in the students the intentionality to learn meaningfully.

• Problem-situations can work as advance organizers.

• Problem-situations should be proposed in increasing complexity levels (Vergnaud).

• When facing a new/novel situation, the first step to solve it is to construct in the working memory a functional mental model that is structurally analogous to the given situation (Johnson-Laird).

• Progressive differentiation, integrative reconciliation, and consolidation should be considered when organizing teaching (Ausubel).

• Meaningful learning evaluation should happen as a search for evidences.

• Meaningful learning is progressive.

• The teacher’s role is to provide carefully selected problem-situations, to organize his/her teaching, and to mediate the students’ grasping of meanings (Vergnaud; Gowin).

• Language and social interaction are crucial to the grasping of meanings (Vygotsky; Gowin).

• A teaching event involves a triadic relation (Figure 2) among student, teacher, and teaching/educative materials aiming at leading the student to grasp and share meanings that are accepted in the context of a given teaching subject knowledge area (Gowin).

• This relation can also be quadratic when the computer is used as a learning mediator, and not just as an educational material (Figure 3).

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**Figure 2.** Gowin’s triadic model (Moreira, 1993): Gowin sees a triadic relationship among Teacher, Educatve Materials, and Student. To him, a teaching learning situation is characterized by a “negotiation of meanings” between student and teacher regarding pieces of knowledge conveyed by educative materials.
Learning should be meaningful as well as critical, and not mechanical, rote (Moreira).

Critical meaningful learning is favored by the search for answers (questioning), through the use of a diversity of materials and teaching strategies, and by disclaiming the narrative model in favor of a student-centered teaching, instead of focusing on the memorization of already known answers (Moreira).

11.5 Sequential aspects

Steps 1 and 2 of a PMTU

1. Define the topic to be approached by identifying the declarative and procedural aspects as accepted in the context of the teaching subject in which this topic is inserted.

2. Propose situation(s) – discussion, questionnaire, concept map, problem-situation(s) – that lead the student to externalize his/her prior knowledge, independently of being, or not, accepted within the context of the teaching subject, but that might be relevant to the meaningful learning of the topic (goal/objective) on the agenda that is being undertaken.

Step 3

3. Propose introductory level problem-situations that consider the student’s prior knowledge so as to prepare him/her to the introduction of the knowledge items (declarative or procedural) to be taught; these problem-situations might involve, from the very beginning, the topic on the agenda though not with the goal of starting to teach it; such problem-situations should serve as advance organizers; these situations add meaning to the new knowledge, but, in order to achieve this, the student should perceive them as problems and should be able to mentally model them.

Mental models are functional to the learner and result from his/her perception and prior knowledge (invariant operators); these initial problem-situations can be proposed through computational simulations, demonstrations, videos, life problems, representations brought about by the media, classical problems from the subject matter, but they always have to be in the format of an accessible problem generating mode, that is, never just as an exercise of a routine application of an algorithm.

Step 4

4. Once initial situations have been carried out, introduce what is to be learned, taking into consideration the features of progressive differentiation, that is, starting from the most general and inclusive aspects to provide an introductory view of the whole, which means presenting an overview of the most important features of the teaching unit, but immediately followed by examples and by approaching quite specific aspects; teaching strategy might be, for instance, a short lecture followed by a small group collaborative activity, which, in turn, can be followed by a presentation or discussion activity by the large group;
Step 5

5. Next, the most general and structuring aspects (that is, what is intended to be taught) of the teaching unit content should be resumed with a new presentation (it can be another short oral lecture, a text, or the use of a computational resource), though, in a higher complexity level in relation to the first presentation; problem-situations should be proposed in an increasing level of complexity; new examples should be given, emphasizing differences and similarities in relation to situations and examples already presented, that is, promoting integrative reconciliation.

After this second presentation, a collaborative activity aiming at the students’ social interaction, negotiation of meanings, with the teacher as mediator, should be proposed; such an activity might be problem solving, construction of a concept map or a V diagram, a lab experiment, a small project, however, it has to involve negotiation of meanings and teacher mediation;

Step 6

6. To conclude the unit, the process of progressive differentiation should be continued, summing up the most relevant features of the given content, though under an integrative perspective, that is, aiming at integrative reconciliation; this should be carried out through a new presentation of meanings in a brief oral lecture, the reading of a text, the use of a computational resource or an audio-visual program.

What matters here is not the strategy itself, but the way to handle the unit content; after this third presentation, new problem-situations should be solved at a higher complexity level than the previous ones; these situations should be solved in collaborative activities that afterwards will be presented and/or discussed in the large group with the mediation of the teacher;

Step 7

7. Learning evaluation according to PMTUs should occur along their implementation, recording everything that might be considered as evidence of the occurrence of meaningful learning of the content handled in class; furthermore, there should be a an individual summative evaluation after the sixth step, in which situations implying understanding, grasping of meanings, and, ideally, a transferring skill should be proposed;

Such situations should be previously validated by teachers/professors with expertise in the given teaching subject; performance evaluation of the PMTUs student should be equally based both on the formative evaluation (situations, task collaboratively solved, teachers’ records) and on the summative one;

Step 8

8. A PMTU will only be considered successful when the students’ performance evaluation can provide evidences of meaningful learning (grasping of meanings, understanding, explaining skills, competence in applying his/her knowledge to solve problem-situations). Meaningful learning is progressive and mastery of a conceptual field is also progressive, thus, the emphasis must be on evidences, and not on final behaviors.

11.6 Transversal aspects

Throughout the steps, teaching materials and strategies have to be diversified, questioning has to be privileged in relation to ready-made answers, and dialogue together with critique should be favored.

As a learning task, in activities developed along the PMTUs, students might be asked to propose their own problem-situations in relation to a given topic.

Although the PMTU should emphasize collaborative activities, it can also include instances of individual activities.

11.7 Diagrams

In order to approach in a diverse way the structure of a PMTU and to exemplify diagrams, which can be useful in the proposed collaborative activities, two different types of diagrams are presented here.

V diagram

Figure 4 shows a V diagram (Gowin, 1981) to streamline the construction process of a Potentially Meaningful Teaching Unit.

Concept map

Figure 5 presents a concept map to represent in another way the construction of a Potentially Meaningful Teaching Unit.

Examples

PMTUs are being used to teach different topics in physics. Two examples are provided in Appendices 1 and...
2, but they are being used in other fields such as immunology, in biology; equilibrium, in chemistry; equations of differences, in mathematics; …

12. Findings
The purpose of this presentation is not to report research findings, though PMTUs have been already used in some research studies, in Brazil, specially in Professional Master’s Degrees in Physics Teaching. In all cases, evidences of meaningful learning were found. However, the most important finding was motivation. Students were highly motivated with the methodology and with topics like particle physics and quantum mechanics.

Figure 4. A V diagram for constructing a PMTU.
Figure 5. A concept map for the construction of a PMTU.
EXAMPLE 1

PROPOSAL OF A PMTU FOR TEACHING THE STANDARD MODEL OF PARTICLE PHYSICS

M.A. Moreira

Objective: to teach the Standard Model of Elementary Particles in High School

Sequence

1. Initial situation: to build with the students a concept map about the subject matter; firstly, ask students what constitutes this subject matter while writing on the chalkboard what they are saying; next, mark the words students point out as those they believe to be the most relevant ones, then, place them in a hierarchic diagram (concept map); finally, ask each student to explain, in writing, with their own words, the map that was constructed in group; this individual explanation should be handed to the teacher at the end of this initial activity, which happens in the first class/meeting of this PMTU.

2. Initial problem situations: Examples a) If the nucleus of the atom is made of positively charged particles (protons), why doesn’t it explode?; b) If negative and positive electric charges are attracted to one another, why aren’t the electrons absorbed by the nucleus?; c) If electrons and protons have mass, what is the role of gravitational interaction in the atom stability?; d) What is the role of neurons in the structure of the atom? e) Would it make any sense to think that basic atomic particles (electrons, protons, and neutrons) could be made of other even more elementary particles? These situations proposed here, which are based on the type of knowledge students have explicit in the prior class, should be discussed in the large group with teacher mediation and not necessarily should come as answers to the proposed problems.

As a next action, individual copies of the article Partículas e interações (Moreira, M.A., 2004, Física na Escola, v.5, n.2, pp.10-14), should be distributed among the students who should be given some time to read it and, after reading it, gather together in small groups (two to four participants) to build a table that should be analogous to Table 1, in the article, though simplified. After finishing this task, groups exchange their tables and each group corrects, comments and suggests changes in the other group’s table. When each group gets back its table, it can modify it and hand the teacher this final version. This step of the PMTU will take two to three classes/meetings.

Revision/review

3. Revision/review: The class can start with a review/revision that can be a mini lecture/class on what has already been handled up to that point about the constitution of what the subject matter comprises, so as to open up room for the students’ questions. Next, a 20 to 30 minute video on Elementary Particles (e.g., v. BBC. The. Big. Bang. Machine. MVGroup) is presented. After the video presentation, the following articles are distributed among the students Um mapa conceitual para partículas elementares (Moreira, M.A., 1989, Revista Brasileira de Ensino de Física, v.11, pp.114-129) and Um mapa conceitual para interações fundamentais (Moreira, M.A., 1990, Enseñanza de las Ciencias, v.8, n.2, pp.133-139).

Another concept map

Students are, then, asked to read them and, in small groups, they draw a concept map of elementary particles and fundamental interactions, that is, a map that integrates, in a simplified way, the two maps presented in the articles. At least some of these concept maps are to be presented to the large group (in Power Point, on the chalk board, posters, or banners of paper and markers). Each group maps should be handed in to the teacher who will revise them and give them back to the students the next class, and the students, as they wish, can modify them so as to come up with their final version of their map. This activity will take two or three classes.

New problem-situation at a higher complexity level

4. New problem-situation at a higher complexity level: To construct a V diagram of the Standard Model; to present a brief initial lecture with examples about what a V diagram is and on what constitutes its proposal,

* Professor of Physics in the College Courses of Physics and of Modern and Contemporary Physics in the Professional Master’s Degree Program in the Teaching of Physics at the Physics Institute, Federal University of Rio Grande do Sul (UFRGS), Brazil.
that is, what its role is; emphasize its epistemological nature; next, to distribute among students copies of the
article “Um Vê epistemológico para a Física de Partículas (An epistemological V for Particle Physics)”

A V Diagram

Ask students to construct, in small groups, a V diagram to the Standard Model, with the following basic
question “How does the Standard Model of Elementary Particles show that Physics is a human construct
and that all scientific knowledge is constructed? “. Some of these diagrams should be presented to the large
groups for discussion, and all of them should be handed in to the teacher for a qualitative analysis; as a
result of this evaluation, the students can, is they want, reconstruct these diagrams. This activity will take
two or three classes.

Individual summative evaluation

5. Individual Summative Evaluation: This activity will take one class and will have already been proposed to
the students, thus, it will not come to them as a surprise; it proposes open questions in which the students
can freely express their own understanding of the Standard Model; ask questions, propose a schematic
representation or diagram that can show evidences of meaningful learning; any evaluation instrument based
on “right or wrong” answers should be avoided.

Final integrative dialogic lecture class

6. Final Integrative Dialogic Lecture Class: At this point, it is time to retake the total content of the PMTUs,
review the maps and the V diagram based on the articles studies in previous classes; it should be called
attention to the descriptive and explanatory potential of the Standard Model in its relation to the constitution
of matter; difficulties that were overcome by this theory, confirmed previsions, as well as still existing
difficulties that can lead to changes or to its disclaim in favor of other better explaining one.

7. Learning evaluation in the PMTU: It should be based on what the students have produced, on classroom
observations, and on the individual summative evaluation, whose weight/value should not be more than 50%.

8. Evaluation of the PMTU itself: It should be happen in relation to the obtained learning results; then, some
activities should be reformulated, if necessary.

9. Total number of class hours: 9 to 12.
EXAMPLE 2

PROPOSAL OF A PMTU FOR TEACHING TOPICS OF QUANTUM MECHANICS AT HIGH SCHOOL

Adriane Griebeler

Objective: to facilitate the grasping of meanings of basic concepts in Quantum Mechanics in High School — quantization, uncertainty, quantum object, state, state superposition.

Sequence

1. Initial situation: students are motivated to develop a mind map for Quantum Physics (QP). In this map, they are free to establish associations among their knowledge chunks, representations, and cognitive actions based on a key word or on a central image. So, students feel at ease to establish relations between QP and other areas of Physics or/and their daily life and/or their social representations. Maps should be handed in to the teacher. In order to think about the given topic, students receive the lyrics and listen to the song Quanta, by Gilberto Gil. This activity will take one class.
   a) Where is QP applied? What does QP study?
   b) How does QP differ from the other areas of Physics (Mechanics, Thermodynamics, Electromagnetism, etc.)?
   c) What is a quantum of matter? And a quantum of energy?
   d) What is your opinion about the following adds/headlines/titles (Magazine cut-outs or sites that talk about “Quantum therapies” brought by the teacher)?
   e) Have you ever had any type of contact with the type of therapy that some people call “quantum”?

   These questions/situations should be discussed in the large group with the teacher as mediator, aiming at listening to the stands of the whole group and at stimulating/favoring interest on this subject, with no need to get to a final answer.

   Next, an individual copy of the text Física Quântica para Todos (partially adapted from Nunes, A. L., 2007, Física Quântica para Todos, XVII SNEF.), available in the teaching support materials organized by the teacher. Students are given some time to read it, then they gather together in small groups to discuss it, and, afterwards, they can either sum it up, or create a diagram, or a drawing collaboratively. Products of this activity are handed to the teacher that will evaluate them qualitatively and will hand them back to allow students to redo their work considering the feedback comments they have received. This stage will take three classes.

Growing/Deepening/Strengthening knowledge

2. Growing/Deepening/Strengthening knowledge: Concepts of quantization, quantum object, uncertainty, state, and superposition of states are handled here. These contents are presented in texts and slides, as large group discussions are favored. At the end of the introduction of these new contents, the cut-outs and adds are presented again to question students on the validity of what such material proposes, as well as their views on up to what extent these appropriations are legitimized by Physics. This stage takes three classes.

New situation

3. New Situation: These concepts are presented again in a video, “Mecânica Quântica” (Quantum Mechanics) produced by Discovery and accessed at <http://www.youtube.com/watch?v=pCgR6kns5Mc>. Next, students, in small groups, are asked to construct a concept map for Quantum Mechanics. Beforehand, there is a brief introductory lecture on how to build a concept map followed by some examples of it. Then, maps are constructed and exchanged among the groups to have them compared and to get peer suggestions. Some of them are presented to the large group. All maps are handed in to the teacher for evaluation.
will be qualitatively evaluated and, then, returned to the students that might reformulate them and hand them back to the teacher. This activity takes three classes.

Comparing maps

4. Comparing maps: In the following class, there will be an activity involving the mind maps developed in the first class and the concept maps drawn the class before. A qualitative comparison between these two types of maps aiming at looking for aspects comprising alternative conceptions (misconceptions), or social representations, about Quantum Physics, which might have been presented in the mind maps of the first class and which might be absent in the concept maps. Such an aspect will be used to approach the subject again and to explain to the students that Quantum Physics cannot be used as a scientific foundation for topics those advertisements presented.

Progressively differentiating

5. Progressively differentiating: New problem-situations will be presented in relation to the concepts of quantization, quantum object, uncertainty, state, and superposition of states, mostly as images such as, for instance, the one of the Schrödinger Cat, which is available at http://averomundo-jcm.blogspot.com/2009/10/gatos-e-virus.html, and the development of a classroom newspaper will start with small articles, comic strips, and/or images on the studies topics. The teacher will mediate this newspaper development that, when finished, will be exhibited in school and available to the whole school community for reading. This activity will take three classes.

Individual evaluation

6. Individual evaluation: Individual evaluation will comprise open questions involving the key-concepts of the given unit. This activity will take one class.

Final class and evaluation of the PMTU in the classroom

7. Final class and evaluation of the PMTU in the classroom: This activity involves the analysis of the answers to the proposed questions of the individual evaluation. It will also include final integrating comments on the approached content. There is also an oral evaluation by the students about the teaching strategies that have been used and about their own learning. This activity will take one class. Students’ comments will be recorded, if they comply with it.

Evaluation of the PMTU by the teacher

8. Evaluation of the PMTU by the teacher: Aiming at this, there will be a qualitative analysis by the teacher of the evidences he/she has, or not, perceived that might point out to the meaningful learning of the unit key concepts, both in the individual evaluation as in the participant observation, as well as in the classroom evaluation of the PMTU by the students in their last meeting.

9. Total number of class-hours of the PMTU: 16

References


**Affiliation and address information**

Marco Antonio Moreira  
Instituto de Fisica, UFRGS, Brasil  
Caixa Postal 15051  
91501-970 Porto Alegre, RS, Brasil  
http://moreira.if.ufrgs.br  
moreira@if.ufrgs.br
Thinking the Content for Physics Education Research and Practice

Laurence Viennot
PRES Sorbonne Paris Cité, Université Paris Diderot, LDAR

Abstract
Content analysis, it is unanimously agreed, is a fundamental component of physics education research. In this address I will discuss, on the basis of several examples, how various research standpoints resulted in different ways of reexamining - "reconstructing"; or "spotlighting" - the content for teaching: student-led, teacher-led, responsive, proactive. In so doing, I will reconsider, in particular, the merits of "simplification". I will plead for a way of spotlighting the content for teaching that leaves room for the search for consistency and conceptual links, making these explicit, while respecting a constraint of accessibility. The examples of colour phenomena and the transfer of light will serve to illustrate this objective. The final discussion will bear on how students' intellectual satisfaction might thus be increased, and constitute a powerful incitement for them to engage with physics.

Keywords
Physics Education Research, Content analysis, Concept-Driven Interactive Pathway

1. Introduction
Everyone agrees that content analysis is a constitutive component of physics education research (PER). Since this research domain was first studied, in the seventies, a thorough examination of the content has been considered the first essential step of any investigation, in contrast with more general approaches to “science education”. However, some collective works or meetings were launched in the nineties (Fensham et al. 1994, Bernardini et al. 1995) with the declared goal of stressing the crucial importance of reflecting upon the content that is to be taught, and conveyed an implicit criticism of contemporary research, seen as too generalist. Since then, several research programs, such as “Didactical structures” (Lijnse 1995, 2002), analyses of “Learning demand” (Leach & Scott 2002, 2003), or discussions on “Learning progressions” (Duschl et al. 2011), have converged in underlining that content analysis is central and, to a great extent, problematic, in physics education research. The influential movement of “Educational reconstruction” (Kattman et al. 1995, Kattman & Duit 1998) has strongly reinforced the idea that research in education for a scientific domain has to involve, as a basis, a “dialogue” between content analysis and a knowledge of students’ common ideas. When it comes to discussing the appropriate conditions for teacher training, the strand of “Pedagogical Content Knowledge” makes ample room for the idea that the content should not be analyzed and discussed independently from the other components of the teachers’ competence.

An idea serving as a (nearly) common denominator, in this respect, is that content should be known by researchers in PER, analyzed, elementarized, simplified, and reconstructed for teaching. In most of the diagrams proposed to schematize appropriate interactions in this process, a dialogue is suggested (double arrows) between “subject matter analysis” and “students’ pre-scientific conceptions” – as in the case of “Educational reconstruction” (ibid.) - or equivalent wording is used. Although they are crucial factors, the roles of the teachers’ level of acceptance of a reconstructed content and of their transforming trends (Pinto 2005) will not be broached in this paper. However, it seems clear – a minima - that, in the process of content reconstruction, formal accessibility is a constraint to be respected, in view not only of students but also of the teachers.

This paper addresses the following question, here limited to the domain of physics: to what extent and how was the content actually revisited in the frame of more or less recent investigations in physics education research? Far from being a complete account of all that has been produced in recent years, the objective of this paper is rather to sketch possible modalities for basing a content analysis on research in physics education. After an attempt to characterize a few of these modalities, an example of a “content driven interactive pathway” - about the absorption of light - will be presented to illustrate how a particular content can be revisited and “spotlighted” for teaching. With this last example, the process exemplified will borrow from several of the types previously characterized. All of these examples are intended to nourish a final
discussion about the stakes of revisiting the content for teaching, keeping in mind the general injunction to simplify while not losing sight of other essential aspects.

In this discussion, a pivotal idea will be that physics is a widely coherent set of theories, aiming at providing a unified and predictive description of the material world.

2. Responding to students’ ideas: a mirroring effect (model 1a)

A first observation is that, in many of the suggestions for teaching made in the wake of research investigations, there was no particular stress or injunction to reconsider the content in a significant way. There was great progress, in such works, because they localized students’ misunderstandings, ascribed mainly to “naïve ideas”, “previous ideas”, “alternative conceptions”, “pre-scientific conceptions”, etc., and ensured that these were given full attention, in particular via targeted questions. Such were the perspectives in Predict/Observe/Explain (White & Gunstone 1992) or Elicit, Confront, Resolve (Mc Dermott 1996). More recently, many strategies based on “cognitive conflicts” and/or “active learning” did not have a content mapping that was clearly distinct from the usual one, although some epistemic aspects were given a new emphasis (see the “epistemic axis” in Meheut & Psillos 2004). Thus, the status of models Vs the “material world” was one of the targets that several sequences about particle models had in common (Meheut & Chomat 1990, Vollebreght 1998), or problem-posing approaches (Lijnse 2002, Gil-Perez 2003) were intended notably to transform the teaching of some topics. But the conceptual structure of the content was not always substantially transformed, far from it.

In order to explain such stability, when observed, a model of the (non)transformation of the content analysis might be proposed (model 1a). It is intended to describe a stabilizing process, outlined in Figure 1. In this model, students’ common ideas are central, as is widely recommended. Once identified, they generate some responses from the designers of research-based teaching learning sequences. But, before that step, it is worth noting that the “common ideas”, to put it briefly, have been most often identified by contrast, and in one-on-one correspondence, with various items of the currently taught content. Let us call these items “references” for the observed common ideas. These references are extracted from the most common mapping of the content. Once the knowledge of common ideas has given birth to some targeted changes for teaching, there is a high probability that the “remedies” will be re-injected in the taught content more or less at the same place as the reference items, and be inserted in the initial global structure. This might explain why the content analyses underlying the design of some research based teaching sequences mirror the most current one.

![Figure 1. Responding to students’ ideas: new taught content closely mirrors initial content. Black circles symbolize changes informed by knowledge of the students’ ideas (grey circles).](image)

For instance, in the first steps of a research investigation about electric circuits, the everyday meanings of current and the students’ sequential reasoning were consensually identified as obstacles to a proper understanding of the content. In terms of content analysis, the suggestions for teaching made at that time were to emphasize such and such aspects, in particular via targeted questions or analogies, rather than to restructure the domain.
According to McDermott (1998, see also Shaffer & McDermott 1992), the recommended guiding process towards a comprehension of electric circuits involves a series of experiments from which students “draw inferences” concerning current and resistances. Students are said to “develop operational definitions through which they quantify the concepts of current, potential, potential difference and resistance”. Even if, via the finite lifetime of the battery, the idea is stressed that what is “used up” is energy and not current, the content analysis underlying this project remains very classical. Its essential novelty resides in the instructional strategy, which is already a very important and valuable first step.

By contrast, in some cases, the recommended conceptual goals may be seen as engaging the content more deeply. In a review about the Learning and understanding of key concepts in electricity, Duit and von Rhöneck (1998) recapitulate the state of affairs in this domain in 1998. Besides the recommended instructional strategies, often based on eliciting students’ ideas and more or less continuous views on conceptual change, they report briefly on various aspects of the “Student oriented structure of science content”. According to this review, two key concerns were: the differentiation between current flow and energy flow and the differentiation between intensity and tension. These aspects cannot really be presented as new, in terms of content analysis, as compared to the current courses in this domain. They were just presented as crucial aspects deserving emphasis. The third “key concern” mentioned in this review, i.e. a systemic view and the simultaneity of changes in a circuit, already pointed out by Härtel (1985, see also Closset 1983, Shipstone 1984), deserves a more nuanced comment, as it may be argued that this was really a novel idea, due to its transferrable aspect (Viennot 2001). This “key concern” announces the more radical type of change described below.

In passing, this first example – electric circuits – shows that the categorization put forward in this paper cannot be clear cut. Rather, it defines some extreme cases of how conceptual goals are redefined for teaching.

### 3. Responding to students’ ideas: a modified content

A few examples – particularly about elementary optical imaging and friction - introduce the following idea: some “responsive” aspects of teaching may, de facto, change the conceptual target itself. What might be seen merely as a “method,” intended to remedy students’ difficulties, in fact goes into the content deeply.

#### 3.1 Optical imaging

Among the best known “common ideas” considered as obstacles in the teaching-learning of physics, are those accounted for with the model of “the travelling image” syndrome. The word “conception” seems appropriate here, to designate commonly observed question-and-answer pairs which are consistent with a view of optical imaging as the reception of an image (or something) travelling as a whole. In the eighties and nineties, several investigations (for instance Goldberg & McDermott 1987, Galili 1996) bore on situations like “a mask on a lens” and the frequent student prediction that it would make “a hole in the image”. Moreover, some criticisms were very soon formulated (Beaty 1987) concerning the possible role of the diagram currently used to find the position and size of an image formed by a thin lens (Figure 2).

![Figure 2. A classic diagram concerning optical imagery with a thin convex lens](image)

The horizontal structure of this diagram and the restricted number of rays represented (rails for the images?) were seen as possible reinforcements for inappropriate views.

In this context, a different type of diagram was proposed and its impact was evaluated (Viennot & Kaminski 2006, see Figure 3).
A student’s comment was particularly striking: “what was really new and decisive for me was the undeviated rays that pass by the lens”. This statement retains attention because, at first sight, these rays around the lens seem totally useless and therefore irrelevant to this topic. However, they attest to a crucial fact: the lens interacts with only a part of the incoming flux, and transforms it geometrically. This diagram with “useless rays” points to the very nature of the process of imaging. Once this is understood, a part of the lens can still be seen as a lens, which intercepts a part of a part of the incoming energy. Ultimately, what is at stake is a first access to the status of an extensive quantity –energy- vis-à-vis this topic of imaging. De facto, the targeted content has changed.

3.2 Solid friction
Nearly as well-known as the preceding example, students’ difficulties with solid friction are often interlaced with their common views about the third law. As a result, a diagram like the one in Figure 4a is often observed for a driver pushing his car toward a garage. When presented with a possible conceptual aid, i.e., fragmented diagrams (Figure 4b, Viennot 2003, 2004a), some students in the first year at university willingly acknowledged the consistency between this model and Newton’s laws: “Yes, this forward force, we need it”. But this first response from the teacher did not suffice, and a student said: “But the ground is motionless, it cannot push”. When the teacher responded once more, this time by pushing on a nearby wall, she was contradicted again: “But the ground is horizontal, it cannot push”. Then a model was proposed for the respective profiles of the ground and of the sole: saw-teeth. Figure 4c shows how evocative this model is, and a student’s comment attests to its explicative power: “it’s like pushing on little walls”.

![Figure 3](image3.png)

**Figure 3.** A diagram proposed to underline the process of image formation

![Figure 4](image4.png)

**Figure 4.** Walking and pushing: a common diagram (a) and two suggestions for teaching (b, c: Viennot 2003, Viennot 2004a, Besson & Viennot 2004)
The point of interest here is that, through successive responses to students’ difficulties and objections, a new aspect of content was injected in the discussion: a first approach to a mesoscopic model, that is, to a scale of analysis now very much in use in physics research (Duran 1999, Krim 2002). A similar approach was used soon afterwards with the topic of fluid statics (Besson & Viennot 2004).

3.3 Some other cases
Table 1 displays some other examples of investigations that have, for a long time now, been taking students’ views into account in this way. A responsive process has led their authors to rethink the subject matter, thus presenting their students with aspects of the content not commonly highlighted.

<table>
<thead>
<tr>
<th>Students’ common perspective</th>
<th>Common comments</th>
<th>New spotlighting of the content</th>
</tr>
</thead>
<tbody>
<tr>
<td>The « travelling image » syndrome</td>
<td>We can see an image without a lens, erect this time. A mask on the lens, then a hole in the image.</td>
<td>A new diagram with “useless” rays, the imaging process, role of energy (Viennot &amp; Kaminski 2006)</td>
</tr>
<tr>
<td>Friction: “the ground cannot push”.</td>
<td>The ground is motionless, it is horizontal, it cannot push.</td>
<td>The mesoscopic approach: a saw-tooth model (Viennot 2003)</td>
</tr>
<tr>
<td>Pressure in fluids: a manifestation of weight</td>
<td>The fish in the sea feels greater pressure than in the cave (same depth)</td>
<td>The mesoscopic approach: The sponge balls model (Besson &amp; Viennot 2004)</td>
</tr>
<tr>
<td>Third law : de facto denied</td>
<td>The table cannot exert a force</td>
<td>The deformable table (Brown 1994, Clement et al. 1989)</td>
</tr>
<tr>
<td>Electric circuits : sequential reasoning</td>
<td>The second bulb (in a series circuit) lights less.</td>
<td>From electrostatics to quasi-stationary currents, via the study of propagative transients (Barbas &amp; Psillos 1997, Chabay &amp; Sherwood 2002)</td>
</tr>
<tr>
<td>Vision without light in the eye</td>
<td>I can see the ray.</td>
<td>Discuss: dazzling, more or less light (de Hosson &amp; Kaminski 2007)</td>
</tr>
<tr>
<td>Archimedes’ principle not seen as an interaction</td>
<td>It has nothing to do with pressure</td>
<td>Discuss: making holes in water (Ogborn 2012)</td>
</tr>
</tbody>
</table>

Of particular interest is the rationale stated by Chabay and Sherwood (2006), concerning their project in electricity and magnetism (Chabay and Sherwood 2002): it takes the common trend toward linear causal reasoning into account. The idea (see also Psillos 1995, Barbas & Psillos 1997) was to do justice to this common approach by explicitly dealing with transients in the realm of electric circuits, thus avoiding abruptly confronting the students with quasi stationary regimes. As compared to the changes previously mentioned, this one is much more radical. Indeed, the teaching of electro-magnetic phenomena was usually divided into electrostatics, magneto-statics, electric circuits in quasi-stationary regimes (including variable currents), and waves. It was really a novel choice to focus on the propagative transitory phase (≈10⁻⁸s) between a static situation – a battery and its ends – and what occurs between the time a circuit is closed and the quasi-stationary regime is established. This choice makes it possible to reconcile the students’ tendency to adopt a linear causal reasoning and the counter intuitive systemic view of a circuit.

The following quote (Chabay & Sherwood 2006) expresses the authors’ perspective very clearly:

Some research and development in physics education has focused on remedying particular problems with the traditional sequence by giving students additional focused practice on selected concepts. However, without addressing the overarching issues of structure and coherence, it is difficult to do more than improve student performance on isolated tasks. We have chosen instead to reexamine the intellectual structure of the E&M curriculum to identify which concepts are centrally important, how these concepts are
related, and how they can be introduced to students at the introductory level in a coherent, comprehensible sequence.

4. Responding to students’ ideas: a new spotlighting of the content (model 1b)
The preceding examples lead to, or echo, a notion previously suggested to characterize what it means to think about the content for teaching: the spotlighting of a content (Viennot 2003, 2004b). In these examples, what has been changed in the research process is a way of seeing the content: angle of vision, field, zoom, contrast. It is not mere simplification. If an “elementarising” process is at stake, this relies by no means on a straightforward mapping of the content. What is transformed is not a series of items, it’s a particular view of the content. In terms of selection, it is also that of a global aspect, not only a matter of local changes. The label “spotlighting” was chosen to suggest that no new content, *stricto sensu*, is invented. As with a photographer with a given landscape, the reflexive decision on what to stress in the taught content leads the planners to emphasize, unify, differentiate, contrast, various elements according to particular goals. The invention is there, only there.

Figure 5 suggests in a metaphoric way what makes the construction of a new spotlighting really different from a series of fragmentary responses (i.e. model 1a): A more global reorganization of the content is aimed at.

![Figure 5](image)

**Figure 5.** Taking into account students’ ideas by spotlighting the content differently for teaching. Black circles symbolize changes informed by the knowledge of students’ ideas (grey circles). Strictly speaking, a three dimensional diagram would be needed to account graphically for the “alignment” of previously unrelated items.

Figure 6 sums up how the dialogue between content analysis and the investigation of students’ ideas may crucially involve an effort to stress the consistency of physics and highlight its crucially important concepts.

![Figure 6](image)

**Figure 6.** Taking into account students’ ideas, possibly in the “work with it” modality (Duschl *et al.* 2011), by differently spotlighting the content for teaching: a process rooted in the search for conceptual coherence (model 1b). Black arrow: the decisive aspect that triggered a restructuring process.

It may happen that the new structuring at least partly “legitimates” some common ways of thinking, producing a “work with it” style described, for instance, by Duschl *et al.* (2011, see also Clement *et al.*
4. Teaching rituals and responsive spotlighting of the content (model 2)
These two ways of revisiting a content analysis in the light of students’ common ideas (models 1a and 1b) do not cover what was done in this respect in previous research. Some revisitings of content were triggered by the pinpointing of teaching rituals (Viennot 2006). Two examples follow.

4.1 From global to local: the hot air balloon
Particularly informative is the common statement in exercises about a hot air balloon. The target is to find the condition in which the internal temperature enables the balloon to stay in the air. The following hypothesis is quasi-universally enunciated: “(...) the pressure in the balloon is the same as the pressure outside the balloon” (Giancoli 2005), which means an isobaric situation. The explicit or implicit reason for this decision is that the hot air balloon is open at its lower aperture. This hypothesis permits an easy calculation of the required condition, via Archimedes’ theorem and a perfect gas relationship. But, although the exercise can be solved easily thanks to this apparently reasonable hypothesis, the situation modeled in this way would be catastrophic for the balloon: a crash is to be predicted. One argument to support this prediction is that, with the same pressure on both sides of the envelope at every point, no resulting force would ensure the balloon’s sustentation. One may also observe that an isotropic field of pressure is not compatible with a thrust in any privileged direction, i.e., upwards, here.

A responsive presentation of the related content, summed up in Figure 7, consists in emphasizing the core of fluid statics theory: it’s all a matter of gradients. No pressure gradient means no upthrust. The fact that the balloon stays in the air is intrinsically linked to the change in pressure with altitude. From the aperture to the top of the balloon, internal pressure diminishes more slowly than external pressure, due to different densities of the air inside and outside the envelope. This argument, which admits that the two pressures are equal at the bottom of the balloon, accounts for the fact that the envelope is inflated and stays in the air.

Figure 7.
Figure 7. Some elements needed to understand how a hot air balloon stays in the air. W: weight of the system (basket+load+balloon). The unlikely cylindrical shape is intended to facilitate the understanding of how a resulting upward force is linked to a difference between internal and external pressure (Viennot 2006)

To sum up this responsive process, the spotlighting of the content changed from a global approach – linked to Archimedes’ theorem - to a local analysis of the mechanical forces exerted on the envelope. In this case, it may be reasonably hypothesized that the observed global approach, leading to a correct answer, is to be attributed more to the teachers’ choice than to the students’ pre-scientific views.
4.2 From the local to the systemic: examples in fluid statics

Some teaching rituals may favor a local analysis and lead to suggestions for content spotlighting centered on systemic approaches. Thus, again in fluid statics, several situations have commonly given rise to local interpretations, like those suggesting that the column of water in an inverted glass (Figure 8a) exerted its weight on the cardboard, itself subject to a force due to atmospheric pressure (Viennot et al. 2009, Viennot 2010). Marie Curie (Chavannes 1907/2003) gave a similar comment for the column of water in a test tube inverted over a tank of water (Figure 8b). In all similar cases, the explanation is inconsistent with Newton’s second law, and it seems appropriate to counterbalance such trends by spotlighting the systemic status of the situation: then the two “ends” of the system, broadly speaking, for instance the top and the bottom of a column of water, will fruitfully be taken into account. Acting on the upper recipient of a love-meter with cold water shows that both “ends” of the system matter. More generally, other examples illustrating that differences make the world go round (Boohan & Ogborn 1997) refer to the same concern (Viennot 2014).

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**Figure 8.** Two analogous examples of ritual and inappropriate analyses for physical systems: sentences in black are erroneous: They are compatible with the idea that an object always exerts its weight on its support. The diagrams are drawn by the author of this paper to point out that the forces mentioned in the quotes are unbalanced.

It is worth noting that, concerning the inverted glass, the responsive process may be said to start with the analysis of rituals, but at the same time these rituals are in resonance with some of the students’ trends of reasoning, namely a local reasoning and thinking that an object always exerts its weight on its support. The label “echo-explanation” has been proposed to designate such cases (Viennot 2010).

In this case as with the previous one (the hot-air balloon), it is particularly manifest that the responsive process centers, on the part of the researcher formulating this proposal, on the desire to highlight conceptual coherence, links and key ideas in physics - here the need to consider both ends of the systems (Viennot 2010, 2014).

A specific model is proposed (model 2, Figure 9) for this process of content spotlighting prompted by a teaching ritual, whether or not it is also seen as a possible response to students’ common ideas.
In fact, this desire has long inspired many teaching projects.

5. **Proactive emphasis on conceptual coherence, links, strong ideas in physics (model 3)**

It is not within the scope of this paper to recapitulate and analyze the multiple attempts made in the recent past to re-think physics for teaching, in the perspective of highlighting conceptual coherence and key ideas in physics, while respecting a constraint of accessibility. But it is worth noting that some famous instances of this effort preceded the start of what we now call Physics Education Research: *The Feynman Lectures on Physics* (Feynman et al. 1964-1966), the *Physical Science Study Committee* project (1960), the *Harvard Physics Project* (Holton 1969), the *Nuffield projects* (Fuller & Malvern 2010), for instance, were clearly inspired by this objective. Contemporary with the first research investigations in PER, the innovative reflections on the theme of *Change and chance* (Black & Ogborn, 1970-1979), or on energy (Boohan & Ogborn 1997) for instance, were of the same type. These high quality projects may be seen as typical of a proactive attitude (see also Michelini *et al.* 2000), which was not rooted in a precise knowledge of what students commonly think, even if some general considerations about the targeted audience were mentioned in their rationale. The reasons for their relative failure (French 1986) might include this lack of precise knowledge about students' difficulties, to say nothing of the teachers'. We simply mention these projects here in order to characterize a case (model 3, Figure 10) among attempts at re-thinking the content. This perspective is still present, to a greater or lesser extent, in more complex landscapes - the above “models”- of subject matter reconstructions.

![Figure 9](image)

**Figure 9.** A model for a process of content spotlighting which is triggered by the analysis of a teaching ritual (model 2). Black arrow: the decisive aspect that triggered a restructuring process.

![Figure 10](image)

**Figure 10.** Proactive reconstruction of the content, not explicitly inspired by a detailed analysis of students’ ideas and difficulties (model 3). Black arrow: the decisive aspect that triggered a restructuring process.
6. A “multi-source” spotlighting of content: two CDIPs

After this attempt at characterizing different starting points, reasons and ways to reconsider the content to be taught, it’s time we remarked that nothing prevents us from blending these types of processes for a new spotlighting of a given topic. The following example is rooted in the combined consideration of some rituals and students’ common ideas, as well as of conceptual coherence, links and strong ideas. The next section is devoted to a brief description of this twofold investigation with a focus on the underlying content analysis. In this particular example, the conceptual structure that was privileged is inserted in the frame of a particular teaching format: concept-driven interactive pathways (CDIP), keeping in mind that the “multi-source” character of a renewed content analysis could be observed with other teaching formats as well.

7. A teaching format: Concept-driven interactive pathways

The expression “Concept-driven interactive pathway” (CDIP) designates a type of teaching sequence with the following characteristics (Viennot & de Hosson 2015):

- It is designed with the goal of facilitating students’ access to the understanding of a given conceptual content.
- It is interactive, implying teacher-student or teacher-group interaction. It may comprise phases like: exploring and discussing students’ ideas, asking for argued predictions or diagrams and discussing these with students, letting students construct and analyse experimental results, injecting new ideas in a transmissive style, having students’ criticize documents, etc. This adjective, “interactive”, refers to this statement: “Teaching is acting on other minds who react in response” (Ogborn et al. 1996, 141).
- It organizes a pathway, that is, a step-by-step process designed to help students progress toward the desired target. Although the structure of the pathway is mainly concept-driven, the development of transversal abilities – such as the critical faculty - is also favoured.

With such a format, the particular spotlighting of the content is of crucial importance, as illustrated below.

7.1 The absorption of light: spotlighted ideas

Two CDIPs on the absorption of light, each intended for an interaction of about one hour, have been designed and implemented. Depending on the targeted audience and school constraints, the first one, centering on the absorption of light by pigments (Viennot & De Hosson, 2012a, b), may constitute a preparatory step for the second one, about filtering process (Viennot 2013, Viennot & De Hosson, 2015), or each may be implemented alone.

Globally these two pathways are intended to spotlight the following conceptual targets:

- The absorption of light by pigments or filters is not an all-or-nothing process.
- It is a multiplicative process, involving multiplication by numbers smaller than 1.
- It is selective, that is, it depends on the wavelength.

These investigations were conducted on the basis of interviews with prospective teachers at university, the first one (CDIP1) with 8 students in the third year, the second one (CDIP2) with 6 students in the fourth year.

Our investigation with the first pathway (CDIP1) revealed that the interviewees were destabilized when the common binary rules – a pigment absorbs, or does not, such and such a part of the spectrum of white light (see Appendix) – turned out to be inappropriate, as when the impact of a red laser beam on a green pigment is quite visible. Moreover, we observed that they had considerable difficulty in understanding what it means to use percentages to analyze the process of absorption. These results provided the arguments at the basis of the construction of the second pathway (CDIP2), which is briefly described hereafter.

7.2 Light and filters (CDIP2)

The results of the first experimentation inspired us to investigate possible ways to help students to understand the multiplicative status of absorption. We chose to use filters, and made the hypothesis that the dependence of absorption on thickness might be an anchoring aspect for the targeted comprehension. Indeed, to understand the role of the successive, equally thick, layers of a filter, one has to understand that if one layer multiplies the incident intensity of light by, say 0.95, the second will let 0.95*0.95 of this initial intensity pass.
During the first phase, the interviewees were reminded of the classical rules, and were given a corresponding table (see Appendix). Then they were asked which mathematical operation came to their mind in this respect. All responded “subtraction.”

Then, they were shown a slide with a slit crossed by filtering strips of increasing thicknesses, made of one, two, three, etc., layers of a light yellow plastic sheet (Figure 11).

![Figure 11](image)

**Figure 11.** A diapositive with a vertical slit (width about 1mm), covered with one, two, three, ..., six horizontal strips made of transparent and thin plastic: light yellow, or light pink

They were then given a curve of transmission for one layer and asked to draw the curve for a strip with two or three superposed layers (Figure 12).

![Figure 12](image)

**Figure 12.** Given the transmission curve for one filtering layer, strips with two or three superimposed layers don’t have a transmission curve of a similar shape

The drawings and the comments that were collected in this phase show how salient the idea of non-selective subtraction was, in other terms, the downward translation of the transmission curve proposed for one layer (Figure 13).
The following conceptual target was to use the idea of multiplication to realize and explain the deformation of the transmission curves with thickness. Then an experiment proposed by the interviewer was performed to show the spectra of light transmitted by each strip of the slide shown in Figure 11. With this object, and also another one made of pink-magenta plastic, some parts of the spectrum (red and green) of the transmitted light seemed nearly unaffected by thickness whereas the blue part disappeared with the three-layer strip (photos of spectra are available in Viennot 2013). The discussion with the interviewer was more or less laborious, until all the interviewees manifested their comprehension of the conceptual target. The subsequent phases were devoted to the transfer of this new knowledge to other situations, a liquid and a gaseous filter, respectively pumpkin seeds oil and the atmosphere. In these two cases, the change in colour of the transmitted light was explained by the interviewees, after discussion, on the basis of the initially provided transmission curve (Table 2, lines 5 and 6). Once the possibility of seeing oil or the atmosphere as filters was admitted, it became clear to the students that successive multiplications would come down to selecting the part of the spectrum where the rate of transmission was the highest, i.e. in both cases the “red” part.

Table 2 outlines the structure of this CDIP.

CDIP2: Main results concerning the students' ideas and reactions

In terms of comprehension, the prevalence and the resistance of the idea of – implicitly uniform - subtraction was very impressive:

Int (Interviewer): What did you use when constructing your answer, a line of reasoning founded on which type of operation?

Vi: Subtraction, mainly.
Or else,

To: We add subtractions.

The comments finally attesting to a real comprehension were all the more striking:

Mi: Given that it is proportional, … (adding filters) we will end by selecting the spectral band of greatest transmission factor …

Th: We’ve just seen that differences were majored when layers were added.

To: Even after having done this (a multiplication) right from the beginning, I wouldn’t have interpreted this as a multiplication.

**CDIP 1 and 2: Main results concerning the students’ metacognitive-affective comments**

A final observation is worth pinpointing here. Beyond numerous expressions of satisfaction, we note the emergence of some meta-cognitive judgments:

Th: We’ve just seen that differences were majored when layers were added. I wouldn’t have spontaneously used the word multiplication, I did not reason like that before coming here. (…) Perhaps, I would use the operation with the right data, but if I was asked for an explanation, I would never have used the word multiplication. CDIP2

We find here an echo of several comments collected during a subsequent workshop in a meeting of the European Science Education Research Association (Viennot & Mueller 2013), which was framed on this CDIP:

- The use of different thicknesses, we usually do it with only one and I had the idea of subtraction. CDIP2
- It made me think about things I knew about intuitively perhaps, but I still think it was as if I did not know about them previously. CDIP2

<table>
<thead>
<tr>
<th>Phase</th>
<th>Our conceptual targets and questions</th>
<th>Material setting</th>
<th>Main aspects of the interaction (planned and/or expected)</th>
</tr>
</thead>
</table>
| Rem   | Students are reminded of the classical rules  
First observation of their reactions  
Question: which operation comes to your mind: +, -, *, /? | A colour mixer | The students appropriate the classical rules; predictions on this basis, observation, discussion, recapitulation.  
Table of rules left to students  
Question “which operation …?” |
| Filt-a | - Draw the curves accounting for the transmission of light through two, then three layers of the same material:  
Do students just translate the first curve downwards, or do they/how do they change the shape of the curve? | + Device to project spectra of the light transmitted through each strip | Predictions with arguments |
| Filt-b | Performing the experiment:  
Do they change their curves? Formulate a conclusion explicitly using selective multiplication? | Spectra observed | Students asked to reconsider the curves, to account for the disappearance of “the blue”: strongly guided discussion |
Observe colours of the oil, then apply a multiplicative procedure to the curve proposed by the interviewer to account for these colours + Sensitivity curves of the cones on transparency.

The interviewer:
- provides help for calculation.
- explains how to use the sensitivity curves of the cones.

See the situation as a filtering case. Transform the curve provided by the interviewer for “one layer”

The interviewer provides help for interpretation of the situation as a case of filtering:
- calculation

Ask about a function accounting for the changes of intensity observed

Input from the interviewer:
(selective) exponential decrease

Global evaluation of the design

Interviewees express feelings

A critical stance also emerged among the interviewees at the end of both CDIPs, in this case concerning the binary rules used in the reminder phases:

- We have to be careful (with rules). CDIP1
- The (classical) rules (still) have a certain validity. CDIP1
- Given this, should we tell our students, we should use the law of additivity bla bla bla! Is it correct to use it? No, it’s true, additivity is OK, it’s for subtractivity (that there is a problem). CDIP2
- Showing the subtraction, if I may say, of colours, and coming back afterwards to something that comes down to percentages, it’s rather, err, I don’t know if you would’ve presented it like that. (…) For a student who is not used to it, it might be very disturbing. CDIP2

8. CDIP1 and 2: the reasons for a spotlighting
These two concept-driven interactive pathways have several common features in terms of spotlighting. They are designed on the basis of a very fundamental idea, sometimes referred to by the interviewees as a “tough idea”. The multiplicative nature of the process of absorption ultimately leads to the exponential dependence of intensity on the crossed thickness (CDIP2). Although this was hardly discussed in the short time we had, the process of absorption is multiplicative because it is statistical. For all of that, the formal complexity, which may seem very little, comes down to that of successive multiplications. It may also seem not to constitute the least “new idea”, despite the students’ recurrent comments. It is not “new physics”, but it is a spotlighting of physics that shows these pathways’ distance from the most prevalent teaching rituals, in this case the binary rules of the absorption of light by filters or pigments - still used without any discussion recently (Mota and Lopes dos Santos 2014). Students’ ideas are also taken into account, with the goal of extending the range of their line of reasoning when they pass from a view limited to subtraction to a more fruitful multiplicative approach. The decision was also taken to underline the links that physics enables us to establish: a multiplicative process accounts for changes in light which interacts with solids, liquids and gases. In terms of formal complexity, the price to pay is moderate. Simplicity is still favoured via the choice of equally thick layers and a discrete approach to exponential function. At the same time, simplification is kept under control as consistency is not seriously at risk. Figure 14 shows a sketch of this proactive and responsive, multi-source process of spotlighting a content for teaching.

9. Recapitulation and concluding remarks
In the light of the preceding analysis and of the various examples analyzed, some ideas seem to deserve consideration. With the first of the models proposed for the reasons for casting a new look at taught subject-matter, it is suggested that taking into account students’ ideas is not enough to ensure an actual revision of
the content. Rather, it appears that a stabilizing process may intervene, the “new” elements being in fact re-injected in the initial mapping of the content. This is not always the case, far from it, and examples have been given in which a new “spotlighting” of the content was designed in response to some features observed in students’ thinking. This said, ascribing a label of “newness” to such and such a suggestion is debatable, and the corresponding categorization cannot be clear cut. Rather, it defines some extreme cases of how conceptual goals are redefined for teaching.

A new spotlighting of a given content may also result from a response to some teaching rituals, with or without a concomitant awareness of students’ difficulties. These difficulties may or may not be in resonance with the rituals, as the label “echo explanation” suggests. In most (all?) cases of a really new look at the content, a thorough consideration of the coherence, links and key ideas of physics is likely to be at work.

Figure 14. A multi-source process of content spotlighting, as in the case of CDIPs about absorption of light described here.

These reflections about new spotlighting distinguish between what it is to fruitfully re-think the content and the mere ideas of elementarisation and of simplification – if understood as unproblematic. In particular, simplification is not the master word in the previous examples. A smooth and horizontal ground may seem more simple than a saw-toothed profile which, however, proves more favorable to a sound comprehension of solid friction. To say nothing of the incoherent “simplicity” of an isobaric hot air balloon. In any case, simplification should be kept under control, and negotiated, keeping in mind the imperative of consistency. It is also worth noting that there is room for opening and enlarging a content analysis without ending up with excessive complexity. The last examples - namely the content driven interactive pathways about the absorption of light just described - illustrate, we think, the merits of a proactive/responsive, expert-led design of « new » spotlighting of content (i.e., led by a researcher and/or teacher): a design emphasizing consistency and conceptual links, as well as spurring an active engagement on the part of the students. Finally we might remark that the adjective “new” may seem deceptive, given that there is nothing new, strictly speaking, in the aspects of physics mentioned in this paper, apart from the decision to cast light on them (Viennot 1995). Here “new” does not mean reinvented physics, it means that attention is given to aspects of physics that have been commonly disregarded, or kept implicit.

One may wonder what possible obstacles may block this open reconsideration of content. Among good candidates, we suggest: a lack of distance with respect to rituals, an exclusive centering on students’ ideas with a « mirroring effect », excessive belief in (and focusing on) the power of new methods, the possible identification of « more rigorous » with « boring », and the common view that what is good for teachers cannot be good for their students. Clearly, more research is needed to give more substance to these assertions.
The preceding reflections also point to two strands of research of crucial importance, concerning fruitful ways to determine the content for research and practice.

One is the connection we can observe in students between an active search for consistency with conceptual links, on the one hand, and their intellectual satisfaction on the other. Without denying the motivation that can be raised via other entries, it would be highly contestable to deprive our students of teaching situations of the kind that make them conclude: “Thank you, you made me think”. But this connection between the affective and intellectual aspects is not straightforward, and deserves thorough attention and research.

Secondly, we have pointed out the limits of approaches to teaching that would rely on a separation between comprehending the content and developing certain competences. With the last examples reported here, it was particularly clear that conceptual development and a critical stance were not independent. A certain level of comprehension seems to be needed to trigger a critical attitude, even if the students’ initial knowledge was a priori sufficient to achieve this goal (see also Mathé & Viennot 2011, Viennot 2013, Viennot & Décamp 2013, Décamp & Viennot 2014). Further research is needed to support this claim. New insight in these research domains would be precious, in particular to inform rational decisions relating to the crucial question of how better to engage students in physics.

References
Teaching/Learning Physics: Integrating Research into Practice


Appendix  Colour phenomena: classical rules

Here the colours are associated with “thirds of the spectrum”

Separating the various radiations that constitute “white” light gives a “spectrum”. The spectrum of white light ranges from $\lambda = 400$ nm to $\lambda = 700$ nm. ($\lambda$: wavelength in empty space; $1$ nm = $10^{-9}$ m)

Here the spectrum is divided diagrammatically into three equal parts.

Coloured lights with a spectrum corresponding to a third of the preceding one are seen respectively as red in the long wavelengths
green in the medium wavelengths
blue in the short wavelengths

Additive mixing: Combining these three lights in various proportions produces a wide range of colours and, when the proportions are right, white.

Adding two of these lights in correct proportion gives respectively a light seen as
- yellow if you add red light and green light
- cyan, if you add blue light and green light
- magenta, if you add red light and blue light

Absorbing role of filters or pigments

A filter (or a pigment) absorbs a part of the spectrum of white light:
- a yellow filter absorbs blue light (a third) and diffusely reflects green and red lights.
- a cyan filter absorbs red light (a third) and diffusely reflects blue and green lights.
- a magenta filter absorbs green light (a third) and diffusely reflects blue and red lights.