Dagmara Sokołowska · Marisa Michelini
Editors

The Role of Laboratory Work in Improving Physics Teaching and Learning

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Preface

The book presents papers selected under the leadership of GIREP vzw—the International Research Group on Physics Teaching, the organization promoting enhancement of the quality of physics teaching and learning at all educational levels and in all contexts. Through organization of annual conferences and seminars, active participation of researchers and practitioners in various GIREP Thematic Groups, and wide cooperation with other international organizations involved in physics education, GIREP vzw facilitates the exchange of information and good practices in physics education, supports the improvement of the quality of pre-service and in-service professional development in physics teaching, promotes research in the field, and facilitates cooperation between stakeholders on both national and international levels. The book continues the work initiated in "The Role of the Laboratory in Physics Education," published by GIREP 40 years ago.

The book is based on contributions presented during the GIREP Seminar 2016 in Kraków organized by the Faculty of Physics, Astronomy and Applied Computer Sciences, Jagiellonian University in Kraków, Poland. The overall aim of the seminar was to draw attention to the variety of aspects of laboratory work, forming the environment where physics teaching and learning take place and being the method for development of physics literacy. The seminar focused in particular on *experimental labs, conceptual labs, multimedia labs, problem solving labs, and the assessment of laboratory work*. The format of the seminar was proposed in the style of the old-time GIREP meetings—with keynotes, panel talks, and poster presentations focused on six themes and followed by sessions of workshops proposed for in-depth discussions in small groups of researchers and practitioners, led by workshop leaders. As a result of 6 invited talks and 61 oral presentations, 54 papers have been received from the authors. The book is built on 22 papers carefully selected in a rigorous double-blinded peer-review process, involving members of the editorial board and twelve additional referees in order to guarantee the quality of the content of this contribution.

Regarding specific characteristics of the contributions, six chapters have been created in which research-based proposals focusing on laboratory work aimed to improve physics teaching and learning are organized as follows.

Part I of this volume, *Background Aspects*, gives a multi-perspective view of the role and strategies in the laboratory work, as for example how to learn from experiments promoting creativity, the types of lab to build modern physics way of thinking, the role of group work in solving experimental problems, the contribution of open-source multimedia materials in physics teaching, as well as an outlook on how distance learning lab can be integrated in introductory physics course and how to approach formative assessment for learning in physics.

Part II on *Experimental Lab* offers four contributions. The first one reports on instructional arrangement of a strategy to overcome difficulties in the secondary students' lab reports showing the limitations stemming from rituals. The second one gives insight into innovations in undergraduate physics laboratories based on open inquiry experiments. The last gives detailed examples on advanced experiments based on modern physics.

In Part III, *Lab work and Multimedia*, the role of computer modeling in physics teaching starting from a researched-based experimentation is presented. The second paper concerns the support of multimedia in the design of IBL activity for pre-service teachers. The subsequent contribution presents a remote lab aiming at personalization of learning in modern physics topics, like optical spectroscopy, in order to plan a system and test it with different scenarios based on inquiry approach. The fourth paper gives a proposal for web-based interactive video activities. The last contribution in this part presents students' ideas about using smartphones in physics laboratory.

Part IV, *Concepts and Labs*, starts with a proposal on how to overcome secondary students' difficulties on energy, while the second paper presents specially designed low-cost experiments helping in understanding concepts in electricity.

The first contribution in Part V, *Assessment for Learning Through Experimentation*, shows the vision on how contemporary physics as a new topic in the curriculum can contribute to individuate gifted students. The second paper presents the problem of measuring skill level development in physics. The last one presents an experience on assessing students' conceptual understanding in a modern physics lab work activity.

Part VI, *Low-cost Experiments and Inquiry*, starts with a contribution showing the results of the mid-term effectiveness of guided IB intervention in science classes in primary school. The second paper describes a specific app developed for measurements and mapping of sound intensity in space that has become the centre of a teacher training course integrated with classroom experimentation on sound at different school levels and motivates the context of social problem by means of measurements for smart city. A low-cost high-tech spectroscope, set up to explore and analyze colors from different sources, is presented in the last paper.

It is our sincere hope that the book will give the reader the opportunity for thorough comprehension of research-based proposals focusing on laboratory work aimed to improve physics teaching and learning, collected in this selection.

The editors are grateful to the authors for their hard, fruitful work and to all the reviewers for their valuable remarks and time devoted to the development of the community of physics researchers and practitioners.

Kraków, Poland Dagmara Sokołowska
Udine, Italy Marisa Michelini

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Part I
Background Aspects

Chapter 1
Empowering the Engines of Knowing and Creativity: Learning From Experiments

Manfred Euler

The Inquiry Cycle: Orchestrating the Productive Interplay of Complementary Modes of Knowing

Physics in school is often rated as difficult, abstract and boring. For many students, the initial interest in the subject diminishes with increasing exposure. While doing physics is strongly dependent upon the curiosity and the creative play of its practitioners, only few productive moments are conveyed to those who have to learn the subject in school. Opportunities to engage in various types of active and creative processes are rare. Solving physics problems is often reduced to doing mathematics in carrying out narrowly prescribed calculations. Only little time is devoted to practical tasks, to inquiry and to design activities. With due variations, this also applies to other subjects from the STEM field. The negative image of the 'hard' sciences and their declining attractiveness has negative consequences for our societies. It is one of the reasons for the imminent lack of innovative minds in these fields. As a countermeasure, many reform initiatives promote inquiry and experience based methods to improve science teaching and learning. On the background these efforts, the status and function of experiments requires reconsideration (Euler 2004).

The present article highlights the productive role of experiments and analogical reasoning in creating new knowledge, an aspect largely ignored in the mainstream educational theories (cf. Clement 2008 for a noteworthy exception). We frame our approach within a generative model that applies both to inquiry in science and design in technical disciplines. There are many ideas on the nature of scientific inquiry and

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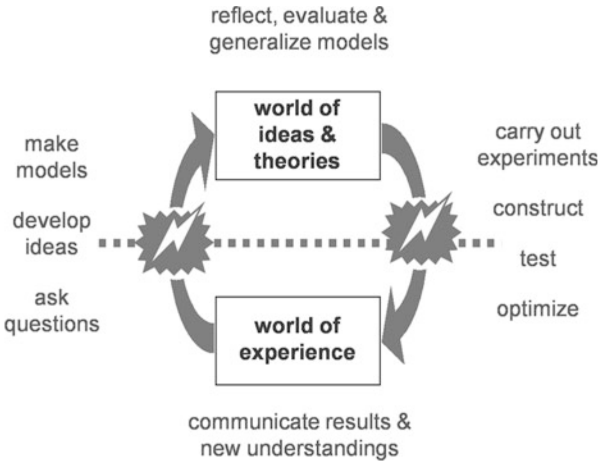

Fig. 1.1 Cyclic model of inquiry and design

design. Most conceptions agree upon their cyclic character that iteratively link two different worlds, the world of experience and the world of ideas and theories (Fig. 1.1). Creative processes, which cannot be described in a fully logic or algorithmic language, play an important role at the interface between theory and practice or idea and experience. Creative linking at the interface works in both directions: bottom up and top down. In research this somewhat idealized view corresponds to the cycle of modeling and experimenting that starts from wondering, asking questions and identifying ways how to create predictions and solutions to a problem on the basis of suitable models. The corresponding processes in the technological design cycle refer to the development and evaluation of ideas, and to construction, testing, trouble shooting, and optimization.

In physics, the model is compatible with the view brought up by prominent researchers, for instance with Einstein's EJASE model of scientific theory construction, where the 'J' addresses the creative jumps between experience and theory (Holton 1998). The modeling cycle requires a clear distinction between the two worlds separated by an epistemic cut. In spite of the non-deductive 'creative' elements at this interface, the complete process described by the cyclic interweaving of generative and evaluative components is rational. Many pedagogical models have been put forward which are more or less refined versions of this basic cycle.

The generative model of the inquiry/design cycle conforms to the demands of educational constructivism that identified favorable conditions for knowledge construction and conceptual change. However, transforming constructivist ideas about learning to efficient constructivist teaching is anything but trivial (Mayer 2004). It appears a too naive assumption that learners are able to discover the relevant structure principles and big ideas of science by themselves without suitable guidance. Evidence from unguided learning clearly demonstrates the benefit of more strongly guided instructions (Kirschner et al. 2006). In the views of these authors, the challenge to constructivist teaching is to unite the intuitively appealing view that learners must become active and construct their knowledge with the requirements of human cognitive architecture. What is so special about science-related cognitive processes that our cognitive systems pose severe impediments to the learning of science in school?

Physics is considered hard by many learners mainly because of its abstractness and its mathematical rigor. A more refined analysis identifies different forms of knowing and their interplay that render the subject difficult and counterintuitive. Physics combines concrete and abstract approaches to create and refine complex and counterintuitive models and theories of the world, highly different from the naïve views guided by experience from our everyday reality. In an admittedly coarse but nevertheless quite helpful dichotomy, two main forms of knowing interact:

- The declarative mode proceeds in a logical, analytical and axiomatic manner based on definitions, rules and structures.
- The procedural mode proceeds in a largely analogical way by deploying experience-based processes and procedures.

These two approaches are largely complementary. One cannot proceed successfully without the other. From an epistemological perspective, the emphasis on declarative knowledge corresponds to the nomologic-deductive view of science while the procedural focus is in line with the semantic, model based view. The former stands for the formal rigor, difficulty and abstractness of the discipline while the procedural and analogical strand is related to everyday experience, to intuition, easiness and tangibility. Many examples show that intuitive physics is fallible. Therefore we need the analytic and rational mode as a corrective that generalizes experience and condenses the knowledge into rules, laws and general principles. The procedural mode is required as the empirical referent of the theoretical strand. Procedural knowledge is necessary to anchor abstract concepts in experience and to unfold the consequences of theoretical models that can be tested empirically.

From a cognitive perspective, the difficulty of learning physics can be traced back to the limitations of our working memory which require the 'chunking' of concepts into smaller units of knowledge that can be handled and connected. In physics, a successful chunking of abstract concepts is largely theory based because it has to include relevant characteristics of a phenomenon and exclude irrelevant, superficial elements. The linking of the condensed concepts to the real world requires some kind of unpacking or dynamical unfolding. This part is largely procedural and experience based. Moreover, the complexity requires externalizing the knowledge by using suitable tools. Here the language of mathematics comes into play. In theory, mathematical methods reduce the cognitive load. They externalize the modeling processes by using suitable e.g. algebraic or geometric tools. In practice, unfortunate for many students, the use of mathematical methods in physics results in the opposite and tends to increase the cognitive load of the subject.

For a successful implementation of inquiry based teaching in physics, the cyclic interplay of theory based condensation and the experience based unfolding of knowledge must be adequately reflected in the teaching methods. As a general prerequisite, the approach needs more time than actually provided in most of the time-tables to fully unfold its potential. Lack of time to adequately engage in the

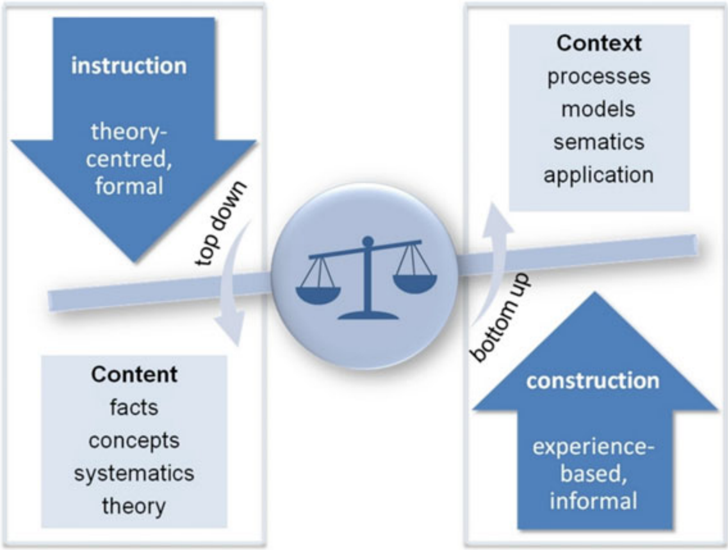

Fig. 1.2 Balance between instruction and construction in teaching

inquiry cycle can be considered one of the reasons why the traditional use of experiments in physics teaching largely fails. It does not improve conceptual understanding, although experiments are beneficial to motivation and raise the interest in the subject (Euler 2010). In order to foster an intelligent interplay of concrete and abstract forms of knowing in the minds of the learners, teaching depends on a reflected orchestration of bottom-up and top-down methods, a balance between autonomous construction on the side of the learners and effective instruction on the side of the teachers. The balance depends on the subject and the degree of experience of the students (Fig. 1.2). Learners tend to favor the more comfortable procedural mode at the expense of the analytic and reflective mode. Therefore they need guidance in reflecting and generalizing their views in terms of unifying principles (e.g. dynamical laws, conservation principles, symmetries and invariants).

In the following examples we present hands-on experiments and models that fit into the sketched framework. We elucidate their role as engines of intuition that promote procedural knowledge on par with conceptual knowledge. With sufficient theoretical underpinning the experiments can unfold a creative life of their own. By activating meaningful analogies, they can open up new views and conceptual links to distant subjects and abstract ideas. Thus they contribute to creating new knowledge. From the demands of abstraction, the experiments are suited for introductory teaching at tertiary level. In secondary education, the examples can be used for qualitative discussions.

Hands-On Nanoscience: Imaging and Imagining Atoms

We start with experiments how to create images of invisible atoms and structures at the nanometer-scale by designing and exploring acoustic models of a scanning tunneling microscope (STM). For millennia, atoms were considered mere things of thought that nobody was able to see and grasp. STM allows researchers to create visualizations of atoms or molecules, to address and even to position individual particles. However, an adequate interpretation of the STM images depends on understanding quantum principles and the mapping process, which differs fundamentally from conventional optical imaging and magnification techniques. STM combines classical engineering with quantum physics. The classical part refers to scanning surfaces at atomic scales with a tip-shaped probe that ends in a single atom. Its motion is controlled by a piezoelectric drive. Quantum physics comes in by measuring the tunnel current between tip and surface.

In view of the conceptual gap between the macroscopic and processes at the nanometer-scale, a classical model-based approach might appear futile due to the quantum nature of the underlying interactions (tunnel effect). Nevertheless, it is possible to devise macroscopic similes of the imaging method by taking advantage of quantum-classical analogies between matter and sound waves. The scattering and tunneling of electrons in STM can be explained intuitively in the wave picture. The electronic wave functions overlap progressively in the near field when the tip approaches the sample. If a voltage between tip and sample is applied, a tunneling current can flow before close contact. Its intensity depends on the degree of orbital overlap and increases exponentially with decreasing distance. In the classical world, the overlap of states corresponds to a resonance. The resonance analogy is the guiding concept to conceive a sound-based imaging system.

Starting from this idea, the imaging principle is readily accessed with a one dimensional scanning model (Euler 2012a). Figure 1.3 shows the device for manually scanning a row of yoghurt bottles. The sound probe is constructed by extending

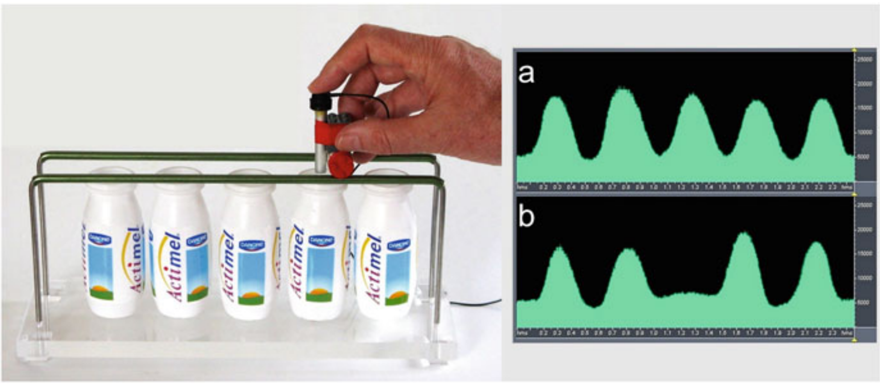

Fig. 1.3 One-dimensional acoustic scanning of resonating yogurt bottles

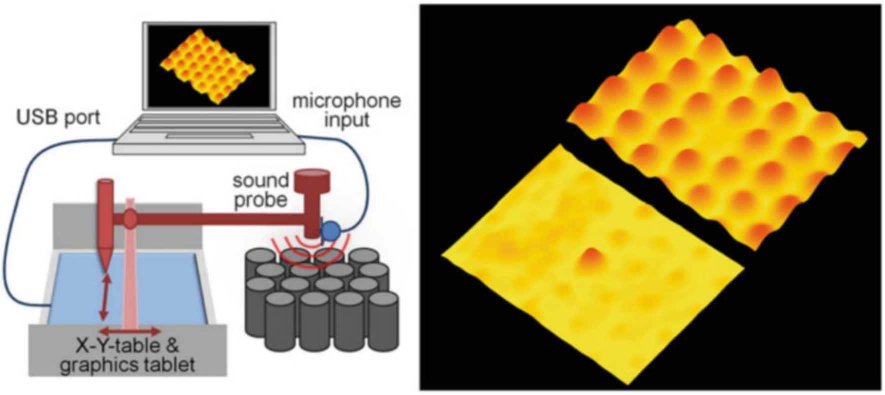

Fig. 1.4 Principle of the acoustic imaging setup and scans of the bottle array with different frequencies. An impurity atom is simulated by changing the resonance frequency of one bottle

an earphone capsule with a narrow metal tube. In order to ease the scan the probe is attached to wheels from a Lego set. Two rails guide the motion. The probe is connected to a frequency generator and tuned to the first resonance of the bottle ($f \approx 2.4$ kHz). It is possible to find the position of the resonators without any technical apparatus merely by listening. The loudness of the resonant mode increases as the probe approaches the bottle's mouth.

In order to measure the sound field a microphone is fitted to a bore in the tube's wall close to its opening. Thus, a simple acoustic impedance probe is created that injects a constant acoustic flow and detects the local variations of sound pressure. Figure 1.3a shows the probe signals from a linear array of five bottles scanned manually at a constant rate. Each bottle is identified by a maximum response. This compares to locating individual atoms in STM. The sound probe is frequency selective. The third bottle in Fig. 1.3b is partly filled with water. It remains undetected because it is out of resonance.

The setup can be extended to a two-dimensional imaging system by using a graphic tablet as position sensor. A computer program stores the sound field data from successive scans point by point and line by line in a two-dimensional array. Students can explore various ways to visualize the data matrix by computer graphics. The full three-dimensional rendering uses colors, shades and light effects to create a topographic impression in Fig. 1.4. The match between the acoustic and the STM images is amazing. An unbiased observer cannot tell if the hexagonal structures represent a regular arrangement of surface atoms or a macroscopic array of resonating bottles.

STM images create the impression of a relief map truthfully depicting the topography of an enlarged material landscape. Atoms resemble tiny heaps of matter similar to dots of Braille letters. The photorealistic design enhances the illusion of solid shapes and well-defined surface contours by adding color, shades and light reflections. However, these emergent macroscopic properties have no counterpart on the level of single atoms. They tend to confuse inexperienced spectators supporting naïve views of atoms as tiny specks of matter made up from portions of a continuous material stuff. The model makes it possible to compare the 'real' system with its acoustic mapping. The image reveals features completely different from tangible reality. The peaks indicate the maximum response above the bottle's mouth. At that point, no tangible matter is present, but the coupling with the lowest bottle resonance is optimal. Detecting the maximum acoustic responds corresponds to localizing individual atoms by the STM-tip.

The frequency selective acoustic imaging corresponds to the spectroscopy mode of STM (Euler 2013). The perfect match between imaging with sound waves in the model and electron waves in STM is based on the analogy between the time independent Schrödinger equation for electrons and the acoustic wave equation. It allows simulating electronic transport and scattering phenomena with acoustic waves. The acoustic models elucidate the nature of STM images and convey the productive tension of imaging and imagining an invisible reality. What we can see and grasp (the intuitive reality) shows only the surface or the interface of a more abstract reality that is hidden to our senses. It is only amenable to imagination, informed and refined by theoretical knowledge according to the inquiry cycle.

Deconstructing an Icon of Nanoscience: A Classical Quantum Corral Model

In the present context, this exercise in 'practical epistemology' can be expanded by discussing STM images of the so-called quantum corral (Fig 1.5, left). This man-made circular arrangement of iron atoms on a copper surface is an early demonstrator for designing a systems atom by atom. Different versions of the corral

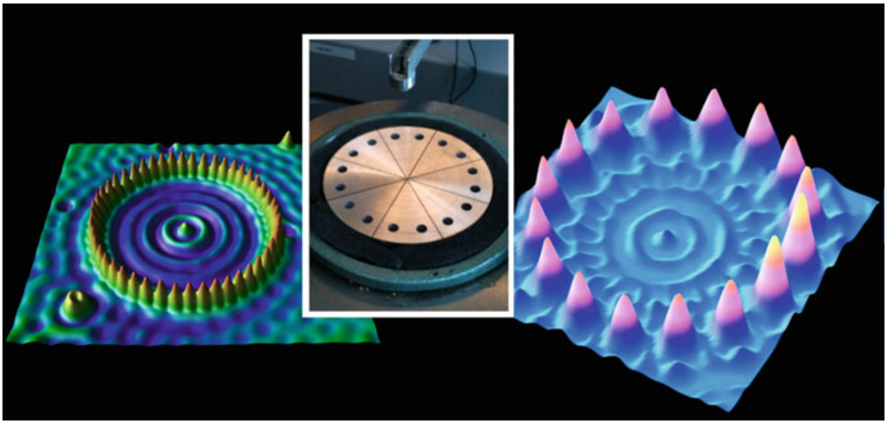

Fig. 1.5 An icon of nanoscience in classical reconstruction; the quantum corral (left) and its acoustic model (right). The middle image shows the acoustic setup with the ultrasound source above the perforated plate. The microphone is located in the center of the circular disk below

have become icons of nanoscience (Crommie et al. 1995) that made their way into textbooks and popular presentations. The quantum corral reveals a strange reality that we describe in everyday language by using a mixture of wave and particle models. The Fe-atoms appear as discrete, localized objects. They seem to stand out from a continuous sea of circular waves that result from the wave nature of the conducting electrons at the copper surface. Their de Broglie-wavelength is larger than the lattice constant of the Cu-substrate. Scattering processes at the Fe-atoms confine surface electrons to the interior of the atomic fence. Their probability density distribution results in standing wave patterns comparable to the frequency dependent modes of a circular drum. STM images display neither waves nor particles; they visualize data. The corrugations reflect variations of the tunneling current that depend on the local density of electronic states. We impose wave or particle models to give meaning to the perceived patterns.

As a challenge to creative modeling we demonstrate how to devise an acoustic version of the quantum corral by systematically exploiting the similarities in the scattering of sound and matter waves. For that purpose, a redesign of the acoustic imaging system is necessary. It has to provide appropriate boundary conditions that simulate the presence of localized atoms confining the two-dimensional gas of surface electrons. In order to keep the dimensions small, ultrasound is used for imaging. The actual design is shown in the center of Fig. 1.5. The acoustic corral is made of an aluminum plate with 16 concentric bore holes. The holes act as resonators and secondary sources that scatter sound waves. In 2 cm distance below another metal plate is mounted. The resulting sandwich structure enforces the propagation of sound waves within a plane and simulates the propagation of electrons confined to surface states. An ultrasonic transmitter ($f = 40$ kHz) is used to scan the structure from above. A fixed ultrasonic receiver in the center of the plate below detects the sound from the scanning process. The arrangement differs from the above scanning schemes in measuring the transmitted sound.

The ultrasonic corral image displays patterns similar to the quantum corral setup that we tend to interpret as localized particle-like and extended wave-like structures. The circular arrangement of the bore holes in the upper plate is clearly visible. They stand for the localized fence of Fe-atoms in the quantum corral. Inside the fence, a pattern of concentric waves indicates interference. The sound signals from the ultrasonic transmitter reach the microphone taking different paths through the bore holes. Their superposition gives rise to a standing wave pattern with maximum or zero sound pressure depending on the relative phase of each individual contribution during the scanning process. In this way it is possible to simulate acoustically the scattering of surface electrons inside the quantum corral. Electrons are injected by the STM probe and propagate along surface states. They undergo scattering at the fence atoms which gives rise to the observed standing wave pattern of probability density inside the circular confinement. The strange nano-reality with its hybrid mixture of localized and delocalized entities can be reconstructed via quantum-classical analogies.

STM images inspired numerous discussions about their nature as they display a quantum reality that transcends the limits of visual experience. For that reason, they are often compared with objects of abstract art (Tumey 2009). Nevertheless, by cleverly applying analogies, it is possible to ground the principles of STM-imaging in everyday experience by using the auditory channel instead of vision. Although the images differ from visual realism, they are closely related to hearing. The underlying concept of near field imaging and exploiting the scattering of waves to localize and characterize events is also relevant to acoustic perception. Loosely speaking, STM images can be considered visualizations of the inaudible electronic sounds of the nanoworld. This analogy will be elaborated further in the subsequent chapter.

Transcending Limits: Tool-Driven Innovation and Conceptual Development

The present experiments help to clarify the special nature of STM images while restricting the theoretical background to a minimum, an approach suitable for introductory teaching. Moreover, the examples demonstrate the role of experimental tools to promote conceptual development. This re-balancing in the role of tools and concepts is also a characteristic trait in the rise of nanoscience. One can discriminate between two kinds of scientific innovations, those driven by new tools and those driven by new concepts (Dyson 1997). Nanoscience clearly belongs to the first category. The rapid development of the field demonstrates the role of instrumental devices as facilitators and catalysts for new insights. It reveals the close interweaving between the productive function of tools and their epistemic role in promoting innovations and generating new knowledge. The invention of the STM triggered off a spectrum of different devices to interact with systems on the nanometer scale (Gerber and Lang 2006). The instruments opened the doors to the nanoworld, not only on a technological but also on a conceptual level.

Conceptually, the high spatial resolving power of STM is a product of near field imaging. The relevant interactions between the wave fields are restricted to the immediate vicinity of the probe tip. The idea of near field imaging is evident in the one-dimensional scanning device from Fig. 1.3. Sound waves with wavelengths of 30 cm are used to localize much smaller structures. In conventional far field optical imaging this is not possible. The aperture restriction, expressed by the Abbé-criterion, results in a minimum resolvable distance of approximately half a wavelength $d_{min}{\sim}\lambda/2$ (Novotny 2007). The near-field scanning probe methods transcend this limit. In principle, also the more recent super resolution microscopy methods exploit the idea of near field interaction in order to create far field optical images, e.g. of processes within the living cell (Hell 2007).

It took a long and winding road to create a wide range of practical near field imaging techniques. However, the principle was around us all the time. Evolution exploits near field imaging in directional hearing, a largely unnoticed example of everyday biophysics! The following experiment demonstrates near field imaging and tracking abilities of the human auditory system (Fig. 1.6). Create a noise by rubbing

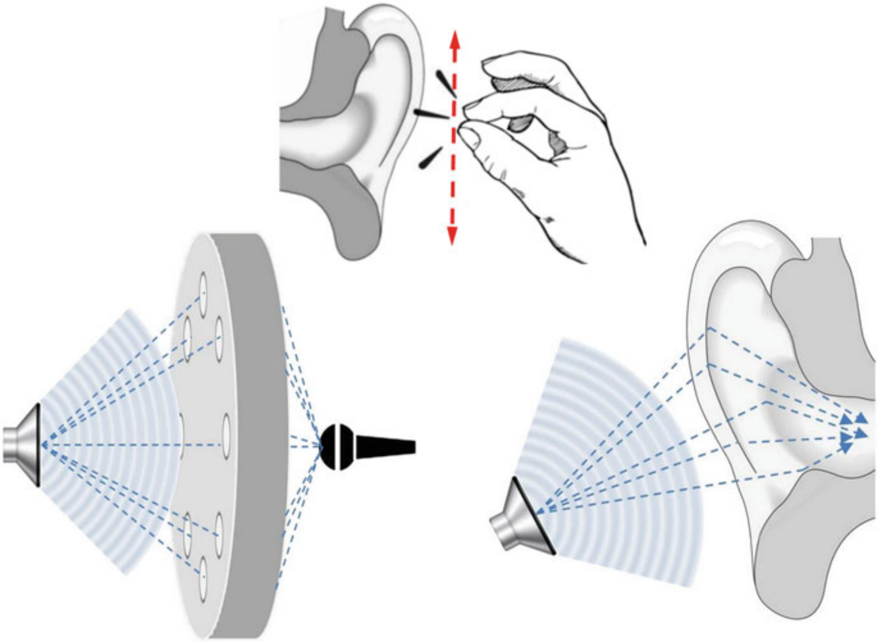

Fig. 1.6 Experiments in near field imaging. The monaural localization of sound sources uses multiple scattering of sound at the outer ear. The principle is similar to imaging the corral structure

two fingers and move the sound source in the vicinity of one ear. Close your eyes and block the opposite ear with the palm of your hand. By using only one ear it is possible to locate and to track the noise source in the near field. The shape of the pinna contributes to this monaural performance. The waves are scattered by the complex topography of the outer ear. The scattered partial waves reaching the eardrum interfere according to their acoustic path difference. Depending on frequency and direction of the incoming sound, the transfer factor can vary by more than 30 dB. We have learned by experience to exploit the transmission characteristics of the outer ears for localizing spectrally rich sound sources. We unconsciously apply strategies closely related to near field imaging with STM in everyday situations!

Roads to Reality: Promoting Knowledge by Reflecting Toy Models and Analogies

The conceptual reflection of the above model experiments demonstrates their power in generating 'fluid' knowledge, prepared for application and productive knowledge transfer. The present approach establishes intriguing links between different domains of science that appear unrelated from a superficial perspective (e.g. between the biophysics of hearing and imaging methods in nanoscience). Further examples along the same line of thought were presented in the lecture. They start from investigating tangible models of synchronization (Euler 2006, 2012b) and elucidate emergent phenomena that embody the gist of complex evolutionary processes. In a biological context, the dynamics of synchronized clocks sheds light on universal self-organization processes in living systems. In the context of physics, it provides a conceptual bridge between the dynamics of classical and relativistic quantum oscillators. Via analogy, it can be used to resolve several puzzling and counter-intuitive features of relativistic dynamics in a fully tangible visual way.

The present experience-based approach strongly depends on analogical reasoning. It complements the theory-driven, axiomatic, deductive approach. In concluding, we reflect on the indispensable role of analogies in promoting new knowledge. In the traditional view in education, analogies elucidate one domain in terms of another (cf. Aubusson et al. 2007). Psychological theories describe analogy building as a mapping between source and target domain. Essentially, this is considered a one-way process: The base domain provides a model for the target domain (Gentner 1983). The mapping is considered to operate on sets of explicit roles similar to the formal steps in deductive and propositional reasoning (Holyoak and Thagard 1989). This algorithmic view is somewhat distant from the actual practice of creating and using meaningful analogies in physics and, from my own experience, it is too restrictive to be fully productive for educational purposes. It neglects the non-decodable productive elements and creative leaps (cf. Fig. 1.1) in deploying, evaluating, reshaping and refining models and analogies. Beyond one-way mapping there is a more symmetric relation between base and target domain. Learning and understanding function in both directions. Similarities and analogies let the ideas flow back and forth. Analogy making elucidates not only concepts and functional principles within the target domain. It can act back and provide a deeper insight into the base domain as well. An essential part of successful analogical reasoning is to evaluate why and to which extent an analogy works. In general, this analysis will reveal that the basic domain must embody relevant structural and dynamical aspects of the target domain in order to provide a successful physical model. Well-founded analogies are based on structure principles and dynamical processes of similar complexity in both domains. Lower complexity analogies tend to fail as they have less explanatory power.

Powerful models carry kind of a ‘surplus meaning’ that fosters largely unexpected insights into new fields. However, it is impossible to fully formalize this feature which is related to universality. It makes up a central feature of creative modeling and facilitates a progression of our knowledge. As a final conclusion, a quote from Einstein, the master of physical intuition, is appropriate. It shows how the stubbornly persistent illusion of our naïve everyday reality can be transcended by creative modeling and successful analogy making (Einstein and Infeld 1938): “It has often happened in physics that an essential advance was achieved by carrying out a consistent analogy between apparently unrelated phenomena. The development of the mechanical and field views gives many examples of this kind. The association of solved problems with those unsolved may throw new light on our difficulties by suggesting new ideas. It is easy to find a superficial analogy which really expresses nothing. But to discover some essential common features, hidden beneath a surface of external differences, to form, on this basis, a new successful theory, is important creative work."

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Chapter 2
Labs in Building a Modern Physics Way of Thinking

Marisa Michelini

Introduction: Our Research Based Approach to Modern Physics in Secondary School

There are very different positions as concern the introduction of Modern Physics (MP) in secondary school (Aubrecht 1989; Gil and Solbes 1993; Hake 2000; Ostermann and Moreira 2000; Silva 2015; Michelini 2010; Michelini et al. 2016). Conceptual knots in classical physics are quoted to argue for the exclusion of MP by the secondary school and currently there is a wide discussion on goals, contents, instruments and methods, and target students. One of the reasons is that in the last 10 years it appears in almost all secondary school curricula in European countries and in all secondary textbooks, even if in not coherent way (Hake 2000; Ostermann and Moreira 2000). The main open research questions involve: goals and rationale in connection with its wider role (culture of citizens, guidance, popularization, education) and aspects to be focused (fundamental, technological, applicative) (Burra et al. 2014; Wagner 2017).

MP in secondary school is a challenge, which involves the possibility to transfer to the future generations a culture in which physics is an integrated part, not a marginal one, in a way that allows the students to manage them in moments of organized analysis, in everyday life, in social decisions. It involves different planes: curriculum innovation, teacher education, physics education research (Hake 2000; Ostermann and Moreira 2000; Duit et al. 2005; Michelini et al. 2016). Here we present our research approach on modern physics in upper secondary school, exemplifying main contributions and results of research on students' learning.

The perspective adopted in Udine Physics Education Research Unit for modern physics is content-based research (Lijnse 1995; Niedderer et al. 2007) in the

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theoretical framework of the Model of Educational Reconstruction (MER) (Duit et al. 2005) and by means of Design Based Research (DBR 2003; Anderson and Shattuck 2012) intervention modules to develop and test research based learning path proposals (Lijnse 1995). Action–research is associated to DBR in a collaborative dialectic between school and university to contribute to classroom practice and to develop vertical T/L path proposals based on experimental work (Michelini et al. 2016). The approaches in our work are therefore not purely based upon disciplinary content (Fischer and Klemm 2005) in order to identify strategies for conceptual change (Vosniadou 2013).

The rationale in learning path proposals is to develop an integrated physics curriculum rather than something that is appended to existing curricula, focusing on foundation of basic physics concepts as well as methods and applications in physics research. The goal in path planning is to offer experience of how modern physics works in active research. Vertical paths are identified as learning corridors (Di Sessa 2004; Meheut and Psillos 2004; Michelini 2010; Michelini et al. 2016) for individual learning trajectories and step-by-step concept appropriation modalities (Michelini and Vercellati 2012). In the learning processes we pay attention to conceptual knots, to the obstacles we have to overcome for reaching a scientific level of understanding and the construction of formal thinking. Rather than finding general results or catalogues of difficulties, our goal is to find new approaches to physics knowledge to overcome identified difficulties (Viennot 2014; McDermott 1991, 2008; Michelini 2010; Michelini et al. 2016) by looking to strategic angles and critical details used by common knowledge to interpret phenomenology (Viennot 2014). We are interested in the internal logic of reasoning, spontaneous mental models, their dynamic evolution following problematic stimuli (inquiry learning) in proposed paths, the ways for building of formal thinking. We study spontaneous dynamical path of reasoning (Michelini 2010), adopting an Inquiry Based Learning (IBL) (McDermott 1991; McLean Phillips et al. 2017) strategy and Investigative Science Learning Environment (ISLE) methods to engage students in experimental/explorative activities, in design and reflection, in multiple explanations to develop scientific abilities and critical thinking (Etkina and Planinsic 2014; Etkina 2015). In the theoretical framework of MER, we build path proposals focused on conceptual learning foundation to offer opportunities not only of learning but also of understanding information to develop students capable of managing fundamental concepts and able to gain competency in the use of instruments and methods, characterizing physics ways of working (Tesch et al. 2004).

Udine Physics Education Research Group (UPERG) carried out empirical data analysis on four main research directions:

- Individual common sense perspective with which different phenomena are viewed and idea organization, in order to activate modeling perspective in phenomena interpretation;
- The exploration of spontaneous reasoning and its evolution in relationship with series of problematic stimuli in specific situations, in order to formulate activity proposals;

- Finding the modalities for overcoming conceptual knots in the learning environment;
- Learning progression from defined low anchor to specific learning outcomes by means of detailed paths (Duschl et al. 2011).

UPERG carry out data collection to monitor the learning progression by means of pre/posttest, to obtain an overview on the student conceptions and the learning impact of the proposal. IBL tutorials monitor the students' learning process, often integrated with mirroring Rogersian method and/or semi-structured interviews. When possible we associate for data collection Audio/Video-recording of small or large group discussions and interactions (Fischer 2006).

The different proposals for MP cover mutually inclusive perspectives, for a global vision on MP:

1. Phenomena bridging theories, for instance light diffraction (Gervasio and Michelini 2009a) and light spectroscopy (Buongiorno 2017);
2. The physics in modern research analysis techniques (Corni and Michelini 2018), as for instance the Rutherford Backscattering (RBS), Time Resolved Reflectivity (TTR), electrical transport properties of material analysis with resistivity versus temperature and Hall coefficient measurements (R&H) (Gervasio and Michelini 2009b);
3. Explorative phenomenological approach to superconductivity (a coherent path) (Michelini et al. 2014a, b);
4. Discussion of some crucial/transversal concepts both in classical physics and in modern physics, for instance the concept of state, the measurement process and the cross section concept (Corni et al. 1996),
5. Mass and energy for a dynamic approach to special relativity (Michelini et al. 2014a, b);
6. Foundations of theoretical thinking in an educational path on the fundamental concepts of quantum mechanics and its basic formalism (Ghirardi et al. 1996; Michelini et al. 2016).

In the following, we shortly describe the main kind of labs we implemented in the MP proposals with an example taken by the developed research based paths. Two case studies are then reported to exemplify the borders on experimental and theoretical approaches: the Experiment based Approach to the Phenomena Laws (EAPL) in diffraction path and the Ideal Experiment Lab (IEL) in quantum physics proposal.

The Labs in Modern Physics

In our six Modern Physics perspectives, we integrate different kinds of Laboratory activities for the specific epistemological role played in modern physics activities and for the results we obtain in developing ownership of the main concepts during research-based intervention modules. They are a sort of methodological proposal.

EAPL Lab

EAPL Lab is the Experiment based Approach to the Phenomena Laws, following the Fourier approach. Students perform a series of experiments to individuate the role of each relevant variable (quantity) in a phenomenon, looking at and manipulating the graphical representation of the data to find rules and laws. Students proceed with a gradual interpretation of the laws by means of different models. The strategies we adopted in EAPL are twofold: (a) Prevision Exploration Comparison by means of tutorials, (b) open problem solving approach: OPS, according to Watts (1991) and Banchi and Bell (2008) inviting students to plan the experimental work without any initial suggestion. The diffraction proposal presented here is a topic in which our EAPL Lab assumes the main role.

CLOE Labs

CLOE Labs—Conceptual Laboratories of Operative Exploration (CLOE) are informal learning environments where students are engaged in little groups in the analysis of mono-conceptual problems related to explanation and interpretation of phenomena. Students explore situations, perform simple experiments/observations using simple apparatus and materials, and discuss scenarios related to everyday life. They are free to use sets of materials offered to explore phenomena, discussing the processes producing them. Emerging questions produce a peer discussion. For each situation students share a partial conclusion and open a new inquiry, which is the first step for a new exploration. It is a sort of hands-on explorative lab undertaken resolved to give an answer to a question posed in a context of materials, i.e.: how are two magnets interacting? When does electromagnetic induction occur? Is levitation the same phenomenon of two suspended magnets? What does the spectrum of a LED look like? Starting from the question, students decide the problem to face and the way to explore it. An example of a CLOE Lab is provided by the way in which condensed matter techniques use basic classical physics in Time Resolved Reflectivity (TRR). The TTR technique is used to study the epitaxial growth of a sample by analyzing changes in the interference pattern of the two laser beams reflected by two interfaces when one of them is changing. In CLOE Labs, students explore the interference patterns obtained by a laser beam reflection by a two glass surfaces including variable thickness of oil and carried out analogous measurements with microwaves and laser light to measure thickness of various thin films of materials. They solve the problem and prepare an expert report. During research based CLOE sessions, the students reasoning paths on the concepts involved in the phenomenological exploration are monitored by means of audio-recording, Rogersian's interviews (Lumbelli 1997), written notes by researchers or written sentences, drawing, maps of pupils collected in open worksheets. We use qualitative research methods to analyze students reasoning data.

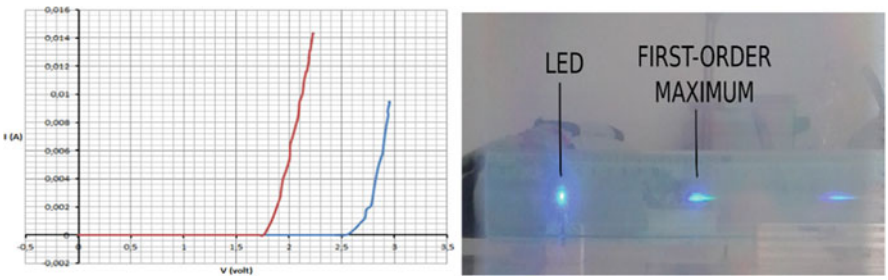

Fig. 2.1 Current-tension (I-V) characteristics curves for a red and a blue LED (left) and spectrum of a blue LED visible along a ruler (right)

CLOE-ISLE Labs

CLOE-ISLE Labs integrate CLOE in the ISLE philosophy, in which the instructor creates conditions for the students to think like a physicist and not to be afraid to throw in ideas that later might be rejected. This “mistake-rich environment” ‘is the heart of ISLE’, as reported by Eugenia Etkina (2015). We use this approach as much as we can and in particular in the Cross-section meaning exploration and in the study of electrical transport properties of solids (Gervasio and Michelini 2009b). The planning role of students is at the center of the methodological proposal. LEDs represent a unique context to develop lots of proposal (Planinšič and Etkina 2014). An interesting research based path is the following. After a study of microscopic interpretations of electrical transport properties of solids (45 students at Quadri Liceum in Vicenza, Italy) and CSL activity by means of Drude’s model (Fera et al. 2014), students faced the intellectual challenge (Viennot 2014) to interpret the emission of light by a LED to bridge from classical to quantum model (energy bands). Students planned and carried out the measurements. Characteristics V-I curves were measured for different LEDs (Fig. 2.1, left) in order to correlate the threshold voltage V to the frequency ν or the wavelength λ of the emitted light, measured with the apparatus described in Fig. 2.1 (right) which allows students to measure the dominant wavelength emitted by a LED in transmission modality.

To verify the sustainability of the simplification made in the experiments, students measured the Plank constant, obtaining the expected result within 3%. The students’ idea was presented and suggested to 32 talented students at a summer school held in Udine in 2016, who were asked to compare the emission spectra of a LED and a gas-discharge lamp, pointing out similarities and differences, and to make an hypothesis on the energetic structure of the LED and gas-discharge lamp by means of a sketch. Interesting results emerged in the data collected that suggest ways to overcome the learning difficulties in optical spectroscopy that have emerged in literature (Fera et al. 2014).

EEL Lab: Extended Explorative Lab

EEL Lab—Extended Explorative Lab is a sequence of CLOE hands-on explorative Labs following a path of reasoning to interpret phenomena and/or to individuate the nature of a quantity, as in the case of the magnetic field in the electromagnetic path (Vercellati 2010) or in the superconductivity path (Michelini et al 2014b). It is important to distinguish between a single CLOE Lab and EEL Lab, the latter having a large educational value for students in building a study method. Students experience how physicists build meanings of quantities by means of an articulated experiment. In EEL Labs the student-centered exploration of CLOE Labs builds a physics way of thinking. An example of an EEL Lab as an open sequence of CLOE Labs is the vertical path from electromagnetism to superconductivity. We build the vertical path by means of DBR, finding how the field-line approach to magnetic phenomena offers an interpretative tool for different phenomena and how electromagnetic induction can play an analogic role in explaining Meissner levitation (Vercellati 2010). Students, for example, use a compass to explore the magnetic field and ask themselves a sequence of questions planning experimental explorations, following them own ideas, as follows: how is the magnetic field distributed around a magnet? How does it change in a field line? Is it a vector? Is it like a force? Which transformation rule does it follows? We learn the students' way of thinking following how they face questions, for example in the superconductivity path where they explore the magnetic nature of a superconductor analyzing the interaction of an YBCO sample with a magnet, identifying those of ferromagnetic, paramagnetic and diamagnetic materials. The vertical path on superconductivity focuses on reasoning for interpreting phenomena (Stefanel et al. 2014) and includes IBL (hands/minds-on) CLOE explorative low and high technology LABs (Bouquet et al. 2009) by means of the experimental material bag developed in the project. The electro-magnetic approach to superconductivity from primary (Michelini and Vercellati 2012) to secondary school (Vercellati 2010) was implemented to study learning processes and reasoning of students (Stefanel et al. 2014; Michelini et al. 2014a, b).

PSL Lab

PSL Lab—Problem Solving Lab is an activity based on experiments or experimental data collection in an advanced lab. Students in PLS have to solve an interpretative problem or to find the value of a physical quantity, taking decisions on what has to be measured and how. PLS contains a relevant educational value in the way in which students assume responsibility of the experimental work, results and relative meanings. It offers methodological competencies in physics and on guidance level (Bosio et al. 1998). We experimented on this approach first for interpretation of the Mott transition with university students analyzing data collected in a cold hand system for resistivity measurement and different dopant concentration Si:As samples

(Giugliarelli et al. 1996). We experimented with many group of secondary students 16–17 years old a PSL on Rutherford Backscattering Spectroscopy (RBS), obtaining very good learning results (Corni and Michelini 2018). RBS is a widely used research analysis technique in material science based on a semi-classical data analysis and is an example of problem solving lab (PSL): students have to interpret spectra obtained in a linear accelerator system. Students discuss the basic concepts involved in the measurement and semi-classical data treatment. Spectra are in the hands of students to offers them the opportunity to: (a) Explore Rutherford historical experiment, (b) understand the role of energy and momentum conservation principles in the context of research analysis, (c) understand how microscopic structures can be studied through indirect information and measurements, (d) interpret spectra as problem solving activity. Students individuate the element(s) of the surface film, calculate the thickness of the surface film, determine the corresponding elements, atomic compositions and thicknesses of the underlying films and determine the substrate composition. We have evidence of the interest and of the orientation role of the PLS intervention module on RBS proposal (Corni and Michelini 2018).

TML Lab

TML Lab is a Traditional Measure Laboratory organized with a sequence of actions and an optimization procedure with sensitive apparatuses for the measurements of a specific quantity, as in the case of wavelength measurement of an optical spectrum of a source, such as a gas emitting lamp, by means of optic goniometer. This kind of Lab is very common in traditional physics courses, where students follow an established procedure with a dedicated apparatus gaining competence only on experimental procedure. An example of MP experiments we developed with TML is by building a prototype of Mossbauer low cost apparatus to use for physics students (Calore et al. 1990). In the case of optical spectroscopy, students measure the wavelengths using different commercial discharge lamp and an optical goniometer as in Ivanjek's work (Ivanjek et al. 2015). In our proposal on optical spectroscopy, we go over to the TML style, asking students to explore the role of gratings and those of slits.

We associated this activity with other kind of Labs here described. Our goal is to explore student reasoning on different situations (Buongiorno 2017) to individuate by means of Design Based Research intervention modules the way to overcome conceptual knots in interpreting optical spectra. Traditional Measure Lab is associated in the last 2 years intervention modules proposed in IDIFO series projects (Michelini and Santi 2008) to 670 secondary school students and Biotechnology degree freshmen (Buongiorno 2017).

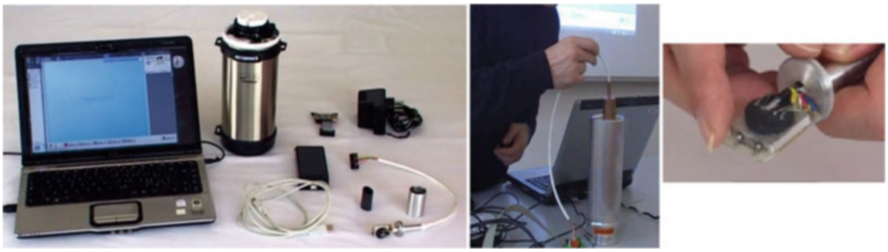

Fig. 2.2 R&H system. The set up for measurement from liquid nitrogen to room temperature: the data acquisition is via USB (top). The four probe sample connection (bottom left). The Hall coefficient measurement set-up at room temperature (bottom right)

ICT Based Lab

ICT based Lab have five different forms.

RTL

RTL—Real Time Lab by means of sensors connected to the computer to see in real-time the phenomenon and its description by plotting the relevant quantity. We have used f this approach widely for position, force, temperature, resistivity and light intensity measurements in single explorative experiments and in the six mentioned educational paths in modern physics by means of commercial systems and system developed by us, as Termocrono (Michelini and Santi 2005), Lucegrafo and R&H system (Gervasio and Michelini 2009a, b). An interesting case study we carried out is on electrical transport properties of solids. In research laboratories, the measurements of resistivity and Hall coefficient versus temperature provide information on electrical transport properties of solids and this is relevant in new materials studies. Figure 2.2 shows the RTL system we developed (Gervasio and Michelini 2009b) to provide measurements for the resistivity versus low T (70–500 K) for metals, semiconductors and superconductors, and for the Hall coefficient at room temperature for metal and semiconductors. The system collects data via USB and works as my apparatus in condensed matter research lab. Students measure the resistivity at different equilibrium temperatures and during a temperature ramp for the chosen samples, as shown in Fig. 2.3.

At room temperature they measure for metals and semiconductors the area s involved in current flux of the sample, transversal tension V_H, the magnetic field B, and the injected current I to obtain the Hall coefficient $R_H = V_H * s/(I*B) = 1/(qn)$, the sign of which indicates the kind of carrier involved. Data of resistivity ρ of the same sample are combined to obtain the mobility $\mu = R_H/\rho$ of carriers (Sconza et al. 1996). Macro-micro explanation perspectives on electrical transport properties in solids has been implemented recently in an intervention module (Fera et al. 2014).

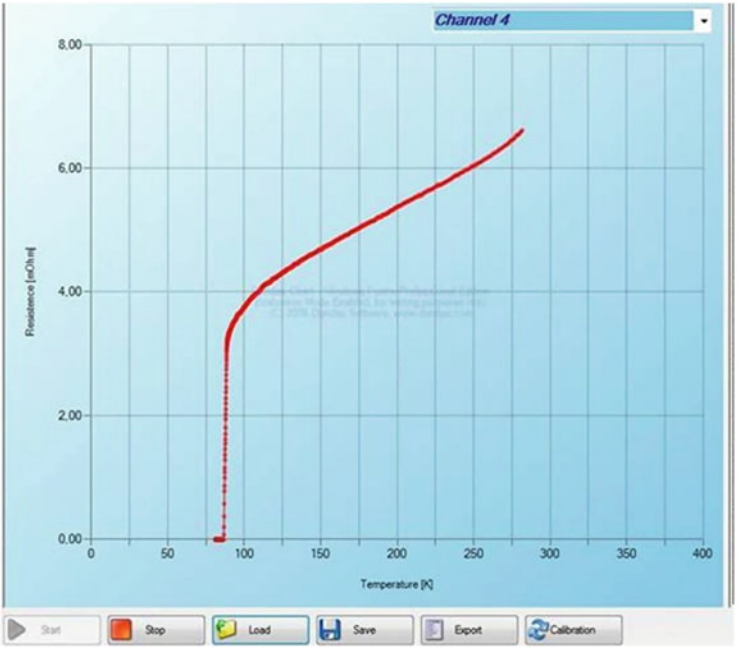

Fig. 2.3 The measure by R&H system of the resistivity versus temperature of a superconductor (YBCO)

CSL

CSL—the Conceptual Simulation Lab is an exploration of the consequence of a model by changing parameters with CLOE modality, as in the case of Huygens principle exploration (Santi et al. 1993), recently recovered in IDIFO projects (Michelini et al. 2004; Michelini and Santi 2008) to suggest ways for diffraction interpretation (Michelini and Stefanel 2015). By Visual Lab simulations (CLS) developed by Kansas University (Zollman et al. 2002), we interpret by means of energy levels the optical spectra, as well as electrical transport properties in solids and superconductivity phenomena in many research based intervention modules for secondary school.

CML

CML—Computer Modeling Lab is an open environment lab where students program the behavior of a system and look to the solutions in relationship with the iterations of list of assignments. We developed in the past two systems (SIGMA and SEQU in Italian). Many commercial systems are now available: we found integrated systems like Coach to be very useful for providing a comparison between data and interpretative models (Van den Berg et al. 2006).

IEL

IEL—Ideal Experiment Lab is an explorative activity in an open environment where students decide the context to explore, deciding the components and the setting, to explore ideal behavior, as in the case of JQM system described here in the path of quantum mechanics (Michelini and Santi 2008).

RLS

RLS—Remote Labs are Systems that comprise real devices, materials and instruments, organized for the fulfillment of experiments controlled by a remote operator (Atkan 1996). ICTs offer a wide variety of tools which, when integrated into different educational activities, help smooth the path into learning. Many remote real experiments have already been carried out through integration of software and hardware in order to set up an experiment, which is accessed remotely either through the Internet or through academic networks. The student can use the RLS to fulfil lab activities similar to the activities occurring in a traditional lab (Matarrita and Concari 2016). In this way delicate, dangerous, expensive apparatuses, like a linear accelerator or a telescope or X-ray apparatuses, become available for student experiments. Personalization and the opportunity to use the apparatus via the internet also gives a role to RLS for simple experiments and enlarges the Lab opportunity for schoolwork. Go-Lab Project created a repository gathering either virtual and remote labs which can be accessed for free by any teaching center, containing for the moment materials for STEM, but MP materials are announced (De Jong et al. 2014). We experiment with good results in modern physics the rich site of the University of Muenchen. The essential characteristics of an RLS developed by that group are the intuitive use and interactivity (operating the technical parameters), the possibility of different points of view of the ongoing experiment thanks to web cams and the quickest possible transfer of the data measured by the user. A reasonable use of sensibly chosen real experiments as remote labs allows a new form of homework and exercises, as well as project work and the execution of experiments, which usually would be a teacher's prerogative only.

Case Studies

Diffraction as Case Study of EAPL

We adopt an experiment-based approach to the phenomenon laws (EAPL) for light diffraction, chosen in the MP approach because it is a phenomenon bridging theories: its interpretation require a new interpretation of light propagation phenomena with respect to geometrical optics and in the framework of quantum mechanics, a new perspective arise to interpret quantum interference. In addition, it is a phenomenon present in many contexts around us and have a large use in research analysis. The EAPL approach offers a quantitative description of the phenomenon and opens multi-perspective paths for further exploration and interpretation.

Research literature evidenced learning knots in the interpretation of diffraction phenomena. Students for example use a geometrical model to interpret diffraction phenomena (Heron and McDermott 1998) and consider identical processes that are different (Ambrose et al. 1999). This happens in many cases when Lab work doesn't play a role in learning (ICPE-GIREP book 1978) and theory dominates teaching, when interpretative models are presented by teachers as solutions to questions not posed by and constructed by students (Greca and Moreira 2000; Etkina 2015). Interpretative models are than confused by students, as they do not have clear idea when to use each model (Rabe and Mikelskis-Seifert 2006). We have evidence on how students are motivated to look at an interpretation after that experimental work (Michelini 2010).

We decided a phenomenological approach based on an online sensor system to gain experience on how laws governing phenomena can emerge from an experimental plan and to gain ownership on the way in which experimental physics works. To offer experience of different interpretative ways used in physics for phenomena interpretation, is a second main goal of the diffraction proposal.

The EAPL proposal on the diffraction is part of an IBL educational path that integrates several ICT systems: the Lucegrafo home made system for light intensity versus position measurements (Fig. 2.4) by means of a phototransistor located on a cursor of a linear potentiometer 10 cm long. The software is self-explanatory and

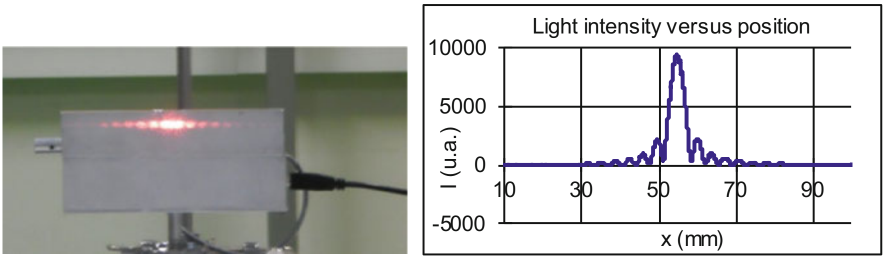

Fig. 2.4 The Lucegrafo system and light intensity pattern and data of a single slit of 0.12 mm width

plot in real time Intensity versus position values together with the table of numerical data, and a cursor (Gervasio and Michelini 2009a).

The strategies adopted in EAPL are two: (**a**) Prevision Exploration Comparison by means of tutorials, (**b**) open problem solving approach: OPS according with Watts (1991) and Banchi and Bell (2008) inviting students to plan the experimental work without any suggestion.

To focus on the relevance of diffraction we ask students to look at the wide presence of diffraction in different contexts and we examine with them different scenarios: in daily experience, in the art, in physics lab and how it establishes the resolution limits in observation of stars. We show how it is not only due to light and how diffraction by particles is relevant in research labs for condensed matter analysis techniques. Students experienced the nature of scientific work: methodological aspects as well as epistemological Nature of Science (NOS) (McComas et al. 2002). They start to look at the interplay between technology and science. The wide use of diffraction offers an example of the social role of science in medicine, biotechnology, material science and art as well as the interdisciplinary value of scientific work.

The analysis of phenomena using computer on-line sensors to construct descriptive laws is a bridge from the phenomena plane to the interpretation (Hirata 1998; Michelini 2010). Our researches, using tutorials with more than 800 secondary 17–18 year olds students, evidenced that this is not enough. We found that about 60% of students remain on a descriptive plan; about 30% attempted to explain the features, focusing only on those aspects that can be justified by geometric optics; only 10% evidenced the need for a new model (Michelini and Stefanel 2015). The path has to be completed enlarging the context of experimental work to 2–3-n slits and to a diffraction grid by CLOE-ISLE Lab in which students plan their experimental work and assume personal responsibility for the interpretation of phenomena (Buongiorno 2017). Specific software for data fitting and a modeling system (Santi et al. 1993) helps to understand the interpretative power the Huygens-Fresnel principle. The analysis of the implication on phenomenological plan of theoretical principles by means of simulations consolidate the physics vision of phenomena (Santi et al. 1993; Michelini 2010) and offer the opportunity to reflect on the role of theory and of the experiments in physics.

The Foundation of Theoretical Thinking in Quantum Mechanics as a IEL Case Study

A little clarification is necessary: physics of quanta, quantum physics and quantum mechanics are very different cultural approaches often confused. In the description of the birth of the theory of quanta (physics of quanta) the narrative treatment of the discussions on the interpretative hypothesis to the phenomena not explained by classical physics prevail over aspects relating to the subject itself and the story answers questions not posed by students or reasoning problems faced by students. The descriptive dimension, even if acceptable on popularization plan, appears NOT to be satisfactory on an educational plan. There is a need to produce the awareness of the reference assumptions of the new mechanics, to offer some indications on the formalism that is adopted: the formalism, in fact, assumes in quantum mechanics (QM) have a conceptual role.

Our proposal is on two plans: (1) Experiments that classical physics cannot interpret to focus on the problems, (2) Approaching theory of QM discussing the new ideas of theory by means of simple IEL experiments in a context.

The core of our proposal is for Quantum Mechanics (not quantum physics or physics of quanta) in secondary school, proposed in parallel with experiments. We have chosen an approach based on the theory of quantum mechanics as the first step toward a coherent interpretation with a supporting formalism, by means of an introduction to the ideas of the theory through the treatment of crucial aspects, cardinal concepts and elements peculiar to QM (Ghirardi et al. 1996). We begin with and focus on the principle of superposition and its implications. On the educational level, we have chosen in-depth discussion of specific situations in a context that allows for the polarization as a quantum property of light. The basic elements are: (1) to explore light polarization on experimental, conceptual and formal levels; (2) to discuss ideal simple experiments involving interactions of single photons with polaroid and birefringent materials (calcite crystals); (3) to describe in quantum terms by two-dimensional vector spaces the states of polarization of light (as is possible for spin). Figure 2.5 reports the rationale of the path (Michelini et al. 2016).

- Malus law is valid reducing light intensity -> polarization: property of single photon
- Exploring interaction of polarized photons (pp) with polaroid, identification of:
  - Mutually excusive properties
  - Incompatible properties and uncertainty principle
- The **state** of pp identify by a **vector** and introduction of the superposition principle **w=u+v**
- *Distinction between state (vector) and polarization property, identifyed by icons living in different spaces*
- QM **measurement** as a transition of the pp in a new state: the precipitation of the system in those measured and its genuine stocastic nature
- Interaction of pp with birifrangent crystals to understand
  - Entangled state
  - No trajectory
  - No locality
- FORMALISM -Transition probability from state **u** to state **w** as projector

$$Pt = Nt/N = \cos^2\theta = (\mathbf{u} \cdot \mathbf{w})^2$$

Fig. 2.5 QM path rationale developed by Udine research group

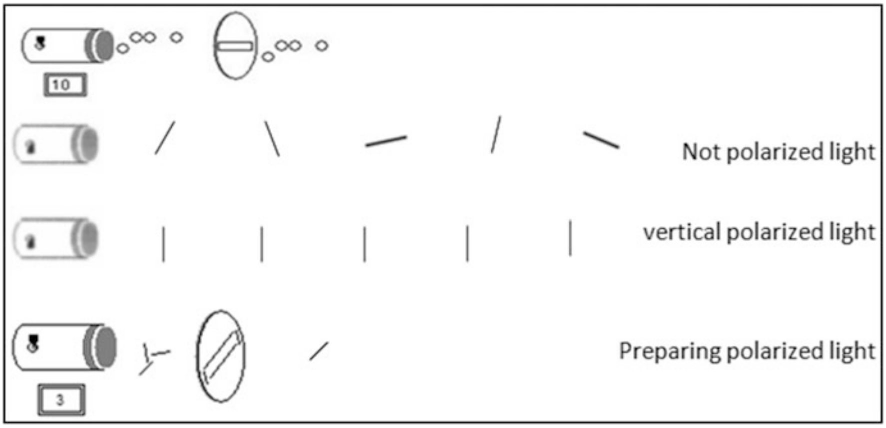

Fig. 2.6 The projector generates beams or single photons together with (or without) shown polarization direction

To introduce the phenomenology of light polarization we use Polaroid filters as explorers on an overhead projector and we leave students to explore polarization behavior with a series of stimuli questions (Michelini et al. 2008). Students become familiar with phenomenology carrying out a series of explorative ideal experiments (IEL). Assuming f light as photons, their state description is built together with quantum ideas using JQM, an open environment simulation system for ideal experiments (Michelini et al. 2014c). In JQM the photons are represented as little balls or little segments oriented according with their polarization, depending on the decision of the teacher offering the activity (Fig. 2.6). The user can set-up his experiment selecting: the photon source characteristics (producing one or more photons—user selects the number—polarized in a chosen direction or not), polarizer filters with chosen orientation, detectors, and birefringent crystals and screens.

Conclusions

In the modern physics (MP) proposals we work on, the main choices are fundamental topics (Einstein's relativity, Quantum mechanics) and reflection on the main basic concepts, such as state, measurement and cross-section, the meaning of which are changed in MP.

We pay attention to phenomena bridging theories from the classical to modern physics, such as diffraction and optical spectroscopy. Experiment based Approach to the Phenomena Laws (EAPL) in this fields helps students to gain competence in building formal descriptive relationships between quantities involved in a phenomenon and to overcome conceptual knots produced by an informative theory based teaching. The personal involvement is a requisite in the learning process and physics is an experimental subject so we implemented different kind of labs for student activities in MP. We started in this respect in 1990 developing Traditional Measure Laboratory proposal for new experiments in didactic Lab as Moessbauer and Hall effects. Research results, as well as students' and teachers' evaluation of the activities, show how students gain an understanding of the nature of the experimental work in physics when they have a personal role and how relevant for physics identity is students' personal responsibility in the link between experimental work and theoretical interpretation of a phenomenon. Starting with exploration from common contexts following the personal curiosity in small groups and sharing ideas is in particular fertile for overcoming conceptual knots and for identifying the nature of physics quantities. We invented explorative hands-on and minds-on mono-conceptual labs (CLOE) for this scope, but an inquiry-based approach builds the physics way of thinking by means of a coordinated sequence of CLOE labs in an educational path based on Extended Explorative Lab (EEL), as we had evidence in electromagnetism and superconductivity path proposal. In the research-based paths in MP we proposed two additional very formative Labs in which students assume responsibility of the experimental work: the Problem Solving Lab, as an experimental open problem solving on research data to interpret it, and the CLOE-ISLE Lab, offering to the students the opportunity to understand what physics is in an operative way. This is what we do by way of formative guidance for students (Bosio et al. 1998).

Our goal is to offer an opportunity to experience how physics research works, the role of theoretical and of experimental work and the way in which we can analyze and interpret data by means of different models. With this goal, we study educational proposals in condensed matter research techniques with a series of Lab based proposals (Corni et al. 1993, 1996; Sconza et al. 1996; Giugliarelli et al. 1996) to underline the relevance of principles and basic concepts as those of momentum and energy conservation in modern physics research work.

In our approach to modern physics, we consider it important to build a physics identity in the learners by enriching experimental experience with interpretative related hypothesis exploration and with the analysis of the implication on phenomenological plan of theoretical principles, like those of Huygens-Fresnel (Santi et al. 1993; Michelini 2010). In the last 20 years, we experimented with a series of intervention modules for curricular proposals based on explorative and personal involvement labs in an inquiry based learning environment where ICT plays important different roles, just as in the modern research context. The ICT-based Labs that we experienced comprise the following: Real Time Lab (RTL) and Remote Labs are Systems (RLS) for measurements, tools for data analysis and data fitting, Conceptual Simulation Lab (CSL) and Computer Modeling Lab (CML) for prevision and comparison of interpretative hypothesis with data, Ideal Experiment Lab (IEL) for theoretical experiments in quantum mechanics and Einstein relativity fields.

We have evidence by physics education research that student centered labs are possible and rich in educational value in a different way in MP compared with classical physics. Their formative role is dependent on the approach and its integration in a coherent conceptual path.

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Chapter 3
The Impact and Promise of Open-Source Computational Material for Physics Teaching

Wolfgang Christian

Introduction

Over the past dozen years, the Open Source Physics (OSP) project has produced some of the most widely used open source interactive computer-based curricular materials for the teaching of introductory and advanced physics courses. These materials are based on Java and JavaScript simulations called Physlets and on new OSP programs and the Easy Java/JavaScript and Tracker programming and authoring tools (Christian and Belloni 2001; Christian 2007; Gould et al. 2007; Christian et al. 2015). This paper outlines the pedagogical and technical features of the OSP project and why we introduce computational modeling into the curriculum. We describe our current effort to create and distribute new material using our tools and how we use the client-server relationship between these tools and the AAPT-ComPADRE National Science Digital Library (AAPT-ComPADRE 2018).

The paper is organized as follows. Section "Open-Source Material" presents open source examples and reasons for adopting open source curricular material. Section "AAPT-ComPADRE Digital Library" describes the resources in the ComPADRE National Science Digital Library (NSDL) and Section "Computer-Based Modeling" describes the benefits of computer modeling in the curriculum. The main features of the Open Source Physics (OSP) Collection are presented in section "Open Source Physics Collection". Section "Community Tools and Books" describes ComPADRE community tools and how they are used to produce electronic books and section "Lessons Learned" summarizes the lessons learned in implementing and teaching with open source computation based curricular material.

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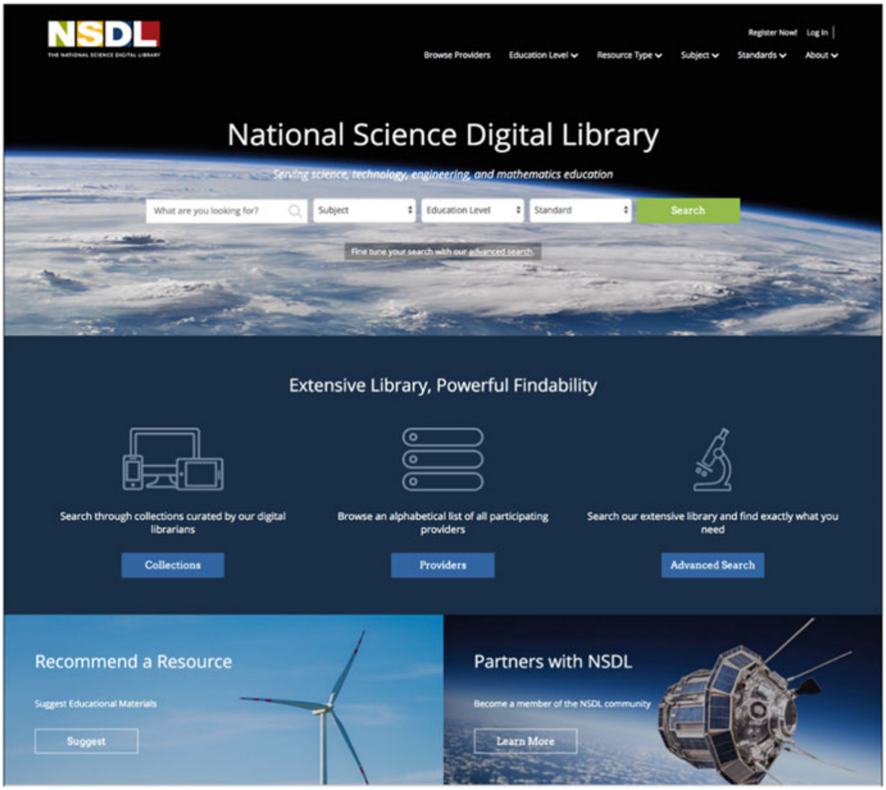

Fig. 3.1 The Open Educational Resources Commons National Science Digital Library contains structured descriptive information (metadata) about web-based educational resources held on other sites by their providers (OER Commons 2018)

Open-Source Material

The development of fast, reliable, and inexpensive internet technologies has accelerated the development and adoption of digital libraries hosting open source curricular material as shown in Fig. 3.1 and these materials have become an important resource for teachers. The following sample of non-commercial educational sites highlight the availability of open source educational resources at all levels:

- The PhET Interactive Simulations project at the University of Colorado Boulder creates free interactive math and science simulations. PhET sims are based on extensive education research and engage students through an intuitive, game-like environment where students learn through exploration and discovery (PhET 2018).
- The CK-12 Foundation provides free and fully customizable K-12 open educational resources aligned to state curriculum standards and tailored to meet student

and teacher needs (CK-12 2018). The foundation's tools are used by 38,000 schools in the US, and additional international schools.

- The Concord Consortium was founded as an educational research and development organization to create large-scale improvements in K-14 teaching and learning through technology (Concord Consortium 2018). The company conducts research on improving science, math and engineering education with the use of technology. It developed the Vernier Software and Technology probeware for classrooms and mobile computers, created modeling software for genetics and molecular education, and developed a Web-based high school.
- OpenStax is a non-profit ed-tech initiative based at Rice University (OpenStax 2018). Since 2012, OpenStax has created peer-reviewed, openly licensed textbooks, which are available in free digital formats and for a low cost in print.
- MIT OpenCourseWare is an initiative of the Massachusetts Institute of Technology (MIT) to put all of the educational materials from its undergraduate—and graduate-level courses online, freely and openly available to anyone, anywhere (OpenCourseWare 2018). MIT OpenCourseWare is a large-scale, web-based publication of MIT course materials.
- The Open Educational Resources (OER) Commons is a freely accessible online library that allows teachers and others to search and discover resources and other freely available instructional materials (OER Commons 2018).

There are many reasons for the popularity of open source material. Lower cost is an important factor but there are still costs associated with customization and implementation. Empirically, the open source approach tends to produce high quality material because many people can contribute. The number of contributors and thus the potential knowledge pool is orders of magnitude larger. Teachers have the opportunity to tap the knowledge of the world's best educators, not just those in their own school/institution. Open source curricular material promotes the sharing of ideas because teachers can it to a variety of use cases, not just the one the creator originally intended. The goal of the best open source curriculum development projects is to allow teachers to focus on high-value interactive teaching tasks because the technical development problems have already been solved.

AAPT-ComPADRE Digital Library

A Google search for pendulum returns 12 million pages while a search for "pendulum simulation" returns 31,000 pages. A search for pendulum simulation without quotes returns one million pages because the words are not required to be adjacent. Clicking on a few links shows that most pendulum simulations are inappropriate for teaching and fake the physics using animation. There is usually no instructional material, no support materials for teachers, and no information about how these materials are correlated to state or national science standards. Most of these simulations also support a passive (viewing) pedagogy versus an active (interacting) pedagogy. In order to be effective for instruction, curriculum needs to be easy to find, simple, adoptable, adaptable, and coupled with support content for students and teachers.

The ComPADRE NSDL addresses the problems of search overload by creating, hosting, and maintaining collections of educational and community resources focused on the needs of specific audiences in physics and astronomy education. Each ComPADRE collection contains a catalog of materials for teaching and learning that are selected by the editors for the target user community as shown in Fig. 3.2. The collections also provide information resources and community collaboration tools to support the needs of our users, usually in collaboration with partner physics and astronomy education projects. Collections include:

- The Physical Sciences Resource Center which provides a broad range of resources for all audiences.
- The Physics Front which provides links to high-quality lesson plans, activities, labs, and assessments for K-12 physics teachers.
- PhysPort supports faculty in using research-based teaching and assessment in their classrooms.
- The AAPT Advanced Labs collection is devoted to physics laboratories appropriate beyond the first year of university.
- The Partnership for Integration of Computation into Undergraduate Physics (PICUP) expands the role of computation in the undergraduate physics curriculum. PICUP material is available for all educational levels and for multiple computer languages.
- The Open Source Physics (OSP) project provides curriculum resources to engage students in physics, computation, and computer modeling based on Physlet books by Christian and Belloni (2001) and a computational physics book by Gould et al. (2007).

The ComPADRE NSDL provides users with standard and custom library services together with connections to other NSDLs and their users.

Computer-Based Modeling

Models allow students to think about things in terms of simpler artificial things and modeling with computers is no different. Computer models are often introduced by having students interact with an exploratory simulation that engage them in ideas presented by an expert. Students are led to confront another's view of a problem. For example, Physlets shown in Fig. 3.3 are small, flexible scriptable physics engines that help teachers teach and students learn specific physics concepts. While originally a small set of applets designed to complement the *Just-in-Time Teaching* approach (Novak et al. 1999), over time the collection grew to 32 Physlets. Because Physlets are scriptable, instructors all of over the world used Physlets to create

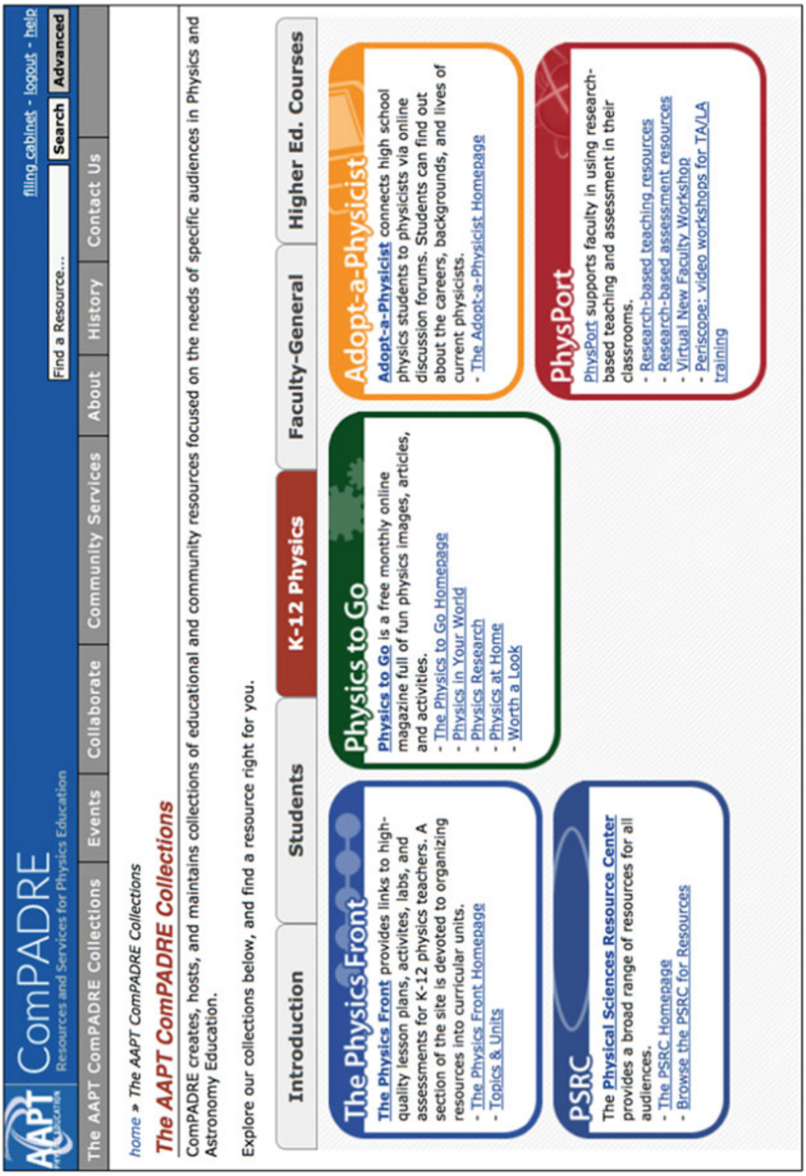

Fig. 3.2 ComPADRE creates, hosts, and maintains collections of educational and community resources focused on the needs of specific audiences in Physics and Astronomy Education. Collections for K-12 teaching for are shown (AAPT-ComPADRE 2018)

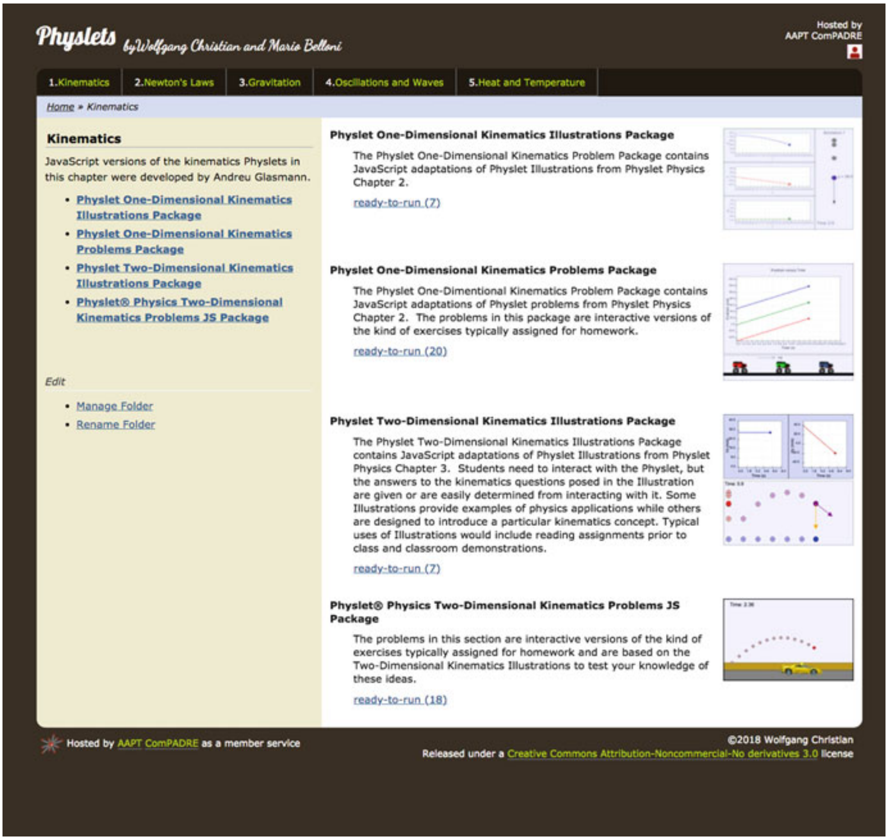

Fig. 3.3 Physlets are small easy access single concept simulations designed to simulate physical phenomena. The Third Edition of Physlet Physics uses HTML 5 and JavaScript to on both desktop computers and mobile devices (Christian and Belloni 2001)

thousands of interactive tutorials, exercises, and problems to support numerous pedagogies (Cox et al. 2005; Belloni et al. 2007).

Although the Modeling Cycle predates computers and can be used without computers, it is well suited for computational modeling if the emphasis on experiment in the original definition is replaced with simulation. Following Karplus (1981), we define the cycle as:

- Quantitative description
- Identification of variables
- Planning an experiment (simulation)
- Performing the experiment (running the simulation)
- Analysis of experiment (simulation)
- Presentation of results
- Generalization

The goal of modeling is to teach in a student-centered environment where students do not solve problems in a formula-centered way. The instruction attempts to enhance student achievement by relying on student engagement and explanation as the dynamic of learning.

At Davidson College, computational activities that require students to construct their own models are introduced after students are familiar with exploratory Physlet-based activities. These more advanced activities are expressive exercises that require students to externalize their ideas and assumptions to create concrete representations that they can reflect on. Students learn the logic of computer modeling using loops and control structures as they study the algorithms used in professional practice to build models. Using Open Source Physics tools, students are introduced to object-oriented programming concepts by using object properties and methods when they create user interfaces.

Open Source Physics Collection

The OSP Collection began with the creation of a new open-source, object-oriented Java code library that provided the input-output and graphical methods needed for example programs and exercises in the new edition of *An Introduction to Computer Simulation* Methods (Gould et al. 2007). While writing this textbook, the authors recognized the value of extending the OSP code library to make it more accessible and useful to educational software developers. As a result, the AAPT-ComPADRE OSP Collection was created to house and distribute OSP source code and to provide curriculum resources that engaged users in physics, computation, and computer modeling. The open source nature of this project encouraged collaboration with educational software developers around the world and including collaborations with Francisco Esquembre to develop the Easy Java Simulations (EJS) authoring tool (2004) and with Douglas Brown to develop the Tracker video analysis and modeling tool (Brown and Christian 2011).

Ideally, computational physics education should reflect current research and professional practice. Every student should know about computational algorithms, have a minimal level of programming experience, and be introduced to computational ways of thinking. Every physics major should engage in a computational project that provides insight and understanding that does not merely duplicate work in theoretical and experimental physics (Fig. 3.4).

Tracker

The Tracker video analysis and modeling program enables students do traditional video analysis and to overlay analytic solutions or simulations based on Newton's second law to compare a model's behavior directly with that of real-world objects

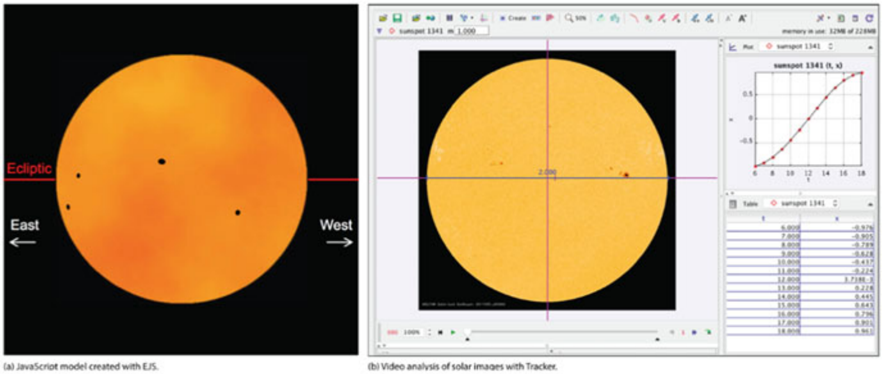

Fig. 3.4 OSP curricula materials used in the teaching of sunspots and solar rotation. (**a**) A JavaScript simulation by Todd Timberlake created using EJS and (**b**) a video analysis of a sequence of NASA photographs by Mario Belloni using Tracker

captured on video. Tracker's "model builder" provides a gentle introduction to dynamic modeling by making it easy to define and modify force expressions, parameter values and initial conditions while hiding the numerical algorithm details. Because the model synchronizes with and draws itself directly on the video, students can test their models experimentally by direct visual inspection, a process that is both intuitive and discerning.

Figure 3.5 shows a student designed experiment showing a projectile hitting a falling object. Before trying to hit the falling target in a laboratory, the students modeled it as a particle experiencing gravitational and drag forces. They then ran the model to predict the angle needed to hit the target and hit it on the first try.

Tracker has a digital library browser that connects to online libraries and downloads a catalog of Tracker-based curricular material. Clicking on a catalog item downloads it to a local computer where students do the video analysis and modeling exercise.

Teachers or students can package videos and Tracker data together with resources, such as html and pdf documentation, to create their own Tracker-based curricular packages and this material can be submitted into ComPADRE for inclusion in the NSDL.

Easy Java/JavaScript Simulations (EJS)

EJS is a free open-source programming and authoring tool developed in Java and designed to create Java or JavaScript simulations. EJS was designed for computational education and interactive learning, but it is also suitable for use by researchers to prototype applications and by authors to develop and distribute curricular

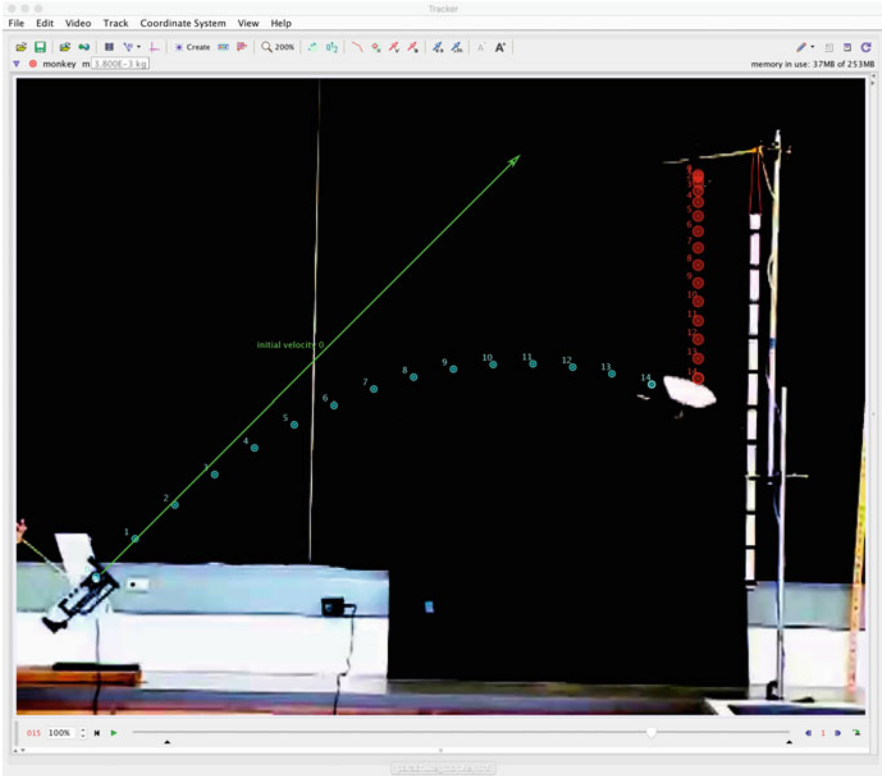

Fig. 3.5 A Tracker video modeling project created by students showing a projectile hitting a falling target

materials. Resources to learn EJS programming, such as instructional videos and textbook chapters, are available in the ComPADRE OSP Collection.

EJS divides a programming problem into three parts: the *Description*, the *Model*, and the *View*. These parts are accessed using the radio button task selectors as shown in Fig. 3.6. The Description is used to document the theory, assumptions, and the range of validity of the simulation using html-based narrative. The Model implements the phenomena of interest in terms of variables that describe the state of the system and algorithms that evolve the system. The View shows a graphical representation of the model and its data and it defines actions that a user can perform in the simulation's graphical user interface (Esquembre 2004). Traditional programming is used in the Model to initialize and evolve the system. The simulation's user interface is created in the View by dragging and dropping icons representing user interface objects, such as buttons and plots, into a hierarchical tree that is converted to Java code when the simulation is compiled.

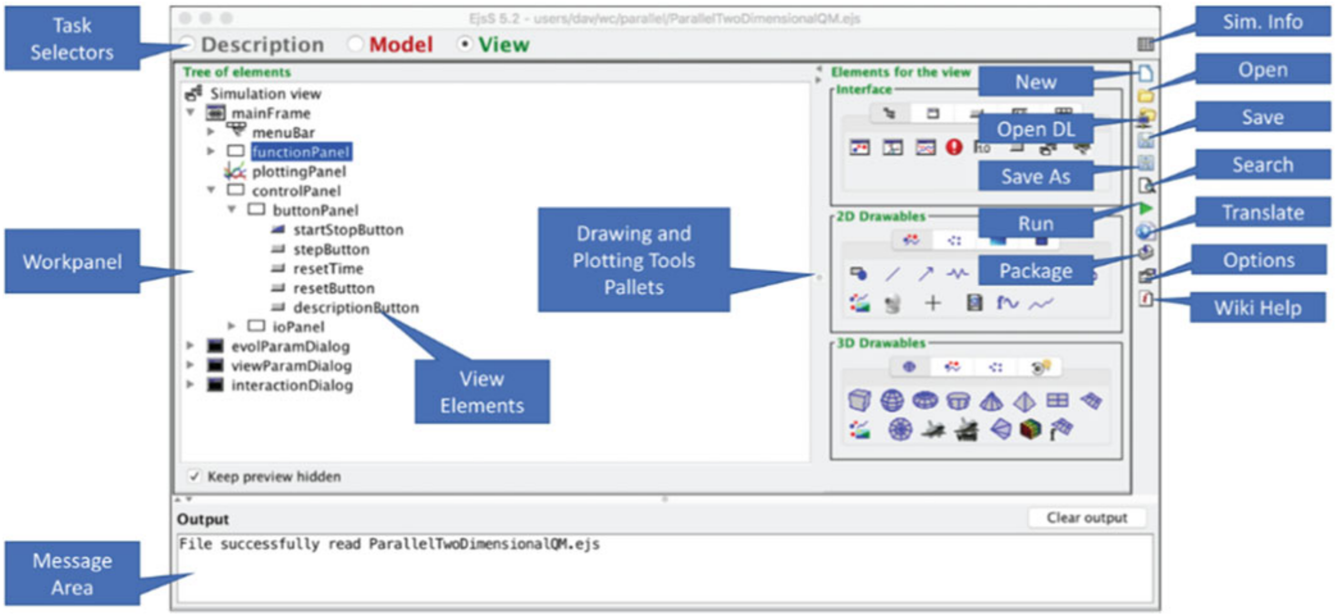

Fig. 3.6 The EJS interface showing Elements in the View, which includes palettes for user interface objects, such as Drawing and Plotting Panels. The user interface is constructed by dragging and dropping icons from pallets into the Tree of Elements

One advantage of EJS for teaching computational physics is that it forces students to separate the program into logical parts and to separate the model from the user interface. Students learn programming syntax, such as loops and control structures, while implementing algorithms used in practice. Students are also introduced to object properties and methods when they create user interfaces by dragging Elements from palettes into a view mock-up and editing their properties by clicking on icons to show object inspectors. Students can spend their time implementing computational algorithms because little user-interface coding is required.

Similar to Tracker, EJS connects to digital libraries to download source code to material into a computational workspace running EJS on a local computer. Users can examine and modify this material and repackage the compiled programs as ready-to-run programs.

Community Tools and Books

Although not every ComPADRE collection uses every feature, the digital library supports community tools, such as discussion groups and teacher authentication for access to answer keys. The OSP collection makes extensive use of filing cabinets to organize and annotate individual items into larger curricular packages. To create an OSP filing cabinet a user first identifies an item and saves it as an annotated reference in hierarchical folders linked to the user's ComPADRE account. The filing cabinet can contain links to external websites or personal documents stored in cloud accounts. AAPT members have additional privileges and can upload personal documents, such as lesson plans and student exercises. These filing cabinets can then be transformed into online books.

Figure 3.7 shows an interactive ComPADRE book by Forinash and Christian (2017) that consists of 33 interactive simulations which require the user to click buttons, move sliders, etc. in order to answer questions about the behavior of waves and sound in particular. There are also dozens of links to YouTube videos and other online resources that pertain to the topics being covered as well as suggestions for laboratory exercises and sound clips for understanding the fascinating subject of sound and music. The goal this book is to create an engaging text that integrates the strengths of printed, static textbooks and the interactive dynamics possible with simulations to engage the student in actively learning the physics of sound.

Lessons Learned

Developing computer-based curriculum material is not easy. You should work on the curriculum development from the start as you work on developing simulations. The curriculum will carry the message in the end. Focus each simulation or programming exercise on an important concept or application as too many options distract. You should pay attention to the details. A small practical problem, such as a

Fig. 3.7 ComPADRE users can collect and organizer resources in a personal collection. ComPADRE can automatically transformed these personal collections into online books

nonstandard file type of missing device driver, can ruin a lesson plan. Always remember that it is hard to do new things in front of students. You should practice with the simulation beforehand and, if you are distributing your curricular material, you should provide an answer key with screen shots of typical output so that teachers will know what results look like when parameters are set correctly. Finally, you should always remember that real curriculum change, which means changing people, takes time.

Acknowledgments The OSP project is indebted to many people. Mario Belloni (Davidson College), Anne Cox (Eckerd College), Todd Timberlake (Berry College), Harvey Gould (Clark University), Jan Tobochnik (Kalamazoo College), and Loo Kang Wee (Singapore Ministry of Education) contribute curricular material. Douglas Brown (Cabrillo College) develops Tracker and Francisco Esquembre and García Clemente (University of Murcia) develop EJS. Bruce Mason (University of Oklahoma) and Lyle Barbato (AAPT) develop and maintain the ComPADRE NSDL.

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Chapter 4
Research Validated Distance Learning Labs for Introductory Physics Using IOLab

David Sokoloff, Erik Bodegom, and Erik Jensen

Introduction

In the U.S., the demand for distance learning (DL) courses continues to grow, driven by student interest and in response to the lack of classroom availability as college and university enrollments reach record highs. Many students' work schedules limit the time they can spend on campus, and many other students live in rural areas where travel to and from campus creates a hardship. For example, an internal survey of introductory physics students at Portland State University (PSU) and at Chemeketa Community College revealed that 59% of them were also working more than 5 h/week—actually, an average of 17 h/week—while attending school.[1] Thirty percent of them would like to take a DL lab. Also, many universities have special programs for which DL learning is an imperative. For example PSU's well-received criminal justice program enrolls 150 students/year, 20% of whom are military personnel stationed overseas for whom DL delivery of the required lab-based science courses is a necessity. Online DL enrollment is increasing at ten times the rate for post-secondary education overall (Allen and Seaman 2011). Still, physics education in general, and physics laboratory education in particular, lag every other discipline in

[1]Internal data for PSU and Chemeketa students in introductory physics courses, for both day-time and evening-time classes 2013–2014 academic year, N = 411.

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online accessibility and availability (Allen and Seaman 2005). Fewer than 5% of all US institutions offering introductory physics offer even one DL laboratory (Reagan 2012).

On-campus, computer-based laboratories have been designed and implemented extensively at the college/university and secondary levels. Interfaces, probes and software for collection, graphical display and analysis of the results of real experiments have been available for Macintosh and Windows operating systems since the early 1990s.[2] These systems allow students to set data collection parameters and to adjust graphical axes before and after data collection. They include options for analyzing data, such as modeling and/or fitting. Unfortunately, their cost and relatively large equipment/supply requirements make them inappropriate for DL.

IOLab

The IOLab is a cart with wheels, incorporating built-in sensors and wireless data communication with a computer.[3] Developed by researchers at the University of Illinois, Urbana-Champaign (UIUC), IOLab replicates most of the sensors currently used in computer-based laboratory systems. It is a wireless unit (powered by two AA batteries), with a cost of around $100 USD (developed and currently distributed by MacMillan Publishers). It has a range of 30 m, communicating with a USB dongle. It rolls on three wheels, and an internal optical encoder measures displacement, velocity and acceleration. It also includes force probe, light intensity sensor, atmospheric pressure sensor, temperature sensor, microphone, speaker, 3D accelerometer, 3D magnetometer, 3D gyroscope, and more. The free IOLab software configures the device, displays data graphically in real time, and includes analysis tools including fit, statistics, and FFT. The accompanying Lesson Player allows data collection to be incorporated into a workbook, with instructions, graphs and student answers/comments displayed adjacent to each other. Lesson Player also provides for setting and saving collection parameters, as is accomplished in *RealTime Physics (RTP)* with experiment configuration files (Sokoloff et al. 2007, 2012). The low cost, self-contained IOLab device and its easy-to-use software makes DL implementation of *RTP*-like labs feasible.

Given the versatility and relatively low cost of the IOLab, it is possible in theory for students to own their own one (like a personal response device—clicker), and do hands-on laboratory, pre-lecture and homework activities at home.

Figure 4.1 shows the graphs collected when the IOLab is given a short push up an inclined ramp and released: moving up the ramp, reversing direction and then moving back down until stopped. Figure 4.2 shows these same graphs with the axes adjusted after the data are collected to display them more clearly. Applying

[2]See for example http://vernier.com, http://pasco.com

[3]http://www.iolab.science/

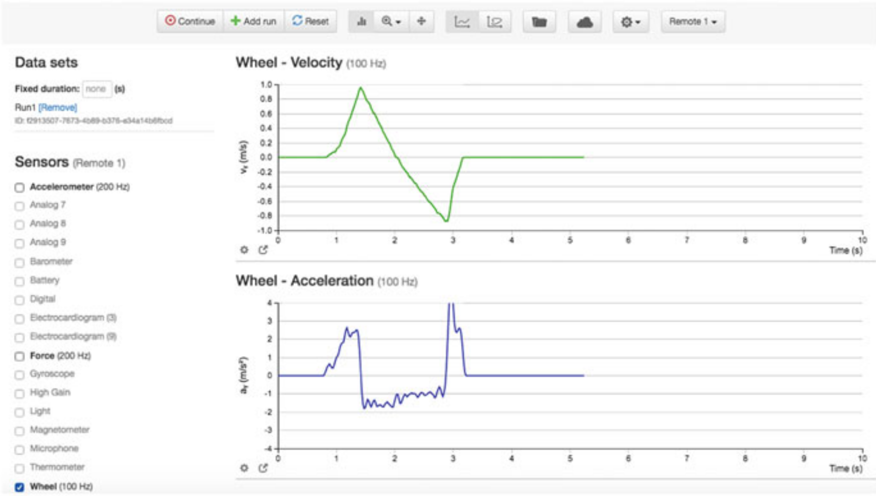

Fig. 4.1 Graphs collected with the IOLab software for the IOLab given a short push up an inclined ramp and released: moving up the ramp, reversing direction and moving back down until stopped

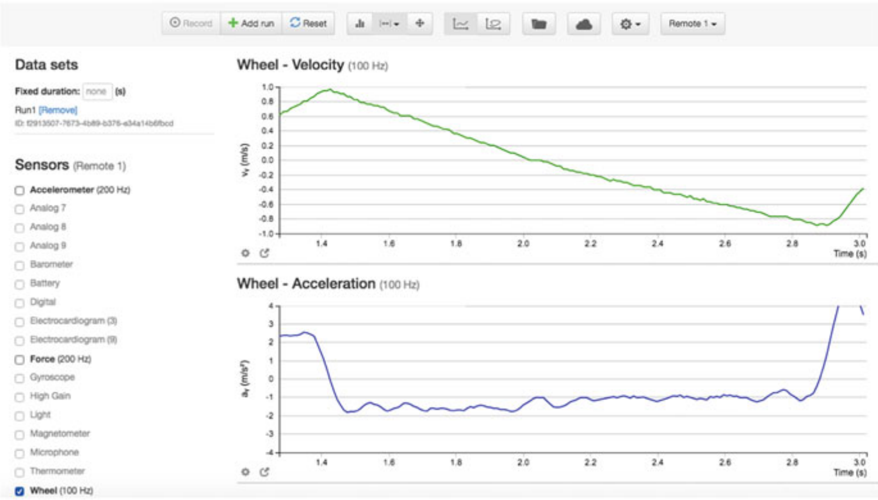

Fig. 4.2 The same data as in Fig. 4.1 with the axes adjusted to display the graphs more clearly

statistics to selected regions of the graphs shows that the acceleration is $-1.50\ \text{m/s}^2$ on the way up and $-1.05\ \text{m/s}^2$ on the way down. This is an indication of a significant amount of friction in the wheels of the IOLab, which has consequences for trying to design activities that illustrate Newton's first law.

RealTime Physics: Active Learning Labs

RealTime Physics: *Active Learning Laboratories* (*RTP)*, is a research-validated, guided inquiry, active learning laboratory curriculum, developed with significant NSF funding. It was first published by Wiley in 1994, and is in its third edition. *RTP* has been demonstrated to dramatically improve student conceptual learning (Sokoloff et al. 2007, 2012). It has been adopted by nearly 200 physics departments,[4] and many others use pre-Wiley, open-source versions or have adopted the *RTP* approach to develop their own labs.

RTP is a series of lab modules that use computer-based tools to help students develop important physics concepts while acquiring vital laboratory skills. Besides using computer probes and video analysis, computers are used for basic mathematical modeling, data analysis and some simulations. *RTP* labs use a learning cycle of prediction, observation and comparison, and have been demonstrated to enhance student learning of physics concepts. There are four modules of *RTP*: *Module 1: Mechanics, Module 2: Heat and Thermodynamics*, *Module 3: Electricity and Magnetism* and *Module 4: Light and Optics.*

The characteristics of *RTP* are:

- Help students acquire an understanding of a set of related physics concepts.
- Provide students with direct experience of the physical world by using computer-based tools for real-time data collection, display and analysis.
- Enhance traditional laboratory skills.
- Reinforce topics covered in lectures and readings using a combination of conceptual activities and quantitative experiments.
- Guide students to construct physical models based on observations of the physical world.
- Are sequenced, and build upon previous knowledge and on each other.
- Include pre-lab and homework exercises.

The current cost of the IOLab is considerably less than the typical price of an introductory physics textbook, so it is very possible for students to have their own IOLab at home, in much the way they are frequently required to purchase a clicker (personal response device). Since DL students already have computer access, we decided in 2014 to explore whether active learning curricula like *RTP* could be adapted for DL use with the IOLab.

[4]John Wiley and Sons data, July 2014.

The IOLab/RealTime Physics Distance Learning Lab Project

With NSF funding,[5] we began in 2015 a project to develop DL mechanics laboratories with the following components:

- Easy to use, inexpensive apparatus (IOLab) for use at home.
- Active learning curricula for use with this apparatus (*RTP*).
- Management system to deliver activities to students and to collect and archive their work (Lesson Player).
- Research validation of learning gains (*FMCE*).[6]
- Assessment of student experiences and attitudes (*E-CLASS*).[7]

The research questions being explored in this project are:

- Can *RTP* be adapted for use with the IOLab and in DL?
- Can significant learning gains be achieved?
- How will students perceive their learning experience?

Example of an RTP Activity Adapted to IOLab and Lesson Player

Figure 4.3 shows an activity adapted from *RTP Mechanics Lab 3* in which students first explore the possible relationship between the force applied to an object and its velocity or acceleration. Note that they are first asked to make and explain a prediction for which quantity—velocity or acceleration—is related to applied force. Figure 4.4 shows the graphs collected by the IOLab when the cart is pulled and pushed in the manner described—a rather jerky motion that emphasizes sudden changes in the graphed quantities. Note that in Lesson Player, the instructions and collected graphs are displayed adjacent to each other, on the same screen.

To assure that learning is supported by the displayed graphs, it is important to direct the students' attention to the correct portions of the graphs. Figure 4.5 shows a series of "scaffolding" questions, designed to ascertain that they know which portions of the graphs represent each portion of the motion of the IOLab. Finally, to reinforce the learning, students are asked review questions about the concepts involved in the activity. Some of these are shown in Fig. 4.6. Note that the persistence of the collected graphs on the Lesson Player screen makes it easy for students to base their answers on an examination of the real results that they have just collected from the physical world.

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[5]National Science Foundation IUSE grant, DUE – 1505086, July 1, 2015-June 30, 2017.

[6]https://www.physport.org/assessments/assessment.cfm?A=FMCE

[7]https://www.physport.org/assessments/assessment.cfm?I=56&A=ECLASS

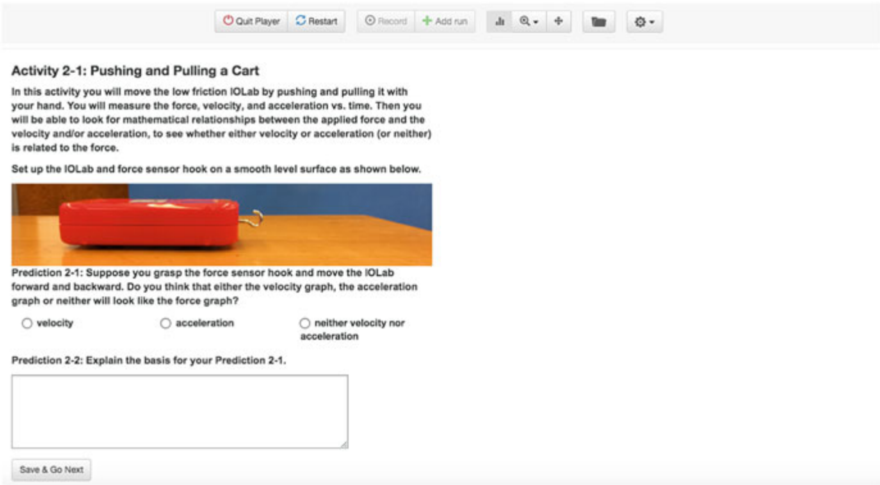

Fig. 4.3 Activity from IOLab 3 (adapted from *RTP Mechanics Lab 3*) in which the relationship between applied force and velocity or acceleration is explored. Displayed in Lesson Player. Reprinted with permission of John Wiley and Sons, Inc.

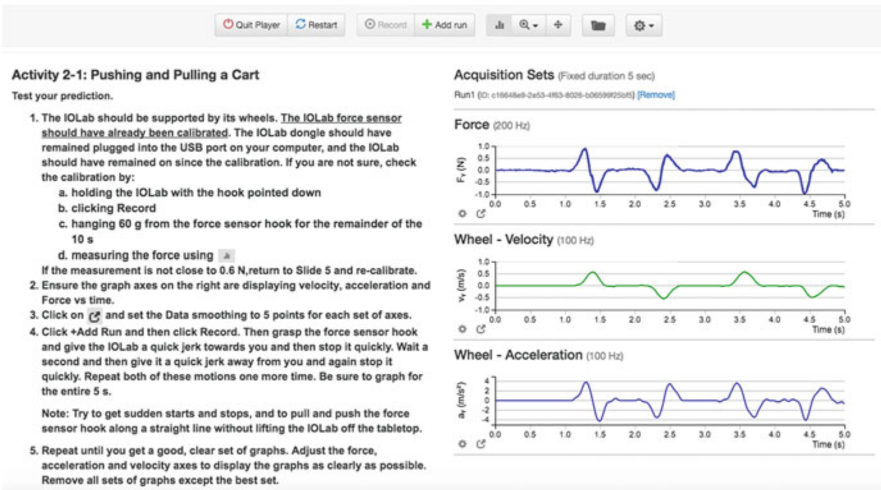

Fig. 4.4 Instructions for the activity in Fig. 4.3, with data on the same screen in Lesson Player. Reprinted with permission of John Wiley and Sons, Inc.

Nine labs that have been developed so far, largely based on *RTP* and retaining features like Prelab Preparation Sheets, Homeworks. These are:

Lab 1 Introduction to IOLab and Software
Lab 2 Introduction to Motion
Lab 3 Changing Motion

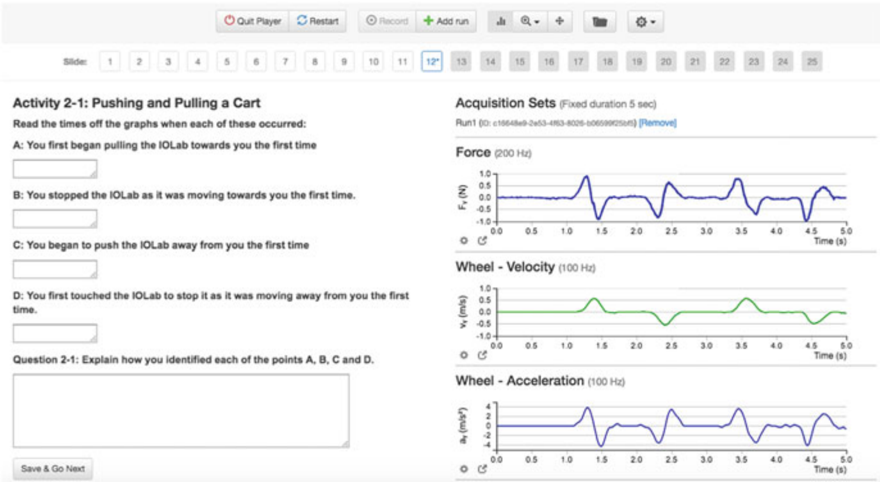

Fig. 4.5 Example of scaffolding questions to guide students in the activity in Fig. 4.3. Reprinted with permission of John Wiley and Sons, Inc.

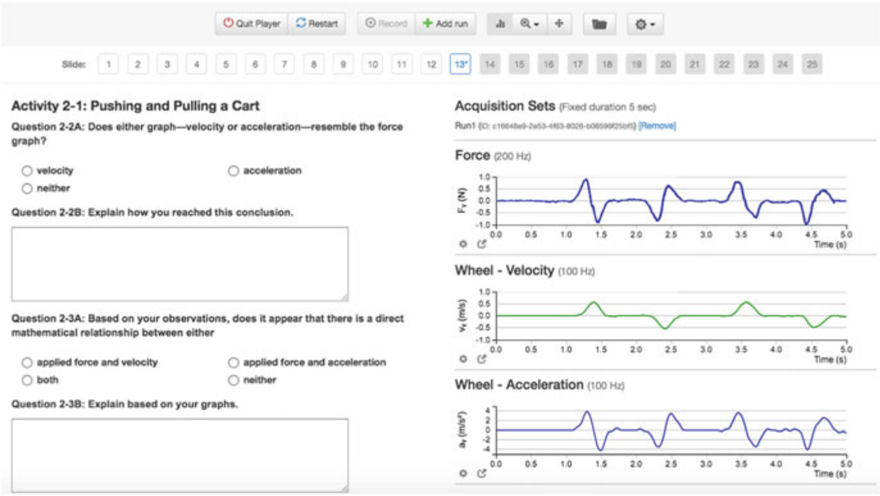

Fig. 4.6 Probing review questions to guide students to review the concepts illustrated by the activity. Reprinted with permission of John Wiley and Sons, Inc.

Lab 4 Force and Motion
Lab 5 Two-Dimensional Motion (Projectile Motion) (*Using video analysis with Tracker*.)
Lab 6 Impulse and Momentum
Lab 7 Work and Energy

Lab 8 Rotational Motion
Lab 9 Simple Harmonic Motion

Progress of the IOLab DL Lab Project

The initial round of adapting *RTP Mech*anics labs as IOLabs began in Summer, 2015. These labs were tested with students in controlled, laboratory environments at PSU (Fall, 2015) and Chemeketa (Winter, 2016). PSU is an urban, public university with a diverse and largely commuter student population. Chemeketa, a 2-year college offering associate and technical degrees, is also a commuter campus with a diverse student body. Student understanding of mechanics concepts was assessed by pre and post-testing with the *FMCE* (See next section.). In addition, we studied student graphs and lab sheets in detail. The IOLabs were then revised and optimized during Spring, 2016 based on this research evidence, and on the needs of DL.

Also, Lesson Player became available during Spring, 2016, and the labs were reformatted using Lesson Player for implementation during Summer, 2016 in the laboratory at PSU and for the first time in DL mode at Chemeketa. The *FMCE* was again administered, as was a detailed evaluation of the students' experiences on both campuses. Additional revisions were made in the IOLabs and in the IOLab software based on the *FMCE* results and observations of students' work. These revised labs were tested during Fall, 2016, this time in lab environments at Chemeketa and PSU, and in DL mode at PSU.

Where possible and appropriate, in each test of the IOLabs, we have had control groups that were doing traditional lab activities instead of the IOLabs. While the *FMCE* has been administered in each test of the labs, and the results used in fine-tuning the lab activities, the *E-CLASS* has not yet been administered. We have been waiting until the lab write-ups stabilize before assessing student attitudes using this instrument. It will be administered in the next implementations of the IOLabs during Summer, 2017.

Conceptual Learning Assessment with the FMCE

The *Force and Motion Conceptual Evaluation (FMCE)* was developed to assess students' understanding of kinematics, Newton's laws and energy concepts. It has been described in detail in the literature (Thornton and Sokoloff 1998). It is a multiple-choice test with questions constructed based on previous research using open-ended assessments and interviews. The questions are asked in a number of different forms and contexts, making it possible to examine in detail what physical models students are using to answer the questions. Because it is easy to administer, it makes possible the tracking of student progress and persistence of learning during a course.

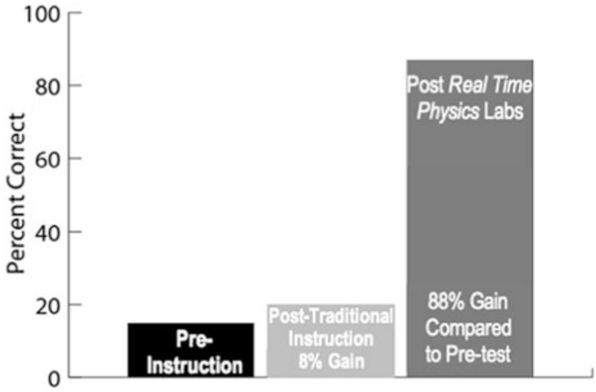

Fig. 4.7 Results on the *FMCE* at University of Oregon before instruction, after traditional instruction and after *RTP Mechanics* instruction

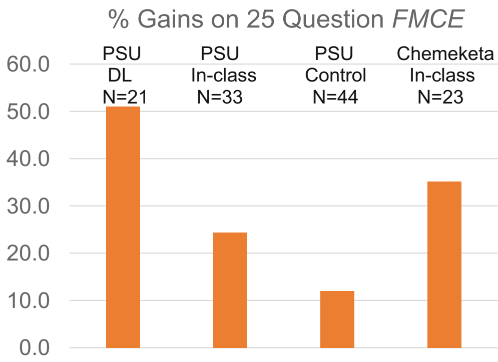

Fig. 4.8 *FMCE* results for in-class and DL implementations of IOLabs at PSU and Chemeketa, Fall, 2016

Figure 4.7 shows typical *FMCE* results for students in an introductory physics course at University of Oregon before instruction (at the beginning of the term), after traditional instruction (before *RTP* was implemented at Oregon) and after experiencing *RTP Mechanics*. Dramatic conceptual learning gains have also been observed with *RTP* at many other institutions.

Figure 4.8 shows the most recent (Fall, 2016) *FMCE* results for students doing IOLabs at PSU and Chemeketa. To facilitate administration of the *FMCE*, only a subset of 25 questions on kinematics and Newton's laws was used. The "control group" at PSU did traditional labs in class. There was no opportunity for a control group at Chemeketa.

Of note:

- Students for all three implementations of the IOLabs demonstrated larger learning gains than the control group. The control group results were similar to those for traditional instruction at other institutions (See, for example, Fig. 4.7).
- The three experimental groups at PSU were mixed among several lecture sections, with different lecture instructors. While different strategies used in lecture could affect the *FMCE* results, this would not explain the differences between these experimental groups.

- The learning gains for the PSU DL group—while not as large as for the best implementations of *RTP* (see Fig. 4.7)—were much better than traditional instruction.
- At this time, more analysis is needed to determine why the PSU and Chemeketa in-class results are not as good as the DL results. The higher in-class Chemeketa results might be explained by the use of Peer Instruction and Mastering Physics by the lecture instructor.

Overall, we are still disappointed by the learning gains, and feel that they can be improved. We are currently analyzing the results from Fall, 2016 in more detail, again examining the quality of student graphs collected with the IOLab system, and looking for patterns in student answers. We are also in the process of developing a second Newton's laws lab. Attempting to adapt the *RTP Mechanics* labs on Newton's first and third laws presents some challenges. As pointed out earlier, the friction of the IOLab cart is larger than we would like. It is large enough to preclude observations—as in *RTP Mechanics Lab 4*—in which the cart is given a short push and released, and the motion with no applied force is observed. And the highly effective observations of collisions in *RTP Mechanics Lab 9*—helping students to understand the meaning of "equal and opposite action and reaction pairs of forces" and Newton's third law—are precluded by the need for two IOLabs! We expect to have a new lab in place by the next testing of IOLabs during Summer, 2017.

Student attitudes towards the IOLabs were very positive, as indicated in the student evaluation that was administered. Figure 4.9 shows student responses on the most recent evaluations that have been analyzed, Summer, 2016 at PSU. While

PSU LAB COURSE EVALUATION
SUMMER, 2016 N=34

IOLab software is easy to use	3.9/5
IOLab device is easy to use	4.5/5
I enjoyed using the IOLab device	4.5/5
I enjoyed using the IOLab software	3.9/5
Compare perception of learning with this style of lab	4.3/5
Helped me with my conceptual understanding	4.5/5
I liked using IOLab as a tool to learn physics	4.4/5
The homework with each lab was useful	3.9/5
I have gained further insight into the physical world	4.1/5
I have learned useful concepts from the laboratory	4.2/5
The lab added to my understanding of the lectures	4.0/5
I would have rather done these labs at home	2.5/5
If you have knowledge, are IOLabs more useful than the regular labs?	17 AGREE 12 NO KNOWLEDGE 1 NEUTRAL

Fig. 4.9 Student responses on lab evaluation at PSU, Summer, 2016

ultimately results on the *E-CLASS* will be more useful in studying student attitudes towards IOLab learning, the results in Fig. 4.9 are very encouraging.

Conclusions

RTP Mechanics labs have been adapted for use with the IOLab and Lesson Player software. Preliminary conceptual learning results as measured using the *FMCE* at PSU and Chemeketa, in both lab environments and DL mode have significantly exceeded those in the control groups doing traditional lab activities, while not yet equaling those in the best implementations of *RTP*. Student attitudes toward this new style of learning have also been encouraging. We are very encouraged by the results in the first year of this project, and are pursuing a number of avenues—based on research into student graphs and responses to lab questions—that we hope will improve learning even more.

Acknowledgments We thank Mats Selen, the developer of IOLab and Geoffroy Piroux, the IOLab software developer for developing this promising educational device, and especially for being so responsive to our suggestions for hardware and software improvements. The work of Paul Ivanov, a student at Chemeketa, was invaluable in translating the IOLab activities into Lesson Player slides. Finally, this project would not be possible without the insights of David Sokoloff's co-authors, Ronald Thornton and Priscilla Laws in developing *RealTime Physics* labs. We also thank Physics Editor Jessica Fiorillo and John Wiley and Sons Publishers for their willingness to let us develop and test IOLabs based very closely on *RealTime Physics Mechanics*.

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Chapter 5
The Value of Solving Experimental Problems in Groups

David Sands

Introduction

Within the UK, a great deal of emphasis has been placed on learning outcomes as a way of defining what students should achieve, both at the modular level and at the level of the degree programme, with the former feeding into the latter. A module is passed if the learning outcomes are met, so de facto all programme learning outcomes are met if all modules are passed and it is not necessary to test outcomes separately at the degree programme level.

Learning outcomes are typically based on the QAA subject benchmark statements (QAA 2008), which say, in respect of practical skills, no more than that a typical bachelors student should:

- Possess a sound familiarity with laboratory apparatus and techniques if on experimental programmes
- Be able to execute and analyse critically the results of an experiment or investigation and draw valid conclusions.

By way of explanation of the latter, students should be able "to evaluate the level of uncertainty in their results and compare these results with expected outcomes, theoretical predictions or with published data. They should be able to evaluate the significance of their results in this context". In addition, students should also be able to "produce clear and accurate scientific reports".

Clearly, students have to work up to these attainments and this is reflected in the learning outcomes at different stages. At Hull, the learning outcomes for a first year undergraduate (HE level 4) laboratory module are at a relatively low level and include simply the ability to use laboratory equipment as well as the ability to record

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experimental data and evaluate its validity. The outcomes for the third year are intended to some extent to consolidate the outcomes attained earlier and include, for example: identify and use laboratory equipment including specialised instrumentation in a safe and appropriate manner; use appropriate methods of data analysis, including the use of appropriate software. Additional learning outcomes in the third year indicate in detail the kind of skills that students should acquire and include: reporting of investigations, working independently on a practical problem, using specialist measurement and experimental technology as well as the ability to plan, execute and report an experiment and research its background. These outcomes are needed to enable students to undertake a final year project as required by the Institute of Physics.

Satisfactory though these outcomes might appear, they are written with assessment in mind as much as the skills students should acquire. However, not all skills that students should practice lend themselves easily to assessment. For example, modern research is more often than not performed by teams who must work effectively together, discuss problems, divide labour, and implement a common solution. Ideally, students would practice these as authentic activities within the laboratory. Assessing them, however, is problematic and arguably undesirable. As with any skill, development requires practice, but the practice essential to development should not itself be assessed. The desire to achieve good grades would almost certainly skew the students' performance in some manner and the activity would then cease to be authentic. Potentially, any activity designed to assess the skills would suffer from the same deficiency.

There are some skills, therefore, that are best viewed as things that should be practiced and acquired by virtue of that practice, but the extent to which students might master them does not lend itself to prior specification in learning outcomes. In this respect the work by Zwickl et al. (2013) is especially useful. These authors have effectively defined the learning goals of the ideal laboratory under four different headings. The majority of skills identified are quite general and comprise the following.

1. Modelling:
   (a) Modelling the physical system;
   (b) Modelling the measurement system;
   (c) Statistical analysis for comparison;
2. Design:
   (a) Designing the apparatus and experiments;
   (b) Troubleshooting;
3. Technical lab skills:
   (a) Computer-aided data analysis;
   (b) Test and measurement equipment;

4. Communication:
   (a) Argumentation;
   (b) Authentic forms in physics.

These learning goals are much more comprehensive than those encompassed by the learning outcomes described earlier. In fact, they encompass pretty much all the activities that graduates will undertake in a research environment. For a number of years now, students at Hull, have been undertaking a laboratory exercise that allows them to develop to some extent every one of these activities. Especially discussion. The value of group work in helping students to develop their problem solving abilities in physics has a long history (Heller et al. 1992; Heller and Hollabaugh 1992) and at Hull we use group work as an essential aspect of solving experimental problems.

The purpose of this paper is to describe this group activity. Students work in groups of four to design, build and execute an experiment. The task lasts 8 weeks and is a development of work previously reported (Sands et al. 2008), in which students solved two different experimental problems, each lasting 4 weeks. The present task is essentially a single experiment divided into two stages with the whole activity taking between 7 and 8 weeks depending on the performance of the group.

The Experimental Problem

In designing an experimental problem to develop the skills mentioned above, it is necessary first and foremost to be clear about the aims of the laboratory session. Designing an experiment is a skill in itself, but a good experiment cannot be designed without a sound knowledge of the physics involved. For an undergraduate, this implies that the physics must be largely known or at least accessible so that the majority of the intellectual effort can be devoted to experimental considerations. For historical reasons, part of this experimental class was devoted to consolidating knowledge of operational amplifiers through their practical use, and this element has been retained. In practical terms, this has directed us towards measurements involving optical power or temperature, as these are by far the most common, and simplest, uses of operational amplifiers. Other uses, such unity gain amplifiers for measurement of very low currents, are far more specialized and without care the emphasis of the experiment becomes about this particular aspect rather than a vehicle for the development of experimental skills in general.

For this particular experiment, measurement of temperature was chosen for a number of reasons. First and foremost is the issue of authenticity. Whilst it is possible to use an op-amp to condition the signal from a photo-detector, it is not always necessary: there are perfectly good photo-detectors that will operate over a wide range of incident wavelengths and intensities with a near-linear output. To have to design an experiment that uses wavelengths or intensities such that this kind of detector is unsuitable is to constrain the design of an experiment in ways that verge on the inauthentic. On the other hand, thermocouples typically produce μV/degree K and it is readily apparent that the signal must be amplified in order to be measure on a standard digital voltmeter. For type K thermocouple, which produce approximately 41 μV/degree K, a gain of roughly a thousand is appropriate. This allows students to get to grips with building a real circuit and understanding how the operational amplifier works.

Measurement of temperature also has the advantage that an absolute measurement is required, whereas in much of optics only relative intensities are needed. This, the second reason, requires students to calibrate the thermocouple, but calibration is a concept with which many students are unfamiliar. Observation of the students undertaking this exercise over recent years has revealed that although they receive a formal course of instruction in experimental uncertainties and data analysis, many students are still struggling to grasp the significance of the ideas that have been taught to them. It has been suggested that data analysis constitutes a threshold concept (Akerlind et al. 2011): that is, an idea that takes time to understand but one which, once grasped, transforms a student's view of their subject. Our observations over the years would support that view, but it is not just data analysis that constitutes the threshold concept: it is the very notion of an experimental uncertainty and what it implies about the nature of measurement that seems to cause so much difficulty. In respect of the operational amplifier circuit in this experiment, these difficulties manifest themselves as an unjustified belief in the fidelity of the circuit to reproduce experimentally what has been calculated theoretically. Students struggle with the notion that both the input and feedback resistors have a tolerance associated with them and that, as a result, the gain might be different from the calculated value. Moreover, the existence of an offset is hardly recognised at all initially and it takes some time for the students to appreciate the need for calibration.

The third reason for choosing temperature as a measurement is linked to experimental technique. It is possible to buy digital thermometers at a reasonable price, but they are usually somewhat bulky and unsuited to situations in which a good thermal contact with the measurement probe might be difficult to achieve without drilling a suitable hole in which to insert the probe. A thermocouple wire, on the other hand, can be readily twisted together the make a junction occupying a very small volume and with a low heat capacity. As such, this junction can be used to measure temperatures more accurately than commercial thermometers. In the present experimental problem, these properties of simple thermocouple junctions are exploited to measure the temperature change in a block of metal—a piece cut from a commercially available bar of aluminium alloy of unknown composition—heated by a power resistor in order to determine the specific heat of the metal in question. The two stages of the experiment described earlier correspond to the construction, testing and calibration of a type K thermocouple-based thermometer and the use of that thermometer to measure specific heat.

In order to perform this experiment students are divided into groups of four, each of which is provided with basic components such as strip board, a TL081 op-amp, a length of type K thermocouple wire, a power resistor (15, 22 or 47 Ω), a power supply capable of delivering 2 A at 20 V, an op-amp power supply with ±15 V outputs, a selection of resistors and any other components needed to complete the circuit. In addition, students are provided with some materials, such as expanded polystyrene, to use as thermal insulation, but in the main students are expected to improvise in this respect.

Students' Performance

It will be apparent from the foregoing above that students are guided by the equipment available as to the method to employ: use the power resistor to heat the metal from the temperature rise and the total energy dissipated calculate the specific heat. However, there is no requirement to follow this method: students are left free to choose whatever method they wish within the constraints available. Some groups in the past have attempted to use a change in the temperature of a water bath following immersion of the metal, either hot metal in a cold bath or cold metal in a hot bath, but without fail all groups, on finding it difficult to control all the variables in other methods, finally adopted heating by the power resistor.

The provision of basic resources directing students towards a preferred method is pedagogically sound: discovery approaches to learning work best when the discovery is guided (Kirschner et al. 2006). There is much that the students have to discover for themselves within this method and plenty of room for individual differences in both the experimental technique and the data analysis to manifest themselves.

The approach taken by the author as laboratory supervisor is very much to guide this discovery and to use the students own actions as triggers for discussions around experimental technique. There are several identifiable trigger points for further discussion.

1. The need for calibration of the op-amp circuit thermometer. As discussed above, many students initially hold the view that the circuit will amplify perfectly according to the calculated gain and do not see the need for calibration. This allows a discussion around offsets and tolerances in the resistors.
2. The calibration itself. No doubt drawing on their experiences in school, students initially seek two fixed points for calibration corresponding to an ice/water mixture and boiling water. However, whilst there is a readily available means of producing boiling water in the form of an electric kettle, there is no means within the laboratory for maintaining water at the boiling point for long enough to calibrate the thermometer. Students are then led to the realisation that a much simpler method of calibration exists: let boiling water cool and record both the output voltage from the amplified thermocouple along with the temperature of the water. Even here, though, opportunity exists for a discussion around errors, as students are slow to realise that the thermocouple junction and the thermometer must be in close proximity if the calibration is to be effective.
3. Thermal contact between the power resistor and the metal block. The power resistor is a standard, off-the-shelf component with an aluminium cladding

designed to be affixed to a heatsink. Students are challenged about the thermal contact between the power resistor and their block of metal. This provokes a discussion about the nature of a so-called "smooth" surface and how thermal contact can be improved. Students eventually realise that a thin layer of heat sink compound applied between the resistor and the metal block is necessary to ensure a good thermal contact.

4. Thermal insulation. Many students' initial response to this task is to ask why they have 8 weeks to complete it when it seems at first sight to be a relatively simple task. However, those same students rush to an initial measurement of the specific heat that is two or three times larger than the specific heat of aluminium, which comprises by far the major component of the alloy they are measuring and therefore provides a good guide to the kind of value that might be expected. This then prompts a discussion about the thermal insulation and how students can measure how effective their insulation is. Students are prompted to the realisation that measuring the temperature as a function of time both during heating and for some time after the heating has been switched off will tell them how fast the metal is cooling and therefore whether significant heat is being lost to the surroundings.
5. Thermal conduction. The same measurements of temperature as a function of time also reveal another potential source of error: a lack of thermal equilibrium. Many groups are tempted to record the temperature as the block is heated and to use the slope of the energy input, calculated as $V.I.\Delta t$, to calculate the heat capacity. However, this takes no account of the process of heating whereby heat generated in the power resistor conducts through the resistor and into the block. By recording the temperature as a function of time, it is evident that if the thermocouple junction is placed on the outer side of the block immediately below the resistor, there is a time lag between the power to the resistor being switched off and the maximum temperature recorded. This is due to thermal conduction within the system. The maximum temperature corresponds to thermal equilibrium and is the temperature required for a given heat input.
6. Partitioning of energy between the metal block and the resistor. Once students have developed a conceptual, mental model of the heat conduction, they realise that energy is partitioned between the metal block and the resistor according to their respective heat capacities. This prompts a discussion as to how the heat energy in the resistor can be accounted for in the final calculation of the specific heat of the alloy.
7. The final result. Having measured the specific heat, students are prompted to ask whether the value is correct. This desire to compare their own findings with "correct" or accepted values is commonplace, but with this experiment there is no such value. Possibly, data on the heat capacity of this alloy is available from the suppliers but if so it has not been sought. The lack of a definite value for comparison prompts a discussion on the nature of experiment, on experimental results and uncertainties and on the justification for a given experimental finding.

Assessments

Students are assessed in three elements: a collaborative group document, a presentation and a personal reflection. The presentation is a group effort performed in front of the whole class. Students are given a maximum of 5 min to present their findings, which is intended to focus minds on the most important aspect of the group's work. The collaborative document serves essentially the same purpose as a report on the group's experiment, but rather than a report, with a formal structure comprising an abstract, introduction, method, etc., the document is more like a log book in which students are expected to record their failures as well as successes. The purpose of this document is as much to show the processes the groups have undertaken to arrive at the final result as it is to present the final method and justify the outcome based on an analysis of errors.

Nominally, each member of a group receives the same mark for the collaborative document, but as not all members of the group contribute equally over the duration of the experiment, students can comment on their peers' performance in their personal reflection. Specifically, students are asked to grade their peers' contributions and where there is agreement within the group that a member has been especially deficient, or especially productive, the grades will be adjusted according to the wishes of the group. This is not intended to be a form of peer assessment in which every mark is adjusted based on peer comments, but simply a mechanism to correct for the obvious difficulty that if all members of the group receive the same marks regardless, some students who do not attend many lab session will benefit unfairly from their peers' work.

The reflection is especially valuable for helping students to identify and articulate the skills they have learnt. Experience has shown that open ended reflection is not very productive but if students are asked a specific set of questions related to the task and the way they performed it, the answers can display a deep personal insight (Sands et al. 2008).

Discussion

As described, most of the learning goals identified by Zwickl et al. (2013) are met to some extent during this exercise. In order to design an experiment, students need not only a good understanding of the physics concepts involved, such as heat capacity and thermal conduction, but also a clear idea of how these concepts fit together in this experiment. In short, students need to create a mental model of the physical processes at work and the measurements that need to be made. However, at the stage of development of these students it is probably not possible for this model to be generated prior to the beginning of experimental work. Instead, the model is developed during the experiment, which means that a large element of trial and error and troubleshooting is occurring. In addition, the thermocouple amplifier circuits rarely work first time and troubleshooting is often required at this stage of the experiment.

In the main, students find this exercise very enjoyable, as judged by the open comments in the module evaluation questionnaires. Space does not permit a full analysis, but concentrating on the comments from last year, two themes consistently emerge: teamwork and problem solving. Those students who appreciate this exercise cite those factors, often in combination, as the most enjoyable aspects. However, not all students take this view. There are some who find the idea of working without a script quite stressful. These students are in the minority, but opinions tend to be polarised between these two views.

The benefits that students gain from this kind of work are more properly judged from the reflections. Responses vary enormously, from the specific, such as expertise in soldering, to the general, such as the need to think about every aspect of the problem, especially the possible source of errors. By way of example from one reflection chosen at random, one student described one of the things learnt as: "attempting to foresee errors or problems which could crop up . . . this obviously requires more experience but has led me to look at how professional physicist attempt this, such as why the original Michelson Morley experiment was floated on liquid mercury." If this truly reflects what has been learnt rather than what the student believes is necessary to gain marks, it is very encouraging.

Not all students benefit to the same extent, but the gains include;

- Increased confidence in their knowledge and understanding of physics arising from an authentic opportunity to discuss physics and put their knowledge to practical use;
- A real appreciation of errors and their sources;
- The need to take account of different sources of error in their modelling of the experiment and their subsequent experimental design;
- Knowledge that there is no such thing as a "right" answer and that there is only the experimental outcome and its justification in terms of the experimental design and procedure;

Conclusion

An investigative laboratory class has been described that offers students an authentic opportunity to record, explain and justify their experiment. Working in groups and guided by the laboratory supervisor in a process of discovery, students design, build and execute an experiment. In so doing, the students go some way to achieving most of the learning goals identified by Zwickl et al. (2013) for the advanced laboratory. The benefits to students include practice in modelling, design and technical labs skills and most importantly, authentic forms of communication, both within their groups and with academic staff, with the latter occurring around a number of identifiable trigger points.

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Chapter 6
Formative Assessment in Physics Teaching and Learning

Nikos Papadouris and Costas P. Constantinou

Introduction

Assessment constitutes an integral component of any educational system. It centers on the collection of evidence at multiple levels (teachers, students, schools, educational systems) and is intended to serve the purposes of accountability. Assessment can provide evidence-based insights that can support the continuous effort to better serve the overall goal of educational systems to enhance the quality of teaching and learning (National Research Council 2001).

There are multiple forms of assessment that vary depending on the purpose they are intended to serve. A common form of assessment includes the collection of information about students' achievement with the intent to assign a grade, usually at the end of instruction. Indicative examples of this include the administration of tests after the completion of individual teaching units or at the end of a semester or an entire school year. Another example includes the assessment of students through high-stake exams (e.g. university entrance examinations) to determine students' success (or failure) or rank them based on their achievement. These examples are instances of summative assessment in the sense that their purpose is to provide evidence of learning after instruction. An alternative approach to assessment involves the collection of evidence on students' learning while instruction is still underway, with the intent to influence teaching/learning and enhance its quality.

The key distinction between these two approaches to assessment is that while the former focuses on the collection of evidence of students' learning with the mere purpose of describing their performance at a specific point of time (e.g. after instruction) the latter extends beyond this in that it places emphasis on acting on

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the assessment information with the intent to actually influence the ongoing teaching/learning process and increase the likelihood of students' attaining the targeted learning goals. This latter approach is called *Formative Assessment* and it has come to receive much recognition as a powerful means of enhancing students' learning (Black and Wiliam 2009).

The present chapter focuses on formative assessment in the context of Physics teaching and learning. It sets out to convey a sense of the key characteristics of formative assessment and illustrate how it may play out in physics teaching and learning.

Formative Assessment: What Does It Involve and What Do We Know About Its Potential Effectiveness?

Formative assessment is centered on (a) the continual collection of evidence about the current state of students' learning and (b) the processes of interpreting it and acting on it to enhance teaching/learning while it is still in progress. For instance, the teacher could interpret the evidence of students' learning and respond to it by undertaking adaptations and amendments to his/her teaching plan to better address the needs of his/her students. An additional example of how the teacher might act on the assessment information includes providing students with relevant feedback to help them move towards the learning goals.

Feedback is an indispensable component of formative assessment, which is considered pivotal to its potential effectiveness (Hattie and Timperley 2007). In the context of teaching and learning, feedback can be defined as the actions resulting in students receiving information about their performance on a task. This feedback could be either formal (e.g. written feedback on a specific task completed by the students) or informal (e.g. during classroom discussions). In any case, it is important to stress that feedback needs to be formative in that it should extend beyond merely indicating performance (success/failure) to explicitly seeking to influence students' subsequent actions in a manner that could facilitate learning. For instance, it could aim at helping students appreciate the gap between their current state of learning and the desired state, as specified by the respective learning objectives. Moreover, it could indicate productive next steps that students could take to gradually bridge this gap (Sadler 1989).

In broad terms, the various approaches to formative assessment fall under two general categories: planned or spontaneous/interactive (Cowie and Bell 1999). The first category involves collecting assessment information at predefined points through specific instruments, with the purpose to gain insights into students' attainment of the respective leaning objectives. This information is reviewed and interpreted by the teacher (or another peer as in the case of peer-assessment) who then undertakes to respond to this information in ways that could facilitate teaching/learning. On the contrary, the approaches falling under the latter category (spontaneous/interactive) do not take place at clearly specified points and do not involve structured data collection. Rather, they commonly take place during student-teacher interactions and rely on informal data collection procedures. These interactions carry rich information about the current state of learning, which can be used to inform the teaching and learning processes. Even though the teacher could plan to organize classroom discussions (or discussions with smaller groups) the content of these discussions cannot be fully determined in advance since it largely evolves dynamically in the sense that it is shaped by the information exchanged between the students and the teacher. This is an inherently complicated approach to formative assessment requiring the teacher to interpret students' inputs in real time, draw inferences about their needs and make decisions as to how to respond to the students' input and how to build on those to steer the discussion in a manner that could facilitate learning (Ruiz-Primo and Furtak 2006).

There is broad consensus within the education research community about the potential effectiveness of formative assessment as a means to facilitate learning. Perhaps, the most widely cited reference in support of this claim is the review synthesis published by Black and Wiliam (1998). Black and William reviewed research publications that reported findings that could be brought to bear on the potential of formative assessment to enhance learning. The key outcome of this synthesis is that formative assessment is likely to induce substantial learning gains, whose effect size tends to be larger than the typical sizes reported in educational research studies.

Illustrating Formative Assessment in Context: The Case of the Energy Conservation Principle

This part seeks to elaborate certain essential features of formative assessment in context. In particular, it focuses on the application of a specific approach to formative assessment (i.e., provision of written feedback to the students by the teacher) in the context of a specific physics topic, i.e., the energy conservation principle. We use this as a context to illustrate three essential components of formative assessment: (a) the collection of assessment information, (b) the interpretation of this information to diagnose the current state of learning, and (c) the process of acting on this interpretation to facilitate learning. Our intention is to illustrate how these may appear in the physics classroom environment and reveal some of the intricacies involved in each. Even though the discussion is anchored to a single case we believe that it suffices to convey a broad sense of how formative assessment can play out in the physics classroom. Also, we believe that the discussion does afford generalizations beyond the scope of this single case, making it possible for readers to appreciate how formative assessment may manifest itself in physics teaching/learning more broadly.

Collecting Evidence of Students' Current State of Learning

An integral component of formative assessment is the collection of evidence to diagnose the current state of students' learning. A very common source for this information in the case of physics teaching/learning includes students' written responses to open-ended tasks. This source has been extensively employed in the field of Physics Education Research but also in various physics teaching programs (McDermott 2001). Open-ended assessment tasks typically confront students with specific phenomena or physical systems and probe them to reason about aspects of their operation using relevant concepts. An important characteristic of these tasks is that they require students to engage in qualitative conceptual reasoning, as opposed to employing quantitative, algorithmic approaches to solving standard exercises. Also, students are explicitly asked to elaborate on their reasoning so as to enable the teacher to gain insights into their thinking and discern ideas they seem to have grasped and obstacles they seem to encounter. Indicative examples of such assessment tasks include asking students to explain particular observations taking place in a specific system or formulate predictions about its temporal evolution. Key to the effectiveness of this data collection method is that the relevant systems should be unfamiliar to the students in the sense that they should not have been presented with these tasks before. Requiring students to apply, and reason with, relevant concepts in novel situations could provide a useful indication of their understanding. Another important feature that is decisive to the effectiveness of open-ended tasks as a source of assessment information is the extent to which their design and use are guided by a sound theoretical perspective as to the corresponding aspects of students' understanding they can be used to assess.

To illustrate the power of open-ended tasks as a source of assessment information let us take the example shown in Fig. 6.1. This task is intended to facilitate the collection of information about students' ability to analyze the operation of a specific system by means of the energy conservation principle. This system involves a solid rubber ball falling vertically onto a marble floor, after it had been released from a certain height (1.5 m). Students are asked to reflect on the probability associated with

A solid rubber ball is released from an initial height of 1.5 m; it falls vertically onto a marble floor and rebounds.

What is the most likely scenario regarding the maximum height at which it will rebound?

1. The ball will rebound to exactly 1.5 m.
2. The ball will rebound to a height higher than 1.5 m.
3. The ball will rebound to a height lower than 1.5 m.

If you think that any of these scenarios is impossible, state it explicitly.

Provide a detailed explanation of your reasoning.

Fig. 6.1 An open-ended task assessing students' ability to reason with the energy conservation principle is a specific physical system three scenarios about the height to which the ball will rebound (i.e., exactly 1.5 m, lower than 1.5 m or higher than 1.5 m) and offer a justification. This task is intended to assess students' understanding of a number of aspects associated with energy conservation (Papadouris et al. 2014). These include the ideas that (a) while energy conservation does not allow predicting the configuration that will be attained by a system in future times it does forbid any configuration that increases the total energy, (b) the boundaries of a system might be set to either preclude (closed system) or allow (open system) exchange of energy with its environment and this distinction enters the equation that encompasses the first law of thermodynamics, and (c) while energy is always conserved in quantity it tends to degrade in quality in terms of the ease with which it can be retrieved and taken advantage of.

A correct response to this task involves readily rejecting the possibility that the ball will rebound at a height bigger than the initial height since this would violate the energy conservation principle. Also, in responding to this task one should identify that the most likely scenario is that the ball will rebound to a lower height. There are at least two alternative justifications to support this. The first refers to an open system comprising the earth and the ball. The total amount of energy in this system will gradually decrease since there will be a transfer of energy to the environment around the system (i.e., the surrounding air). This will make it impossible for the ball to rebound to the initial height. The second justification focuses on the delineation of the boundaries of a system that would preclude any exchange of energy with its environment (a closed system) thereby ensuring that the total amount of energy stored in the system remains constant in quantity. Underpinning this second justification is the idea that the energy of the system will become distributed in more and more parts of the system and get stored in forms that cannot be easily retrieved (e.g. internal energy of the air). Both of these justifications boil down to the fact that there will be a gradual decrease in the maximum amount of energy that is available to be stored in the ball-earth system in the form of gravitational potential energy as the ball rebounds and rises in height. Finally, a complete response to this task involves acknowledging the theoretical possibility that the ball might be able to rebound to the exact same height (1.5 m) in the idealized situation that totally precludes dissipative effects (e.g., air drag and the corresponding transfer of energy to the surroundings through the process of heat).

Processing Assessment Information to Diagnose the Current State of Students' Learning

Students' responses to open-ended assessment tasks encompass important information about their current state of learning. An essential element of formative assessment involves extracting and processing this information to make sense of students' reasoning and identify where they are at with respect to the targeted learning

Table 6.1 Possible student responses and corresponding conceptual difficulties

	Interpretation of students' reasoning	
Responses	Conceptual difficulties	Productive resources
The ball will rebound to a greater height because of elasticity	This statement violates the energy conservation principle; it implies that energy can be produced. This position signals students' lack of understanding of the very essence of energy conservation	Experiential insights: interaction with trampolines. Students could be guided to contrast and compare this with the system under investigation to identify differences and reflect on the ensuing implications in terms of energy analysis
The ball will climb to a lower height because an amount of energy is consumed when the ball collides with the ground	This statement violates the energy conservation principle since it implies that energy can disappear	Something is lost during the operation of a real system and the interactions among its various parts; students could be guided to build on this intuition and revisit and refine "energy loss"
The ball will not make it to the initial height because energy conservation does not hold in this case. It only applies to ideal cases which preclude effects that consume energy, such as friction	Students tend to subscribe to the erroneous position that energy conservation only holds in ideal situations (e.g. frictionless motion) and does not apply to real, non-idealized, physical systems	The statement "the total amount of energy in the system remains constant" does not hold unconditionally Students could be guided to reconsider and delineate the boundary condition that distinguishes between the systems in which it does hold (closed systems) and those in which it does not (open systems)
The ball ought to rebound to the exact same height! Any other scenario would be violating energy conservation	This statement draws on the first law of thermodynamics largely neglecting the second law; It implies lack of understanding of the idea that while the quantity of energy in a closed system remains constant it degrades in quality	Confidence on energy conservation Students could be guided to build on this and integrate the feature of energy degradation. Thus, they could be guided to appreciate that while energy in a closed system is conserved in quantity it tends to become distributed in more and more parts of the system and degrade in quality (e.g. get stored in the air increasing its internal energy)

objectives. This might lead teachers to detect specific difficulties encountered by the students as well as productive resources they seem to possess.

Table 6.1 provides a set of hypothetical, although typical (Papadouris et al. 2014), non-valid (or, at best, incomplete) student responses to this task (first column) with the intent to illustrate the richness of the information encompassed in students' responses to open-ended assessment tasks. The second and third column of the table summarize insights that could emerge from the close examination of these responses and the interpretation of the information they carry with respect to the students' current state of learning about the energy conservation principle.

The *first* response is tantamount to violation of the energy conservation law in the sense that it allows for the interaction between the rigid floor and the rubber ball to somehow transfer energy to the system, thereby making it possible to climb higher than the initial height. Presumably, this line of reasoning might be triggered by a misleading analogy between this system and the trampoline system, with which students may have had extensive experiences. Obviously, jumping on the trampoline presents a very different situation entailing a more complicated energy analysis that would need to take into consideration energy input from chemical processes in the human body. This analogy and its limitations might serve a productive role in helping students to further develop their understanding. For instance, the teacher could invite the students to contrast and compare these two situations and reflect on the ensuing implications in terms of both, analyzing the pertinent instances of energy transfer and transformation and applying the first law of thermodynamics.

The *second* response could be stemming from students' intuition, reinforced by everyday experiences, which suggest that processes tend to stop rather than run perpetually. This might be construed by the students as a cue that energy is gradually consumed until it eventually disappears.

The *third* response conceives of energy conservation as an idealization, rather than a generalized principle. Finally, the *fourth* response reflects students' understanding of the idea that energy cannot be destroyed but also reveals their tendency to neglect the feature of energy degradation, i.e., the tendency of energy to gradually become distributed to more and more objects within the system and get stored in forms that cannot be easily retrieved and taken advantage of.

Reviewing students' responses and reflecting on their essence and the connotations they carry can offer valuable insights about the students' current state of learning with respect to the targeted learning objective(s). These responses can provide useful insights into specific difficulties encountered by the students (second column of Table 6.1). Also, they can provide information about students' productive resources that may be assumed in instruction and used as leverage points that could be built upon to help students further develop their understanding (third column of Table 6.1). For instance, while the error-prone disposition to believe that something is lost during the operation of a real system may beguile students into assuming that what is actually lost is energy it could also serve a productive role in helping students emerge with more coherent understanding. In particular, capitalizing on the students' experiences with processes in the real world which indeed tend to gradually diminish rather than run perpetually, and building on their intuition that something gets lost could provide a useful background structure for instruction. In particular, students could be guided, against this backdrop, to develop the idea of energy degradation. Thus, students could be guided to refine their intuition by making the distinction between the quantity and the quality of energy and appreciating that what actually decreases is the quality of energy (in terms of the ease with which it can be usefully retrieved) rather than its quantity.

Acting on the Interpretation of Assessment Information to Promote Students' Learning

An additional integral component of effective enactment of formative assessment in the classroom involves acting on the interpretation of the assessment information (e.g. students' conceptual difficulties and productive resources) to facilitate teaching/learning. Two possible ways of doing this involve (a) adapting the instructional planning to better respond to students' needs and (b) offering students with explicit feedback and appropriate guidance for how to move towards the learning goals.

Making Instructional Decisions to Align Teaching with Students' Actual Needs and Resources

The teacher could draw on the assessment information prior to instruction to adapt or supplement the activity sequence he/she was planning to enact so that it becomes better aligned with the needs and characteristics of the particular group of students. For instance, the teacher could take care to ensure that the students will be explicitly confronted with the specific conceptual difficulties they seem to encounter. This is important for helping students realize and appreciate limitations and weaknesses in their understanding. In addition, the teacher could make necessary arrangements in the teaching plan to ensure that the students will receive appropriate scaffolding to strengthen their understanding and overcome their conceptual difficulties in a manner that builds on their existing resources.

Offering Students Feedback for Next Steps in Their Learning Pathway

A very common approach to formative assessment involves the provision of written feedback to the students as to how to move towards the learning goals. Formative feedback explicitly seeks to help students improve their performance. This is in stark contrast to the approach commonly assumed in conventional teaching which focuses on assigning students with a grade (e.g. a numbers, symbol or verbal qualifier) that merely reflects their performance without offering any evaluative comments (Ruiz-Primo and Li 2013).

There is accumulating evidence revealing the potential of formative feedback as a means to enhance learning (Hattie and Timperley 2007). Realizing this potential, however, hinges on (at least) two critical factors. The first pertains to the characteristics of the feedback itself. The extant research literature provides indications for various characteristics that seem to contribute to the utility of feedback in terms of facilitating learning (Hattie and Timperley 2007). Indicatively, some of these characteristics refer to how this information should be expressed and communicated to the students. For instance, the feedback comments should (a) be expressed in a manner that it understandable by the students, (b) not contain an excessive amount of information that may overwhelm students, (c) be non-judgmental, and (d) be timely. Another set of characteristics refers to the substantive side of the feedback comments (i.e., the actual information they contain). Indicatively, effective formative feedback should provide information about (a) what has been achieved by the student(s) with respect to the targeted learning goals, (b) what has yet to be achieved, and (c) concrete guidance for immediate next steps that would help the student(s) make a reasonably large step towards the learning goals (Sadler 1989). Table 6.2 focuses on these three features in the context of the example of the assessment task on energy conservation. It summarizes a hypothetical student response to the assessment task with the bouncing ball (first column) and highlights key elements of formative feedback, in the context of that particular response (second column), in order to demonstrate its evaluative nature.

The second factor that holds decisive role in the effectiveness of written feedback relates to the extent to which the students genuinely engage with the process of interpreting the feedback and their readiness and ability to act on it. Feedback comments that appear powerful at face value are not likely to have any significant impact on learning unless the recipient student(s) invest the time and effort to engage with the process of interpreting and acting on them. This involves parsing the feedback comments to extract information about what they have achieved with respect to the learning objectives, what would be an appropriate next step and how they are to make it. This is a hardly trivial task and there is evidence suggesting that students often refrain from engaging with this process or fail to do so in an effective or systematic manner (Winstone et al. 2017).

Concluding Remarks

Formative assessment has received much attention as a means of improving the quality of teaching and learning in the classroom. Even though there are both, sound theoretical grounds and supporting empirical evidence that do justify the high expectations placed on the potential effectiveness of formative assessment it is important to stress that realizing this potential is a hardly trivial task that is contingent on several conditions. To recapitulate, some of the most important conditions include (a) the collection of useful assessment information through appropriate means, (b) the meaningful interpretation of the assessment information, and (c) the

Table 6.2 Example of feedback comments

Hypothetical student response	Example of corresponding formative feedback
The ball will bounce to a lower height than the initial. Energy conservation only holds in ideal situations. In a real system like this one there is friction and air drag. This means that some energy will be lost at every bounce. So, the ball will climb to lower and lower heights until all the energy is consumed and the ball will stop bouncing.	*You have stated that the energy conservation principle cannot be applied unconditionally. This is good thinking.* [Acknowledgement of what has been achieved by the student]. *However, the law of energy conservation is applicable to non-ideal systems as well. You will find it useful to consider the condition that should hold if energy is to remain constant in quantity in a specific system.* [Identification of what has yet to be achieved and what needs to be done in this direction] *You are correct to point out that friction and air resistance play a role in this system.* [Acknowledgement of what has been achieved by the student]. *However, you seem to have the intuition that something gets lost or destroyed due to friction and air drag. This statement is not valid. Your intuition is not entirely wrong; you should build on it by clarifying what "energy loss" might mean. In particular, whose energy is being lost? Is that energy consumed/destroyed or could something else be happening to it?* [Acknowledgement of what has yet to be achieved and what needs to be done in this direction]. *Below is a sequence of questions you will find useful in moving forward.* *(a) What are the parts of the system you are analyzing?* *(b)Based on these parts, is it a closed or an open system?* *(c) Does this have any implications on how you apply the energy conservation principle?* [Guidance for next steps that the students could usefully pursue in order to refine their reasoning and deepen their understanding].

process of acting on the interpretation of the assessment information to facilitate learning.

Another set of requirements to which we have alluded in this chapter include teachers and students' readiness and preparedness to meaningfully engage with the various aspects of formative assessment. Teachers are expected to be able to use appropriate means of collecting meaningful assessment information, interpret this information to diagnose the current state of students' learning and effectively act on their interpretation through appropriate means. It should be stressed that teachers should not be expected to competently enact these processes unless they receive appropriate support for this. Indicatively, this support includes participation in professional development courses and access to relevant resources such as a pool of examples of successful enactment of formative assessment in various situations. On the other hand, students should also receive explicit support and guidance for how to productively engage in formative assessment. For instance, this guidance includes promoting an assessment culture in the classroom that encourages the habit of seeking feedback and acting on it to improve (Winstone et al. 2017).

Even though these requirements do not provide an exhaustive list they do suffice to make the case that the effectiveness of formative assessment cannot be taken for granted and really tapping into its power is a rather demanding, although certainly worthwhile, undertaking. Also, they do reveal the need for additional research to further improve our understanding of the various factors that come to influence the effectiveness of formative assessment (and how) and inform attempts to usefully integrate it in teaching/learning practice.

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Part II
Experimental Lab

Chapter 7
Integrating NOS in LAB Work

Claudia Haagen-Schützenhöfer

Introduction

Laboratory based instructional practices are still regarded as one major ingredient for successful science teaching—by students as well as by teachers. These deep rooted myths about practical activities generally enhancing the quality of science teaching are however challenged by the existing empirical data (e.g. Lunetta et al. 2007; Singer et al. 2006). Though numerous goals are attributed to practical work current practical experiences mainly centre on the mastery of subject matter. Typical practical working environments involve students in following rigid procedures but fail to integrate reflection or discussion (Lunetta et al. 2007; Maltese et al. 2010; Millar and Abrahams 2009) and thus to promote conceptual understanding. Using the instructional design of 'Replication[1]' we followed another strategy. Here, the emphasis is rather put on "understanding the nature of science" and "understanding the complexity and ambiguity of empirical work" than on "enhancing mastery of subject matter" (Singer et al. 2006, p. 3).

[1]In the context of this article the term 'Replication' denotes an instructional arrangement where students repeat practical activities based on their own lab reports.

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Effectiveness of Practical Activities in Current Secondary Education

The popularity of lab work in science teaching is usually justified by the variety of goals that may be attainted. America's Lab Report (Singer et al. 2006) provides a good overview of the most prominent motives for integrating laboratory based instructional practices into science instruction:

- Enhancing mastery of subject matter;
- Developing scientific reasoning;
- Understanding the complexity and ambiguity of empirical work;
- Developing practical skills;
- Understanding the nature of science;
- Cultivating interest in science and interest in learning science; and
- Developing teamwork abilities (Singer et al. 2006, p. 3).

Even though teachers intend to attain these desirable goals, data indicate (Lunetta et al. 2007; Singer et al. 2006) that they are not successful in providing appropriate practical experiences by the kind of current learning environments:

In the majority of cases typical practical activities are just used to verify or apply rules that were already part of instruction. Instructions of practical task tend to be quite "tightly constrained" ('cookbook' or 'recipe following' practical tasks) (Millar and Abrahams 2009, p. 62) mainly focusing on procedures.

The emphasis is rather put on "manipulating equipment [than on] manipulating ideas" (Hofstein and Lunetta 2004, p. 39) which fosters the development of manipulation abilities instead of establishing solid scientific concepts. Students are trained to aim at task completion as a major goal while reflective processes and steps are neglected, since they are frequently regarded as too time consuming. Additionally, some articles (Hart et al. 2000) report that tasks proved to be rather complex and thus lead to cognitive overflow as students have to perform numerous tasks simultaneously. This situation is even deteriorated when teachers fail to explicitly articulate science learning goals for practical activities to their students (Millar and Abrahams 2009) and thus limit their practical experiences to mere task completion.

Another problem area identified by several authors (Lunetta et al. 2007; Singer et al. 2006) is lacking integration of practical activities and general instruction; they remain as isolated events. In many cases hardly any relationship is established between the experiment carried out and its theoretical background. As a consequence students lack appropriate conceptual frameworks that help to integrate the experience collected during practical work adequately (Driver 1983).

Research data reflect this chasm between intended goals and general reality of practical work. A survey of the existing research (Lunetta et al. 2007) on school laboratories and practical work yields a variety of outcomes. Disagreement among researchers about what constitutes practical work (as well as a lack of clarity about the goals of practical tasks) may cause these conflicting results. However, widespread beliefs that practical activities automatically improve students' achievement—above all the mastery of subject matter—cannot be supported empirically. Americas' Lab Report concludes that "Laboratory experiences have the potential to help students [. . .], [but] [t]he potential is not being realized today" (Singer et al. 2006, p. 9). As way out of this unsatisfying situation it suggests to follow instructional design principles (Singer et al. 2006, p. 6) that have proved successful and to conduct systematic research to guide the design of instruction integrating practical tasks.

Practical Work Aiming at Alternative Goals

Taking the outcomes of research into account we intended to design an instructional arrangement that fosters reflective processes and does not focus on the mastery of subject matter in the first place but rather on "understanding the nature of science" and "understanding the complexity and ambiguity of empirical work" (Singer et al. 2006, p. 3). We opted for this strategy based on the following empirically grounded observations:

> "While research has generally shown that laboratory work is not always a useful strategy for teaching science knowledge, this investigation has shown that it can be successfully used for other purposes" (Hart et al. 2000, p. 672).

> "Tobin and Gallagher (1987) found that science teachers rarely, if ever, exhibit behaviour that encourages students to think about the nature of scientific inquiry and the meaning and purposes for their particular investigation during laboratory activities" (Hofstein and Lunetta 2004, p. 39).

Using practical work for introducing students into the nature of science seems quite an obvious thing to do. Two issues are, however, to be considered when designing practical exercises focusing on 'The Nature of Science':

First of all, a widespread but misleading belief is that students are able to comprehend the way scientific knowledge is acquired by simply copying scientific working methods e.g. in labs. If we have a closer look, preconditions for scientists and students are quite different in the process of research; or as Tamir (1991, p. 16) puts it "little of what the student does is what the research scientist does." (Hart et al. 2000, p. 661).

Secondly, it has to be taken into account, that scientific knowledge is not simply accessible through mere observation. "Thus, observation is not a matter of passively receiving information about the world. People will see different things according to their expectations, and the theoretical frameworks they hold." (Hart et al. 2000, p. 658). So students can hardly acquire scientific knowledge by just performing practical activities. One essential prerequisite for successful research is a researcher's stable knowledge base which determines the process of observation and which functions as signpost for the integration of experience acquired through observation into already existing knowledge.

To sum it up, the mere application of practical work does not necessarily result in acquiring knowledge about 'The Nature of Science' as an implicit additional goal. Here teachers need to be first of all clear about teaching goals they desire when planning practical experiences and second they need to be concrete when communicating them to their students.

Replication: An Alternative Instructional Design for Practical Work

The main idea of the teaching concept 'Replication' was to create a laboratory scenario which supports students in better understanding the process of scientific research and in particular how subject knowledge is acquired and established within Scientific Communities. In our approach we tried to identify process components on the levels of research laboratory and school laboratory which are related. Finally we arrived at three categories to highlight, on documentation, communication and replication of research results. In our laboratory scenario students were first encouraged to reflect on these aspects while doing a lab exercise. In a second step, these three issues were transferred to the dimension of scientific research.

The Implementation of 'Replication'

The instructional approach based on the replication of experiments was tried out with two secondary school classes, in total 43 students (aged 16) in Year 10. Since a lab track[2] had been introduced for Year 9 of this secondary school, the students were quite familiar with 'conventional practical work' as described in section one of this article.

The first step of the instructional arrangement 'Replication' provided that kind of conventional practical experience the students were used to. A very usual practical activity was to serve as basis for reflective processes and discussion in later parts of this teaching concept.

The first step of 'Replication' took place shortly before the summer holidays and aimed at introducing the topic 'Oscillation'. In self-selected groups of three students conducted experiments to determine the period and the spring rate of two given springs. The set-up of the activity was quite close to what they were familiar with and to what can be classified as conventional. The students' task was to follow a traditional instruction in 'cook-book style' and to produce one written lab report per

[2]The Austrian Curricula for Physics as well as for Chemistry and Biology do not embed isolated school labs as obligatory components of instruction. Practical work is usually conducted in whole-class activities in small groups.

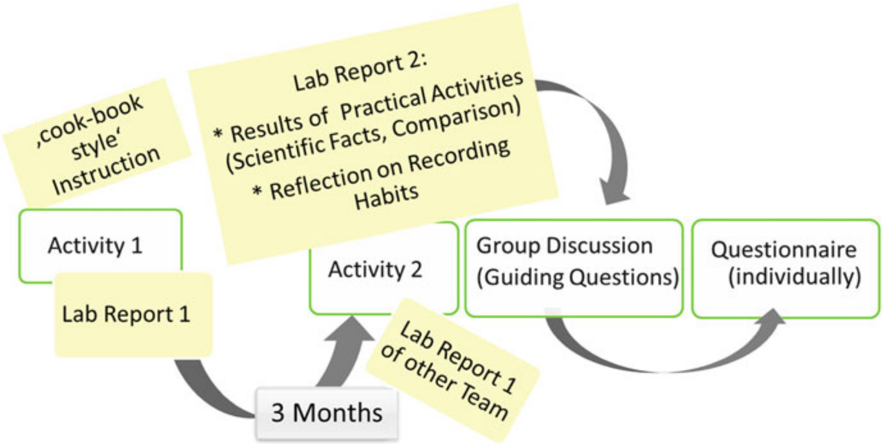

Fig. 7.1 Instructional design of 'Replication'

group. Guidelines concerning form and content of lab reports had been worked out during the physics lab they had attended the year before and the desired structure was also inherent in the given instruction:

1. Objectives of the practical activity
2. Equipment
3. Description of the setup of the experiment
4. Description of the experimental procedure
5. Data, results and discussion

After the students had conducted the experiment, the teacher collected their lab reports. The results of the activity were not discussed in class; the teacher just went on with the topic 'Oscillation' without referring to the experimental activity carried out by the students.

Nearly 3 months later, at the beginning of the next school year in autumn, the teacher introduced the topic 'Waves' by repeating the basics of 'Oscillations'. This marked the beginning of the second step of the lesson concept 'Replication' (see Fig. 7.1).

The students, now in Year 11, had to get together in the original working groups in which they had performed the 'spring experiment' 3 months earlier. Then they were provided with instructions for another practical activity. What caused surprise and amazement was, that the given instructions were their own lab reports produced earlier, during Activity 1. For what is referred to as Activity 2, the students were asked to replicate their experiments determining the period and the spring rate of the given springs, following their own lab reports. As output each group had again to write a lab report. This time the lab report was supposed to contain next to data and results of the current experiment, a comparison of results achieved in the original experiment and its replication, a short analysis of this comparison, as well as a reflection on their recording habits in the lab reports. The purpose of this

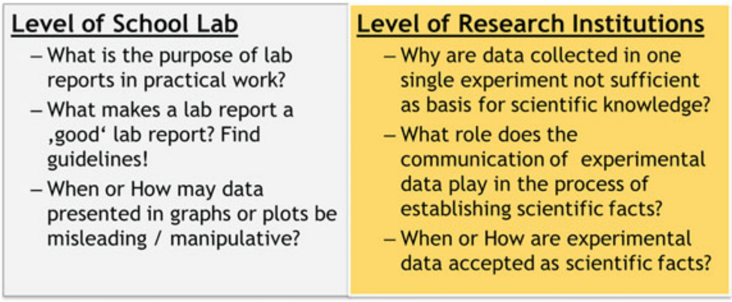

Fig. 7.2 Group discussion—guiding questions

instructional arrangement was to encourage discussions among students what their results mean and how useful the recordings in Lab Report 1 were.

After these reflections centring very much on their immediate and personal experiences, the third step (see Fig. 7.1) aimed to extend these ideas towards a broader context. Therefore a group discussion scenario, guided by key questions (see Fig. 7.2), was created. Here students were also expected to assign functions to the three process components (documentation, communication and replication) focused on. Additionally, they were encouraged to identify parallels and differences in practical work conducted in the context of schools and in the context of research institutions. Finally the students were asked to individually fill in a questionnaire on the experiences they had collected in the course of this teaching module.

Results and Discussion

For evaluating this alternative instructional approach towards practical activities three different tools served as data sources:

- Lab reports of Activity 1 and Activity 2
- Field notes of classroom observation
- Questionnaires

The analysis of the lab reports was based on an evaluation scheme developed for this purpose (Haagen-Schuetzenhoefer 2012). The three main rubrics (see Fig. 7.3) were: *Content Points Covered* [I], *Types of Information Given* [II] and *Linguistic Aspects* [III]. The first category, *Content Points Covered* [I], refers to the five sections of lab reports mentioned earlier and evaluates their elaboration. Categories two and three are based on Keys' method of analyzing lab reports (Keys 2000) and on assessment scales for writing (Tankó 2005). Each category is rated as "Given" or "Not Given". Within the section *Types of Information Given* [I], statements are categorized into five different types of information (*methodological* [I.1], *factual* [I.2], *observational* [I.3], *inferential* [I.4] and *meta-knowledge* [I.5]).

I. Content Points Given		Given	Not Given
1. Objectives:			
	a. Objectives or purpose of lab activity are defined.		
	b. The problem is stated clearly.		
2. Equipment/Materials:			
	a. All materials needed to complete the experiment are listed.		
	b. Appropriate names are used for equipment.		
a. Description of the Setup of the Experiment:			
	a. Description and/or sketch of the setup of the experiment are given.		
	b. The setup of the experiment leads to the collection of relevant data.		
b. Description of the Experimental Procedure:			
	a. Step-by-step description of how the experiment was performed is given.		
	b. Description is clear so that the experiment can be repeated.		
c. Data / Results / Discussion			
	a. Data is recorded adequately (including symbols and units).		
	b. Calculations are made based on the raw numbers.		
	c. Mistakes made while conducting the experiment are discussed.		
	d. Graphs are given.		
	e. Graphs are labeled and have a descriptive title.		
	f. A conclusion is given.		
	g. The conclusion is based on the experimental data.		
II. Types of Information		**Number of occurrences (relevant)**	**Number of occurrences (irrelevant)**
	1. Methodological		
	2. Factual		
	3. Observational		
	4. Inferential		
	5. Meta-knowledge		
III. Linguistic Aspects			
	1. Appropriate wording		
	2. Impersonal mode of expression		
	3. Expansion of primary clauses indicating logical semantic relationship between events		
	4. Words indicating explanations for events		

Fig. 7.3 Evaluation scheme for lab-reports

While the first two rubrics focus on the content level of lab reports, the third category evaluates linguistic patterns. Four *Linguistic Aspects* [III] are assessed in this rubric: *Appropriate Wording* [III.1], A*ppropriate Mode of Expression* [III.2], *Use of Expansion Strategies* [III.3] and *Occurrences of Words indicating Explanations for Events* [III.4].

The lab reports written by each group during Activity 1 were analyzed as well as those of Activity 2. Lab Report 1 indicates to which extend students are able to perform a simple experimental activity and record an appropriate documentation of it. Though this class had been used to such a type of practical tasks as well as to the production of lab reports for long, none of the lab reports of Activity 1 fully achieved the tasks set. No group was able to work out all five categories (see above) of the report entirely, although four of five categories just required copying information from the instruction, which was given on the projector. Starting with the first content category ‘Objectives of the practical activity’, it is quite irritating that several groups did not explicate any task here. These results show that most students were not aware of the purpose of this experimental activity at this stage. So it seems that they concentrated rather on following the instructions step by step than attributing a purpose to the activity.

Even worse are the results for the third category ‘Description of the setup of the experiment’. In most lab reports this was not treated at all or it was merged with the second category ‘Equipment’ and contained just a list of equipment components without further explanation or any sketches. Contrary to this, each group provided a ‘Description of the experimental procedure’, though the quality was in several cases inadequate due to two features: First of all, the use of language in the lab reports was improper for this type of text. Descriptions are frequently personalized (‘I’, ‘we’) and rather detailed, containing redundant and not relevant information (e.g. the colour of masses attached to the spring, the number of spring windings). Secondly, content points of major importance were simply not mentioned (e.g. reference point for measuring the extension of the spring). This indicates that several students had difficulties in distinguishing relevant from non-relevant aspects of this activity. Their behaviour was not goal-oriented due to the lack of obvious learning goals.

Similar findings could be obtained concerning the fifth category ‘Data, results and discussion’. This last section is rarely elaborated; most lab reports contain just tables showing readings taken in the experiment and short calculations, without hardly any interpretation of these data. Several difficulties occurred when students had to plot graphs. Axis frequently remained unlabelled and different scale sizes were chosen. So the graphs for spring one and spring two could not be compared properly and led to misinterpretations in a few groups. Generally speaking, the results of analyzing the lab reports of Activity 1 mirrors the findings of current research as discussed in the section on ‘Effectiveness of practical activities in current secondary education’.

The lab reports of Activity 2 contain by and large all categories. The section ‘Description of the setup of the experiment’ includes in the majority of cases clear descriptions or at least detailed sketches of the setup. Although some groups were still not able to use an appropriate formal register suitable for the text type ‘lab report’, the category ‘Description of the experimental procedure’ contained all essential piece of information. Labelling the axis of the graph with quantity, symbol and unit did not work in all groups, but at least one of these labelling components was used in all graphs.

Field notes taken during the group discussion (see Fig. 7.4) were meant to provide insight into reflective processes concerning our superior learning objectives

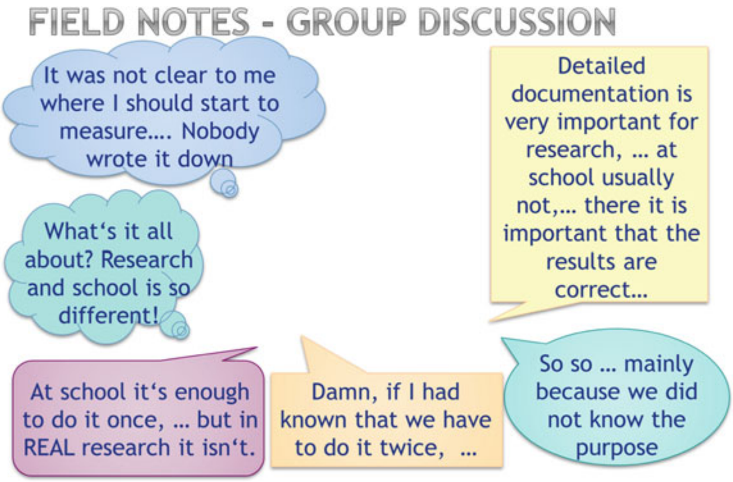

Fig. 7.4 Quotes of the group discussion

'understanding the nature of science' and 'understanding the complexity and ambiguity of empirical work'. On the whole, student negotiations and individually filled in questionnaires indicate that all groups succeeded in linking what they had been doing to the way scientists work. The extent to which individual students were able to grasp the limits of this comparison differed. Although, they had regarded repeating their own experiments as quite strange at first, most of the students finally could attribute several meaningful functions to that procedure. Here is a list of the most frequent aspects mentioned: improving one's recording habits, finding guidelines for 'good' lab reports, thinking about working methods in 'real science' or 'becoming aware of rigid routines of practical activities'. Finally it turned out that the role of discussing experimental data within a scientific community and the necessity of validation for establishing results as scientific knowledge, was quite new for most students.

Conclusion

The intended purpose of the instructional design presented was to perform a practical activity which focuses on learning goals other than 'enhancing the mastery of subject matter'. Students were engaged in reflective processes on different levels through the chosen sequence of instruction. On the one hand, we provided the experience that following rigid rituals when doing conventional practical work may be a limiting factor for the output of this practical activity. On the other hand, this lesson arrangement offered opportunities to think about certain aspects of science (documenting, communicating and verifying results and procedures from practical work).

While research generally indicates that practical work as it is currently used in teaching is not necessarily a successful strategy for enhancing scientific content knowledge, our attempt has shown that practical work may be a benefit for other purposes.

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Chapter 8
Open Inquiry Experiments in Physics Laboratory Courses

Jaap Buning, David Fokkema, Gerrit Kuik, and Tabitha Dreef

Introduction

Over the years a lot has changed with regard to the undergraduate physics laboratory courses that have been offered at the two Amsterdam universities.[1] Originally the emphasis was on skills and concepts, usually directly linked to physics topics covered in lectures. Students were given detailed instructions telling them exactly what to do, with results being totally predictable. In recent years we have shifted to open inquiry experiments. In this paper we present our ideas and the setup of our physics laboratory courses and we will pay specific attention to the way we assess students. We will illustrate our ideas with examples from a solar cell experiment.

Physics laboratory courses can roughly be divided into three types: skill lab, concept lab and process lab. In a skill lab a student develops practical scientific skills like handling equipment, working safely with a laser or being able to apply error propagation. Concept labs aim to provide students with a better understanding of physics phenomena. In a process lab a student uses skills, concepts and cognitive processes to solve (simple) problems and by means of an experiment answers a research question. The type of lab that will be implemented in a laboratory course will depend on the objectives of the specific course.

In total we run ten different physics laboratory courses for approximately 850 students each academic year. The objectives of all these physics laboratory courses are:

[1]Since 2013 the two universities in Amsterdam, the University of Amsterdam and the Vrije Universiteit Amsterdam, offer a joint Bachelor's and Master's degree in Physics.

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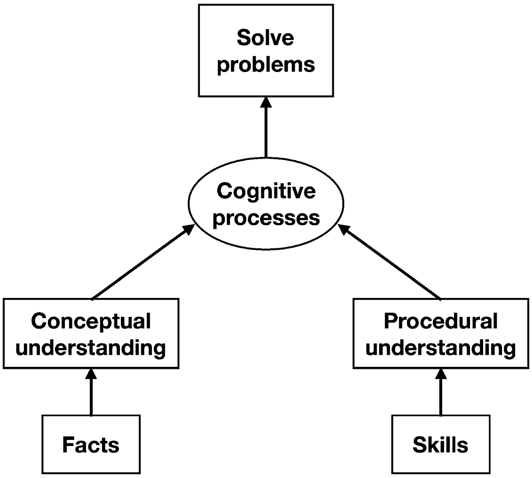


Fig. 8.1 Model in which conceptual and procedural understanding are combined to solve problems (Gott and Mashiter 1991)

- Train students in scientific reasoning skills.
- Provide students with opportunities to develop their experimental skills.
- Improve students' oral and written communication skills.
- Prepare students to conduct research in (experimental) physics.

To achieve these objectives all our physics laboratory courses are designed as process labs where students perform open inquiry experiments. In the laboratory courses students develop experimental skills, which equip them to conduct thesis work in a research group at the end of the Bachelor's programme.

Experimental Skills

In an open inquiry lab students find an answer to a research question by means of an experiment. With appropriate guidance students can develop a lot of experimental skills during the labs. Solving experimental problems does not only require conceptual understanding, but also procedural understanding (Fig. 8.1). Conceptual understanding is the understanding of ideas in science based on facts, laws and principles, while the procedural understanding is the understanding of a set of ideas, which is complementary to conceptual understanding but is related to the 'knowing how' of science and is concerned with the understanding of how to put science into practice (Gott and Duggan 1995).

Gott and Duggan (1995) developed the model shown in Fig. 8.1 by defining 'concepts of evidence'. These concepts of evidence are procedural concepts associated with design, measurement, data handling and evaluation of the whole task. In our lab courses we use their ideas, but we define experimental skills instead of concepts. Hereby we do not focus on simple experimental skills like using a ruler,

Table 8.1 Classification of experimental skills associated with different procedural concepts: design, measurement, data handling and evaluation of whole task

Design	Identifying variables (dependent, independent) Controlling variables Choosing a proper set-up Choosing sample size (in a counting experiment) Choosing variable type (discrete, continuous, derived)
Measurement	Realizing relative scale Choosing range and interval Choice of instruments Repeating measurements Taking care of accuracy
Data handling	Data analysis Using proper tables Drawing proper graphs (dependent, independent variable) Identifying patterns (linear, parabolic, exponential, …) (Statistical) error analysis
Evaluation of the whole task	Discussing reliability (can the data be trusted?) Discussing validity (has the research question been answered?)

thermometer or oscilloscope. The experimental skills we focus on are higher cognitive skills as classified in Table 8.1.

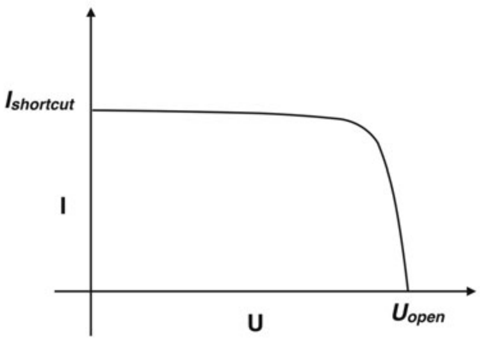
It is important to notice that it will take students several years to become a problem solving scientist. When students enter university they hardly know what scientific research is. In developing their problem solving skills they should first become aware of the specific skills they need to conduct an experiment, then they should learn what these skills are and how to use them properly and after a lot of practice they become an experienced scientist who uses knowledge and skills almost intuitively. In consecutive lab courses we guide students to develop these (experimental) problem solving skills.

Key Activities in the Open Inquiry Lab

In the design of our physics laboratory courses we focus on a number of key activities:

- Mobilize acquired knowledge;
- Relate theory to practice;
- Scientific communication.

Each of these key activities will be described more thoroughly.



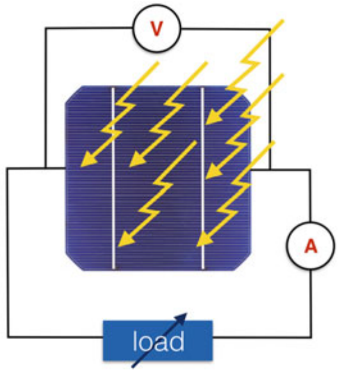


Fig. 8.2 *IU* characteristic of a solar cell with the shortcut current ($I_{shortcut}$) and the open source voltage (U_{open}) indicated (left); circuit diagram to measure current and voltage (right)

Mobilize Acquired Knowledge

During the first stage of an open inquiry experiment students orientate themselves in pairs on the assigned topic, explore the phenomenon under investigation, conduct some preliminary experiments and have discussions with other students and the lab assistant. During the discussions students are asked to clearly express their thoughts, interpret acquired physics knowledge in a meaningful way and relate concepts, laws, facts and ideas to the phenomenon they observe. All this is part of mobilizing the acquired knowledge by students.

Example A lab assistant guides five pairs of students who will conduct a solar cell experiment. The lab assistant starts with a short introduction in which students learn that a solar cell can be described by an *IU* characteristic (Fig. 8.2, left), with *I* for the current and *U* for the voltage. After the introduction students are asked to measure the *IU* characteristic for a given solar cell. Although this is a small assignment, students already need to make decisions regarding the design of the experiment (Fig. 8.3, right), e.g. which load to choose, where to place the Voltage and Amperemeter, what intensity of the light source to use? The discussion afterwards will focus on the shape of the *IU* characteristic, the meaning of the characteristic points ($I_{shortcut}$ and U_{open}) and the issues of energy and power. Because each pair of students made their own choices in the design of this experiment, differences in the *IU* characteristics can be discussed. During the discussion questions will arise about energy, power, (quantum) efficiency, dependencies of the light source and load, influence of shadow or temperature, and so on. When, for instance, the question about energy arises, students have to interpret Fig. 8.2 (left) to derive the energy from this diagram. Probably they will notice that the delivered energy is not the same for each point on the curve, and that the energy depends on the load, a hidden parameter in this diagram. To discuss this meaningfully, it is necessary for the students to

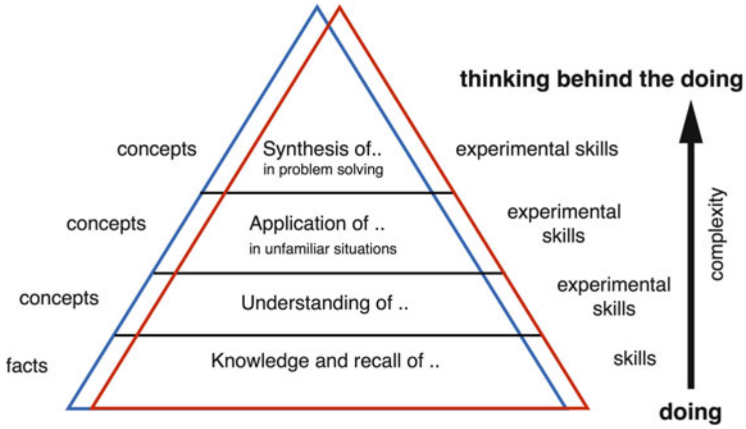


Fig. 8.3 A diagram of a conceptual taxonomy (left) and a procedural taxonomy (right) according to Gott and Duggan (1995)

mobilize their acquired knowledge. The lab assistant supports these group discussions and stimulates students to scrutinize their findings.

Relate Theory to Practice

After the orientation students choose their own research question within the boundaries of the experiment. They use multiple resources to come up with an interesting question, e.g. real life experiences (for instance an article in a newspaper about the efficiency of a solar cell partly shielded from sunlight by a cloud), prior physics courses or questions that arose during the orientation of the topic. It is important that students choose their *own* research question so they can become active learners. Students should realize they are the constructors of their own understanding. Moreover it also improves motivation.

In physics a research question can generally be described by formulating an expectation about a relation between some parameters. A qualitative expectation, e.g. the dependency of the delivered power of a solar cell on temperature, which is more a hypothesis, or a quantitative expectation, e.g. the delivered power of a solar cell as a function of the angle between illumination and the solar cell, which is more modeling, verifying if a phenomenon can be described according a theoretical model.

The next step is that the pairs of students come up with a work plan in which they justify their choices about the design, translate the research question into measurable quantities, give expectations about the results and so on. The discussion of the work plan is an important step in the whole experimental process. A pair that for instance would like to investigate the effect of different temperatures of a solar cell on the maximum power delivered by the solar cell will not get clear results if they are not careful in keeping the distance between the light source and the solar cell constant. Or, when the research question focuses on the delivered energy of a solar cell, students cannot measure the delivered energy directly. They need to understand that by measuring voltage, current and time they are able to answer their research question.

Example In the solar cell experiment students can come up with a number of research questions. One pair chose to investigate the relation of the angle between the solar cell and the beam of light versus the power delivered by a solar cell. A rather simple research question, but it turned out a bit too difficult for this pair because they refused to make a good model of their expectation. The lab assistant did not assist them with the model as the students were expected to come up with it themselves as it is fairly easy. Another pair chose to investigate the relation between the wavelength of the light and the efficiency of a solar cell. This is a more complex research question and needs some understanding of the theory that is not yet discussed in the orientation of the topic. The lab assistant gave this pair some extra help so they could come up with a good work plan.

After the discussion of the work plan preliminary measurements and analyses are undertaken, which can result in an update or even a revision of the work plan (sometimes even in a revised research question). Like in a research environment, all these first steps should be walked through thoroughly before the 'real' measurements and data analysis can take place. And even during the measurements it is important not to delay the data analysis until the end of the experiment. Analysis should start during the process of measuring so students can monitor the progress of their experiment and make small adjustments if necessary. The lab assistant will regularly discuss the results with the pairs and will help the students to confront their results with the expectation they had.

Scientific Communication

The quality of experimental research is determined by the extent the researcher is able to convince other researchers of the reliability and validity of his experimental results, and to justify in a critical dialogue with colleagues how he has conducted the experiment. Theoretical statements need to be substantiated with experimental evidence, and vice versa experimental activities need to be substantiated with theoretical considerations accounting for reliability and validity. In our view the quality of the communication in open inquiry experiments is determined by the extent a student is able to justify his activities.

Example A student performs the experiment with a partner. They communicate about the theory, the activities to be done, how to handle the equipment, the choices to be made and the observations they make. But they communicate in a rather superficial way, not inclined to be critical towards each other's statements. When the lab assistant asks them to justify a particular parameter, or how certain they are about the outcome of their measurements, or to what extent the results are consistent with their expectations, both students have no answers. The lab assistant will then encourage the students to mobilize their knowledge and will give them feedback on the quality of their communication.

Not only the verbal communication plays an important role in the scientific world, but also the written communication. Therefore, students write a report individually on every experiment performed. In the first lab course students write a draft report on the first experiment conducted, which will be provided with extensive feedback by a lab assistant. Students rewrite their draft and the final report will be assessed. On following reports students also receive extensive feedback so they can learn and improve each time they submit a new report.

The Process of Teaching and Learning

The role of the lab assistant is crucial in the process of teaching and learning in the open inquiry lab. In our view learning in the open inquiry lab is a collaborative enterprise between students and the lab assistant (Collins et al. 1989; Roth 1995). The key activities are interactive in nature. Students have to discuss the meaning of concepts, expectations and interpretations. During these discussions they externalize their understandings in a way that they are not only open to public scrutiny but also to critical introspection. The lab assistant will support this process by feedback given just-in-time, so he has to drop his 'natural' behavior to 'teach' and tell students what they need to know.

Lab assistants guide students in developing their experimental skills, but at the same time assistants assess the progress students make in order to give proper feedback. In general, lab assistants find it hard to distinguish between guidance and assessment. Concerning assessment we have to distinguish between summative and formative assessment. Summative assessment, or the grading at the end of the course, is the evaluation of students against a standard. Formative assessment, or assessment for learning, could be defined as a diagnostic tool to check whether teaching has been effective. It intends to improve the quality of learning and engages students in the problems and discourse of a given topic. Good formative assessment means that the lab assistant is able to give proper feedback. Giving feedback is commonly used to refer to information provided by teachers to students about their work.

Boud and Molloy (2013) describe two types of feedback. Feedback type 1 can be seen as a control mechanism. The teacher gathers information about the performance of a student, makes a judgement about the level of this performance and gives some information back to the student to influence the quality of subsequent work and to let the student bridge the gap between the actual level of performance and the desired level. In this kind of feedback the teacher is the one who observes, identifies, makes judgements and gives tasks to the students. The students are dependent on the teachers' activities and students do not need to be involved in their learning process, and they do not make their own judgements. Because of this the teacher is active and the student rather passive. This is not in agreement with our view of an active student, so we need another kind of feedback.

To acknowledge the active role of the learner, giving feedback should be a process used by learners that facilitates their own learning. This type of feedback is called feedback type 2 by Boud and Molloy (2013). The lab assistant accepts that students are the constructors of their own understanding. Characteristics of this type of feedback are:

- Involving students in dialogues about learning, which raise their awareness of quality performance;
- Facilitating feedback processes through which students are stimulated to develop capacities in monitoring and evaluating their own learning.

Feedback type 2 fits very well with the objectives of the open inquiry lab, where we teach students to develop independency and a critical attitude.

To organize feedback of the second kind an interactive learning environment is necessary with several opportunities for discussion with the lab assistant. Therefore a number of discussions serves as the backbone of our guidance: exploratory discussions, to explore the phenomenon and mobilize knowledge; educational conservations, to discuss the research questions of the students; workplan discussion, to discuss the design of the experiment; report discussion, to justify the results and evaluate the whole experiment.

Assessment of Experimental Skills

To assess the student's performance in an open inquiry lab you need more than only a classification like the one given in Table 8.1. Gott and Duggan (1995) also made another classification for the concepts of evidence analog to Bloom's taxonomy for knowledge. In Fig. 8.3 this classification is shown for experimental skills. All the experimental skills can be implemented at several levels, e.g. from simply drawing a graph only following the instructions in the manual to the interpretation of the graph, which will be used in the discussion about the validity of a model. Such a classification is useful to determine the level of performance of the experimental skills.

As a third factor in assessing students we use the level of guidance a lab assistant has to provide. In line with Collins et al. (1989) we define three levels of guidance:

- Modelling: strict guidance where the lab assistant acts as the expert and tells the students what to do or demonstrates how to perform a certain part of the investigation. This level of teaching is appropriate in case the concerned experimental skill is too difficult or does not have priority.

Table 8.2 Classifications used to assess experimental skills of an individual student. In assessing students three factors are at stake: nature of the task, level of complexity of the task and level of guidance

Task	Level of complexity	Level of guidance
Design	Apply skill only, without much consideration	Modeling (show by example)
Measurement	Aware of the meaning of the skill and why it is used	Scaffolding (hints)
Data handling	Application of skill in new situation	Assessing only
Evaluation of the whole task	Apply skill strategically in a complex task	

- Scaffolding: the lab assistant acts like a coach and gives open tasks or some hints.
- Assessing: the lab assistant only assesses the experimental skill concerned. This level of guiding is appropriate in case the lab assistant expects that the student already masters that particular experimental skill.

The kind of guidance students need, the classifications in Table 8.1 and Fig. 8.3 offer us a tool for the assessment of the experimental skills of an individual student. A brief overview is given in Table 8.2. The assessment tool of Table 8.2 is useful for formative assessment as well as summative assessment. For the final grading of the experimental skills all lab assistants fill out a form for each student, following the scheme of Table 8.2. For each task the level of complexity and guidance is specified along with a justification. In a meeting with all lab assistants the forms are discussed to determine the final grade for the individual students.

Example The students of the previous example, who chose a rather simple research question about the relation of the angle between a solar cell and the beam of light versus the power delivered by the solar cell, omitted to translate their question into a proper model (a cosine relation). The lab assistant chose a guidance level somewhere between assessing only and scaffolding, because the required knowledge was well known from secondary school. He only invited them to formulate a concrete expectation, but they remained on an intuitive level suggesting that the relation would be linear, without any justification. Because of this they met problems at a later stage in interpreting their results. The skill to translate a research question into a proper model is part of the design. In this case the task was simple for first year students and the guidance was given at the right level. In the end these students did not got a high grade for design. During the report discussion the lab assistant could clarify his assessment using feedback type mark 2, trying to stimulate critical introspection.

Example The other pair, who chose to investigate the relation between the wavelength of the light and the efficiency of a solar cell, needed a lot of discussion about power, energy of a photon, interpretation of the *IU* characteristic, but they succeeded to get a useful dataset and were able to give a proper interpretation of their graphs. Although the lab assistant chose for the guidance level modeling, the students fulfilled a complex task and they got a higher grade for their experimental skills. Also their performance was evaluated at the end of the experiment.

Final Remarks

In this paper we tried to give insight in ideas and the setup of our physics laboratory courses as lecturers of these courses. We intend to improve our education using insights from literature, our own experience as well as evaluations by students. In this way we have developed the approach described above. Students in this way develop not only experimental skills but also necessary academic skills from the very start when they enter university. Our physics and astronomy research groups appreciate our approach strongly because students are trained in critical thinking. In general, students find the setup of the courses motivating. Although for a number of students the open character of the course is frustrating to them. Especially in the laboratory courses at the start of the first year, students need to adjust to the way of working and they are not yet aware of the experimental skills that are needed to conduct an experiment. But the more students can bring their experimental skills into action, the more motivated they get.

Not only the education of the students is our concern, we need also educate lab assistants. Because of the intensive guidance students get while conducting an open inquiry experiment, we work with a lot of lab assistants. Each lab assistant is assigned to one experiment and supervises up to five pairs of students. Lab assistants are third year bachelor or graduate students. In the same way as students learn how to conduct an open inquiry experiment, the lab assistants should learn how to guide the students. We train lab assistants before a laboratory course, but also coach them in weekly sessions on how to guide and assess students. During the coaching also the staff uses feedback type 2. In this way lab assistants develop their didactic skills throughout a lab course. Based on student evaluations, and observations of lab assistants and staff we actively invest in improving assessment tools for experimental and academic skills, scientific report writing as well as training in group discussions and lab assistant-student interactions to improve the mobilization of knowledge among students and formulation of research questions by students. There is a continuous effort to accommodate students' need to the best we can.

Teaching complex experimental skills requires an interactive learning environment. In our view the teaching and learning process is a collaborative enterprise, where student, lab assistant and staff are all learners. We think that with the design presented in this paper we are able to let students successfully develop their experimental skills with open inquiry experiments in physics laboratory courses.

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Chapter 9
Educational Lab on Optical Diffraction to Bridge from Classical to Modern Physics

Marisa Michelini, Daniele Buongiorno, and Alberto Stefanel

Introduction

Optical diffraction offers an important disciplinary contribute since it played a crucial role on the epistemological plan of physics in bridging from classical to modern theories. In the history of physics, it represented an interpretative challenge in order to recognize the wave behavior of light (Wosilait et al. 1999) and particles. Optical diffraction is a methodological context in which tools and methods linking theory and experiments in physics are prominent, since they allow to gain awareness about the specific modality of investigation in physics, offering the possibility to address the problem of understanding the Nature of Science (NoS) in operative terms (McComas et al. 2002; Lederman et al. 2002; Lederman 2007). Optical diffraction is a particularly important theme on the interpretative level, because it is the phenomenology that also historically led to the transition from geometric optics to physical optics (Gonzales 1993), but also from classical physics to quantum physics being a context in which it is possible to discuss the peculiarities of the quantum behaviour of physical systems (Michelini and Stefanel 2008; Holbrow et al. 2002). It is the fundamental phenomenology from which to start also to tackle a common double-slit interference experiment, the outcome of which is the convolution of a diffraction pattern with a double-slit interference one. It plays an important role also in terms of technological applications, being implicated in the resolution limit of all optical instruments, not least our eye, but also in numerous technological devices also for everyday use, as well as in high sophisticated processes, such as in the reconstruction of the image in holography.

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New theories have been built upon experimental data analysis: experiments that open new interpretations to phenomena, which cannot be explained with the current theories, are known as bridge experiments. Nowadays it is possible to reproduce those experiments with modern devices in order to make students aware of methods and theories of modern physics, eliciting cognitive conflict between observations and hypothesis, in order to build new interpretations of phenomena (Michelini 2010; Michelini et al. 2017a).

Since more than 20 years, a significant R&D work has been carried out from the Physics Education Research Unit (PERU) of the University of Udine in order to develop experimental proposals and prototypes to offer students the possibility of performing bridge experiments from classical to quantum physics on diffraction and discuss the interpretation of the emerging results. An on-line system, named LUCEGRAFO (Gervasio and Michelini 2009) was developed allowing simple and reliable measures of diffraction patterns for quantitative measures performed by students themselves.

Here we present an experimental proposal on optical diffraction to be implemented in a coherent educational path, together with some data analysis on students' learning outcomes.

The Educational Proposal

Our proposal is based on a phenomenological approach to the qualitative and quantitative analysis of diffraction patterns with the use of on-line sensors and modelling activities (Corni and Mascellani 1993; Santi et al. 1993; Michelini et al. 2014). It completely reverses the canonical approach that proposes: (A) to tackle Young's experiment first and only then the diffraction; (B) to focus only on the position of maximums and minima neglecting completely the light intensity distribution.

Thanks to the design and set-up of LUCEGRAFO, a patented system designed and realized by PERU from University of Udine in the perspective of a R&D research (Gervasio and Michelini 2009) that is the development of a previous system (Corni and Mascellani 1993). The system allows to acquire in real time the light intensity distribution produced by the light diffraction from a single or a multiple slit, allowing the acquisition of light intensity with a photodiode and its position, through a potentiometer. It is a user-friendly device for students, it acquires rather detailed and reliable light intensity distributions and allows the setting of the gain of the sensor (thus varying the amplification of the signal) to collect the entire distribution or only of the wings less bright secondary maxima for a more detailed analysis.

Activities with students are typically conducted with the use of IBL tutorials (McDermott et al. 1998) realizing Prevision-Exploration-Comparison (PEC) cycles (Theodorakakos and Psillos 2010; Michelini 2018). The overall structure of these tutorials is designed according to these steps: the situation, usually suggested by the output of the previous tutorial, is presented; a preview of the phenomenon under consideration is requested, a comparison between prediction and observed phenomenon is discussed, A conclusion, even if partial, summarizes the emerged aspects and identifies the new questions to be answered in subsequent explorations.

To illustrate the proposal on diffraction, we follow here the rationale of the tutorials (T1–T11):

T1—The first tutorial proposes the collection and the discussion of the different contexts in which diffraction occurs, in order to identify the specific characteristics of the phenomenon, independently by the phenomenological context considered: waves on the water surface, sound waves, diffraction produced by light (photons), electrons or neutrons.

T2—The second tutorial asks to the students the following previsions concerning two different situations: (A) "The light of a source passes through two close fingers: describe and represent what it is observed and explain." (B) "A laser beam passes through: a 5 mm slit; a 1 mm slit. Draw the light patterns on a screen in the two cases, describe and compare them."

T3—The third tutorial proposes a qualitative analysis of a diffraction pattern produced by a laser beam passing through a 0.12 mm slit. It suggests the following steps: (A) "Make a prediction of what will be observed on a screen and compare it with the observed pattern, after performing the experiment." (B) "Describe and represent a preview on the light intensity pattern." The focus is to point out the global features of the pattern (symmetry, intensity of the central maximum, presence of decreasing intensity maxima and minima and their distribution).

T4—The forth tutorial suggests to explore the parameters affecting the phenomenon. Changing the slit-screen distance, students discover that the pattern is an angular distribution, being larger/smaller increasing/decreasing the distance between the slit and the screen. The distance between minima and the central maximum is proportional to the distance of the slit from the screen. Changing the width of the slit (0.12, 0.24, 0.48 mm) or the color of the laser light (red, green, blue) and exploring the diffraction pattern on the screen at the same distance from the slit, students discover that it remains qualitatively the same, being affect only the distance between minima/maxima.

T5–T7—After the qualitative (or semi quantitative) analysis of previous steps, students are request to design their own measurements to quantitatively describe the diffraction pattern, showing them the opportunity offered by the LUCEGRAFO system and providing them some materials in which the kind of measurements that could be performed are briefly outlined but not described in depth. The three tutorials, T5–T7, propose to the students a synthesis of their own proposals for the quantitative measurement of the diffraction pattern performed in the experimental lab using LUCEGRAFO. The possibility to acquire at the same time position and light intensity offers both the opportunity to perform as usual the data analysis to find the relations between minima and maxima orders and the respective positions, and the more significant relation between maxima intensity and their positions and/or orders.

Students are required to extract from data positions and intensity of maxima and positions of minima. Students have to understand that, being diffraction an angular

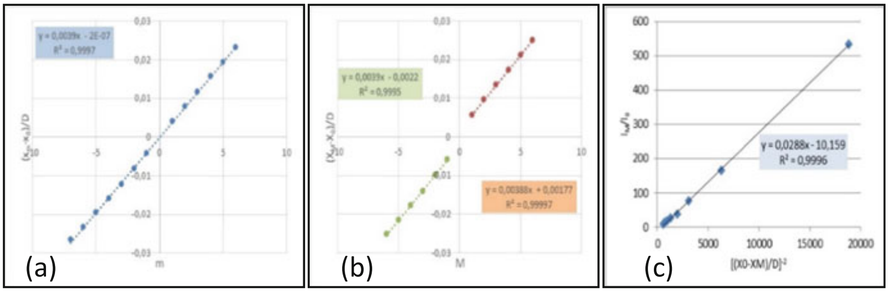

Fig. 9.1 Plots from data analysis. The linear correlation between positions of minima with their order individuates the first phenomenological law $(x_m - x_0)/D = km$ (**a**). The linear correlation between position of maxima and their order individuate the second law $(x_M - x_0)/D = n/2(2M \pm 1)$ (**b**). The law on intensity emerge from the plot of I_M/I_0 versus $[(x_M - x_0)/D]^2$ (**c**) where the slope $(\lambda/\pi a)^2$ emerges comparing measurements with different slit width and color laser beams

distribution, it is convenient to plot $(x_m - x_0)/D$ versus m and $(x_M - x_0)/D$ versus M, where m (M) is the minima (maxima) order, x_m (x_M) is the minima (maxima) linear position, x_0 is the linear position of the central maximum and D is the slit-screen distance. Data analysis shows (Fig. 9.1a) a linear correlation between $(x_m - x_0)/D$ and the order m:

$$\frac{(x_m - x_0)}{D} = k \cdot m$$

The comparison of this result with different slits shows the dependence of the slope with the inverse of the slit width a:

$$\frac{(x_m - x_0)}{D} = \frac{k'}{a} \cdot m \qquad \text{(Law 1)}$$

The same analysis in the case of maxima leads to the following:

$$\left(y = nx \pm n/2 \qquad + \text{ for } x > 0 \text{ and } - \text{ for } x < 0\right) \quad \text{(Law 2)}$$

where $y = (x_M - x_0)/D$ and $x = M$. The slope is twice the intercept (Fig. 9.1b).

The emerging law for maxima intensities I_M versus their positions results to be (Fig. 9.1c):

$$\frac{I_M}{I_0} = \left(\frac{D\lambda}{\pi a}\right)^2 \frac{1}{(x_M - x_0)^2} \qquad \text{(Law 3)}$$

Some students prefer to express the ratio of intensities of each maximum with those of the central one versus M, finding the equivalent law:

$$\frac{I_M}{I_0} = \frac{4}{\pi^2(2M+1)^2} \qquad \text{(Law 4)}$$

Some other students analyze the central maximum with Δx versus the slit width a, individuating an inverse relationship. Very often students do not use the tutorials in this phase of the activity. They design experimental work, performing the experimental activity, reflecting on how to produce quantitative description of the phenomenon under analysis in order to provide an explanation: they experience critical thinking and they gain scientific abilities.

T8—The eighth tutorial invites students to consider Fraunhofer conditions and a wave model to predict maxima and minima on the screen and to compare the emerging rule for maxima:

$$\sin\theta = (2M+1)\frac{\lambda}{2a}$$

with the previous Law 2. Students perform a similar activity for minima, comparing

$$\sin\theta = m\frac{\lambda}{a}$$

with Law 1.

T9—The nine tutorial suggests students to consider Law 2 and Law 3 to find Law 4, and by putting

$$z = \frac{\pi a \sin\theta}{\lambda}$$

the new law for data fitting emerges (Fig. 9.2):

$$I(\theta) = I_0\left(\frac{\sin z}{z}\right)^2 \qquad \text{(Law 5)}$$

Note that Law 5, in secondary school, only sometimes is just introduced and, as far as we know, never justified. Another approach to the same set of laws offers to students Law 5 as a fitting result of the intensity distribution and students are asked to find the rules for the angular position of minima and maxima, obtaining:

$$\sin\theta = m\frac{\lambda}{a}$$

and

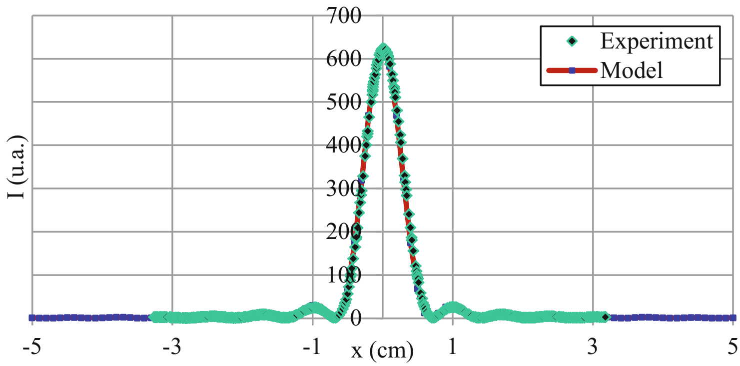

Fig. 9.2 Dots are the data collected by LUCEGRAFO for a red laser beam passing in a slit of 0.12 mm located 2 m apart from the data collection system. Line is the fitting curve by means of the Law 5: $I_M = I_0\ (\sin z/z)^2$, with $z = \pi a \sin\theta/\lambda$

$$\sin\theta = (2M \pm 1)\frac{\lambda}{2a}$$

respectively.

Having Law 5 in the hands, as emerged from data analysis, allows students to gain confidence in physics phenomena exploration and in their possibility to understand how data manipulation offers general laws towards interpretation. Students are motivated by the intellectual challenge and trust on physics as an interpretative subject for phenomena.

T10—The tutorial 10 invites students to use the HFS parametric simulation system (Santi et al. 1993) which implements the Huygens-Fresnel principle to a finite number N of point sources along the slit and calculate the superposition of the secondary waves on a screen. No additional hypothesis or conditions are necessary in order to obtain Young-2 sources typical distribution and the typical diffraction pattern from a single in the case of $N > 50$ sources, with the possibility to change N, a and D (Fig. 9.3).

T11—The last tutorial suggests to compare two waves (E_1 and E_2) classical superposition $E_1^2(x, t)+E_2^2(x, t)+2E_1(x, t)E_2(x, t)$ with the transition probability for a photon in the state $\mathbf{U} = a\mathbf{H} + b\mathbf{V}$ to the state L, expressed by $[(\mathbf{U} = a\mathbf{H} + b\mathbf{V})\cdot\mathbf{L}]^2 = a^2(\mathbf{H}\cdot\mathbf{L})^2 + b^2(\mathbf{V}\cdot\mathbf{L})^2 + 2ab(\mathbf{H}\cdot\mathbf{L})(\mathbf{V}\cdot\mathbf{L})$ in order to understand the new conceptual meaning of quantum interference with respect to the classical one (Zuccarini 2016). Between tutorial phases T10 and T11 the educational path on quantum mechanics is proposed (Michelini and Stefanel 2008; Michelini et al. 2017b).

The LUCEGRAFO system also allows an analysis of diffraction patterns produced by 2 or 3 slits (with the same width and the same distance between them): an interference pattern appears inside the diffraction envelope and, all conditions being equal, the maxima remain in the same positions while they become sharper and brighter as the number of slits increases (Fig. 9.4). The described phenomenological

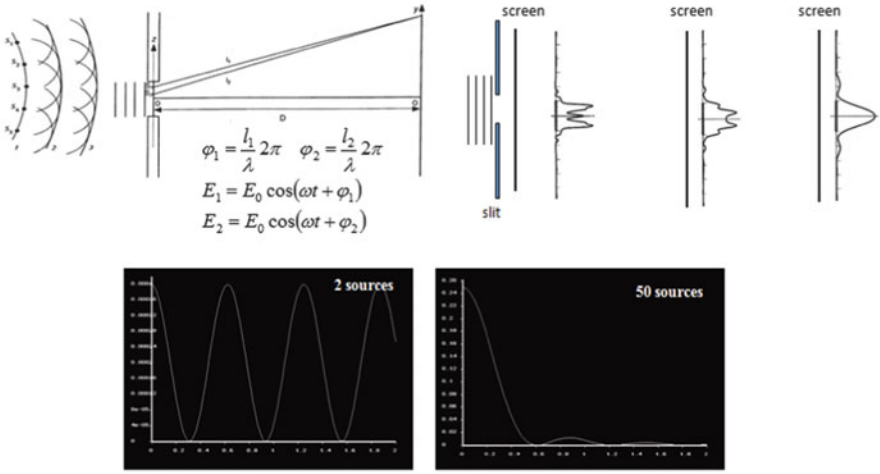

Fig. 9.3 The HFS simulation system (Santi et al. 1993) plots intensity distribution on a screen (along x axis) superposing a number N of waves coming from slit of width a (z direction) at a distance D (top left). Simulation results are shown at different distance D by n > 50 sources (top right) evidencing Fresnel and Fraunhofer ranges. Screen plots with 2 and 50 sources (bottom) show Young's and typical diffraction pattern where a = 0.01 cm and D = 100 cm

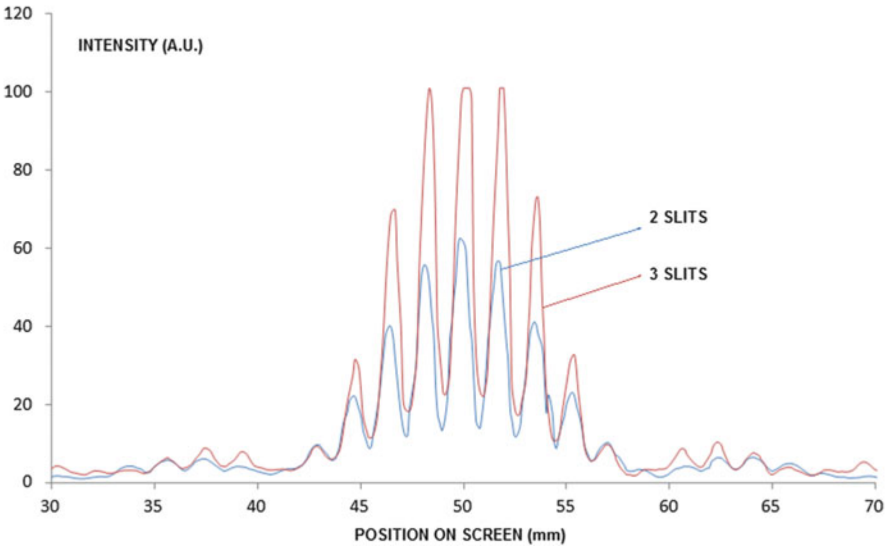

Fig. 9.4 Comparison between two and three slits patterns. Data obtained with the LUCEGRAFO system, subsequently elaborated with a spreadsheet

explorations provide the basis to guess the characteristics of a diffraction pattern caused by a diffraction grating, characterized by a high density of narrow slits. The maxima are very sharp and highly-spaced. If a superposition of colors is used, a grating allows therefore effective maxima separation, and thus the possibility to carry out spectroscopic analysis.

Data Analysis and Discussion

Up to now, the set of activities described in T1–T9 involved in different paths over than 300 Italian secondary school students 18 aged (Michelini and Stefanel 2008; Michelini et al. 2004, 2013) involved in IDIFO Projects from 2006 to 2018 (Battaglia et al. 2011; Fera et al. 2011).

When students are involved into the T1–T7 tutorial phases of the path, they evidence differentiated learning paths, influenced by the model on the phenomenon they develop. Initially, when asked to quote diffraction phenomena they know (see T1), usually students both prepared on optics and not prepared present a miscellaneous of light and wave phenomena confusing for instance refraction with diffraction (in particular associated to dispersion) and tend to use indistinctly the words dispersion, diffusion, refraction, refraction and reflection. It is clear that students need a preliminary overview on the different phenomena occurring when light interacts with an object, before face the phenomenology of diffraction. When students analyze qualitatively the first experimental evidence of diffraction (see tutorials T2–T3), almost 50% of they tend to frame the phenomenology inside a model based on geometric optics. The other half of students recognize that the phenomenology is new, but do not evidence the need of a new model to give account of it. Also reporting the observation of the diffraction pattern produced by a thin slit (0.12 mm), the prevalent phenomenon recognized is the "enlargement" of the beam, and only 44% of student stress the presence of "dots", "segments", "bars", "lines" in the figures. This means that the first half of students are unable to develop a model where the presence of minima can find meaning. On the contrary, 44% evidence the presence of minima develop new conceptions of the phenomenon. These conceptions involved in the majority of case only a descriptive schema, and only in 10% of cases an inchoate idea of a model based on a wave assumption on light nature. The analysis performed in tutorial T4 activate without any external intervention (any explicit explanation) in almost all students a clear perception of the phenomenon, that means the recognition of the following aspects: the presence of maxima and minima along the pattern that is orthogonal with respect to the slit direction, the central maximum more and more intense than the other maxima, decreasing in intensity with distance, the symmetry of the figure. In other word, the analysis of the diffraction pattern with different tasks and following PEC cycles, offer to all students the opportunity to master the diffraction phenomenology. Considering the quantitative measurements suggested in the T5–T7 tutorials it is important underlay that students before the lab sessions usually do not make distinction between parameters affecting the systems (distance between slit and sensor, width of the slit, color of the light) and quantities to be collected (light intensity, position). Moreover for 15% of students the intensity of the laser light and the distance laser-slit or laser sensor are parameter affecting the phenomenon. During the lab sessions all students understood without a guide which parameters they have to fix, and quantities that they can acquire. Rather they need some support concerning the quality of the distribution acquired, the number of different positions are needed to be considered and other general suggestion concerning how it is possible to perform an acceptable experiments. Considering the data analysis, almost all students (95%) obtained the attended linear correlation between minima position and number of order (some problem emerged when the central maximum was saturated). 88% obtained the linear correlation between maxima and number of order (the most frequent mistake being the interpolation of maxima with a proportionality), and 60% obtained the expected $1/r^2$ behavior of maxima intensity, evidencing in 40% of cases difficulties in managing function implying power different by r or 1/r. Moreover, about 60% of students used the phenomenological laws remaining on a descriptive plan; about 30% attempted to explain the features, focusing only on those aspects that can be justified in a geometrical model of the propagation of light; only 10% evidenced that a new model is needed (Michelini et al. 2014). Combining the experimental activity with a modeling lab based on the T8–T9 tutorial, 2/3 of students show that a new model based on a wave assumption on light was developed. Also in this case the first attempts of students privilege the borders of the slits, as well known in literature (Ambrose et al. 1999). The analysis of the interference of the waves produced by two point source, as suggested in (McDermott et al. 1998) was very powerful to aid students to develop almost a qualitative model of diffraction based on Huygens principle.

Activity T8, limited to the fitting of data from an experimental collection, have to complete the path, but T10 and T11 are very formative, so they have been experimented in the 30% of the experimentation mentioned and only recently with 64 students. T10 and T11 are to different kind of ICT-based CONCEPTUAL LAB in modern physics, carried out by means of simulations (Conceptual Simulation Labs—CSL) and Ideal Experiment Labs (IEL) based on open environment software systems.

The parametric simulation in T10 is offered to students for explorative analysis: the simulation applies the Huygens-Fresnel principle to a finite number of point sources along a slit and it calculates the superposition of the secondary waves on the screen. Students explore the consequences of this simple hypothesis, discovering Fresnel and Huygens regime for low D and large D respectively. CLS offers in T10 the opportunity to understand power and limits of the Huygens-Fresnel principle and to use results to relate interpretative hypothesis with experiments (Gonzales 1993; Santi et al. 1993; Michelini and Stefanel 2008). In exploring simulation output, students experience the role of computational physics in theoretical physics and the need of its integration with the experimental work.

Conclusions

We presented here an educational lab, based on a bridge experiment on optical diffraction, to be integrated in an intervention formative module or in an educational path, that allows the exploration of the phenomenon underlying the observations, in order to test interpretative hypothesis.

The proposal is based on a qualitative exploration of the diffraction pattern followed by a deep analysis of the light intensity distribution acquired via an on-line sensor (LUCEGRAFO). This approach was effective in activating a generalized mastery of the phenomenology, after an initial difficulty to frame the presence of minima as a peculiar aspect of a new observed phenomenon. The analysis of the diffraction distribution promoted in the majority of students the competence to construct the phenomenological laws describing that distribution. The modeling activity was useful to activate the change from the descriptive-phenomenological perspective, activated initially in the students thanks to the construction of a model based on the Huygens principle. A partially open knots remained the formal implementation of the model.

The activity could also be effective in overcoming the conceptual knots emerged in the literature as concerning the open problems of the formation of optical spectra making use of a diffraction grating (Buongiorno 2017; Ivanjek 2012; Ivanjek et al. 2015a, b).

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Part III
Lab Work and Multimedia

Chapter 10
Computer Modelling in Physics Teaching

Veronika Timková and Zuzana Ješková

Introduction

Education in Europe faces strong effort towards increased emphasis on the development of skills related to active scientific inquiry. The activities of students should in a simplified way imitate the work of scientists who study the world around us through experimentation as well as development of models and theories that describe observed objects and phenomena. Modelling complementing experimentation is, therefore, a natural part not only of science but also the science education. When modelling systems or processes, it usually leads to developing mathematical models of the situation. Digital technologies can provide a very effective tool to enhance mathematical modelling in physics education, in particular (Heck 2009; Heck et al. 2009; Heck and Ellermeijer 2014). However, with relation to inquiry-based science education (IBSE), much more emphasis is put on students' experimentation and there is much less attempt made in implementation of modelling activities within IBSE. Modelling is not an integral part of science curricula of some European countries, including Slovakia (Establish project, http://ibse.establish-fp7.eu/). In Slovak physics curriculum, it can be found only indirectly in the goals of physics and in target requirements for school leaving examination in physics. Moreover, there is a lack of teachers' and students' materials that would help in implementation of modelling at school. As a result, we have developed a learning scenario on the systematic implementation of computer modelling at the upper secondary school level. The designed learning scenario has been implemented in selected grammar schools in order to answer several research questions.

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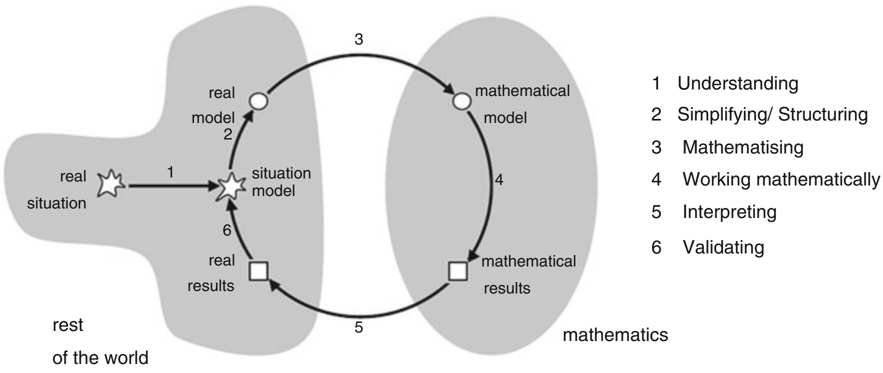

Fig. 10.1 Modelling cycle by Blum and Leiss (2005)

Mathematical Modelling and Computer Modelling

Having a closer look to models and modelling in physics, several definitions can be found (Hestenes 1987; Etkina et al. 2006). By Hestenes (1987, p. 441) "*a model is a surrogate object, a conceptual representation of a real thing. The models in physics are usually mathematical models, which is to say that physical properties are represented by quantitative variables in the models*". The process of modelling can be seen in a modelling cycle proposed by Blum and Leiss (2005; Fig. 10.1) in which the real situation is gradually transformed into a mathematical representation of the situation.

Dynamical modelling is the method that was firstly used by R. Feynman et al. (1964) in his well-known lectures. The method is based on numerical solution of differential equations. At that time Feynman did all the calculations with his students. Nowadays having fast computers with a modelling environment it is very easy and quick to do all the calculations. The available computer software, such like COACH6 learning environment (http://cma-science.nl) enables to develop models of physical phenomena in a text mode using mathematical equations or in an iconographical mode when variables and the relationships between them are represented by graphic symbols (icons) (Fig. 10.2). This way even more complex phenomena can be brought into the classroom and the corresponding models can be developed without demanding mathematical knowledge. The software also allows comparing the created model with experimental data. This approach, which is natural for the work of scientists, can be a part of the students' activities in physics in a reasonably simplified form.

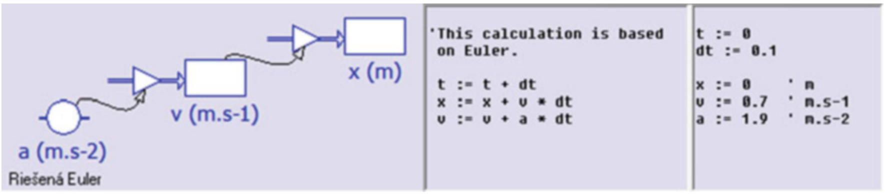

Fig. 10.2 Dynamical model of uniformly accelerating motion of a cyclist in iconographical mode (left) and text mode (middle and right) in Coach 6

Research

Problem of Research

As shown by the analysis conducted by the Establish project partners (http://establish-fp7.eu), modelling is not an integral part of science curricula of some European countries, including Slovakia. Nevertheless, in physics and science education in general, solving problems applying modelling approach is considered an important part complementing the experimental approach. Considering this fact, in this research the focus is on implementation of mathematical modelling by computer (computer modelling) at school. With regard to this research problem we have developed a learning scenario on the systematic implementation of computer modelling at the upper secondary school level, we have designed a set of activities that combine experimental and theoretical approach to solving physics problems concerning motion and we have educated a group of teachers in ICT in IBSE with modelling as a part of the course. The designed learning path has been implemented in selected grammar schools in order to answer several research questions:

1. Is the learning scenario on implementation of computer modelling appropriate for the first grade class of upper secondary school?
2. Are students able to solve problems with the help of computer modelling tools?
3. What is the effect of learning scenario on the conceptual understanding?

To answer these research questions we performed educational research in the school year of 2015/2016.

Design of Learning Scenario on Computer Modelling

To develop students' ability to understand mathematical models and the ability to create mathematical models of simple or complex physical phenomena, the following learning scenario was proposed in order to help teachers to implement computer modelling in the classroom. The learning scenario is based on computer modelling in iconographical mode that is designed to be implemented in the field of Force and

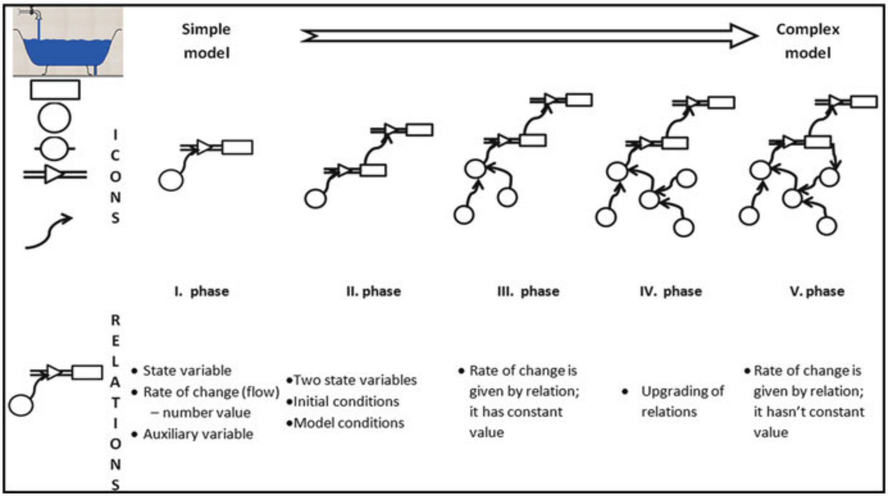

Fig. 10.3 The gradual transition from simple to complex models

Motion part of the first grade classes' physics lessons. The learning path is constructed respecting the principle of combining real life situation videorecorded in advance with modelling approach. The learning path involves five phases (Fig. 10.3).

In the first phase students solve a simple problem. In the following phases, students add new variables and relations between them. In the last phase, students finally develop a complex model that represents a real life problem. In each phase of the scenario, students become familiar with a new function of modelling and therefore have a better chance to examine it and understand it. Based on the learning scenario a set of activities was designed that combine experimental and theoretical approach to solving physics problems concerning motion (Fig. 10.4). Each activity consists of two essential parts respecting the modelling cycle (Fig. 10.1). The first part corresponds to a real situation presented by an experiment or a videorecording of a real situation. The second part corresponds to an iconographic modelling of a real situation resulting into a comparison of the data from experiment or videomeasurement and data gained from the model.

The activity *Introduction to modelling* is aimed at first insight into modelling environment through a familiar situation of a bathtub filled with water. Subsequently, the process of filling the bathtub with water flowing at a constant speed is transformed into the model a runner's uniform motion (*The Runner* activity, Fig. 10.4: I. phase). This model is then elaborated into the model of a motion with uniformly increasing or decreasing speed in the activities *When cyclist pedals his bike*, *Let's slow down together* and *How rubber ball falls.* Here students successively add new variables and change initial and other parameters entering the model (Fig. 10.4: II. phase). After that in *How rubber ball falls* activity students describe parameters not only by numerical values but also by physical relationships

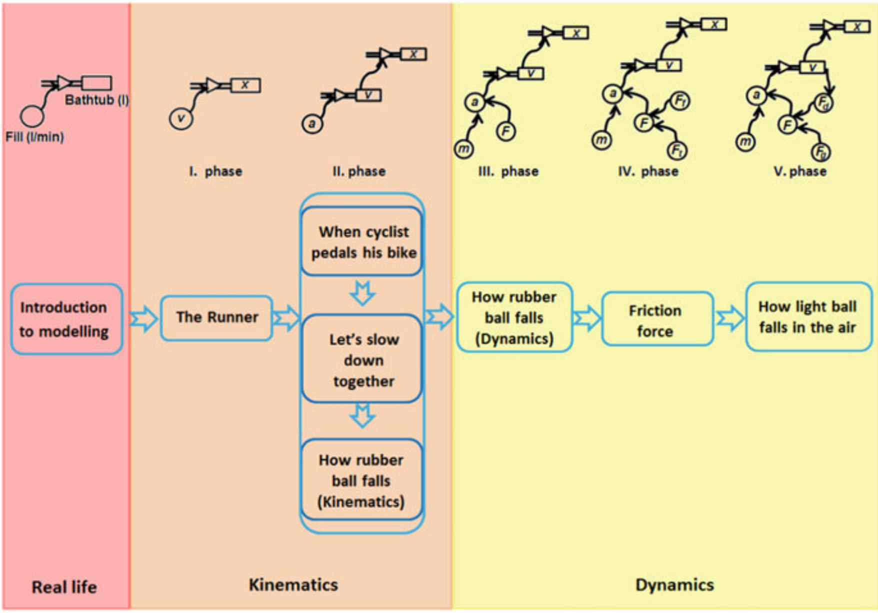

Fig. 10.4 A set of activities concerning to motion based on learning scenario

(Fig. 10.4: II. phase) applying second law of motion for one acting force. The activities *Friction force* and *How light ball falls in the air* represent more realistic motion under the resultant force that can even change its value in the latter case (Fig. 10.4: IV. phase).

Sample of Research

The pedagogical experiment in order to answer the research questions was conducted at three different grammar schools in Slovakia. The experimental group involved two 1st grade classes (class A, 25 students aged 15–16; class B, 26 students aged 15–16) and one 4th grade class (class C, 13 students aged 18–19). Classes A and C were taught by a novice teacher with high level modelling competencies, while class B was taught by an experienced teacher with high level of both pedagogical content knowledge as well as modelling competencies.

Instrument and Procedures

The research questions were answered using different tools, i.e. interview with teachers, observation of lessons, questionnaire answered by students, analysis of students' worksheets, and test on modelling (written assignment 1, 2). The conceptual understanding was evaluated by pretest and posttest consisting of conceptual questions selected from TUG-K (Beichner 1994), MBT (Hestenes and Wells 1992), FCI (Hestenes et al. 1992) test and a few non-standardized questions.

Test on modelling was implemented in two written assignments when students were expected to solve a problem with the help of computer modelling tools. In assignment 1 the problem was similar to the problem solved during the physics lessons (car speeding up/slowing down). In assignment 2 students were expected to solve a more complex problem. Based on the data from videomeasurement students were expected to develop a model of a fall of light ball in the air. On the basis of a model of free fall students should elaborate this model by adding a drag force that depends on the speed of a ball. The evaluation of the test was carried out in correspondence with these two levels of model design.

The pretest/posttest on conceptual understanding of motion concepts consisted of 11 questions, which were selected from conceptual tests Force Concept Inventory (Q5, Q9, Q10, Q11), Test of Understanding Graphs—Kinematics (Q2, Q3 Q4) and Mechanic Baseline Test (Q6) and non-standardized questions (Q1, Q7, Q8). The test items were selected with regard to knowledge and skills connected with modelling, i.e. understanding the rate of change of a physical quantity and relationship between physical quantities with regard to understanding the second law of motion, in particular (Table 10.1).

Reliability of the test was investigated by Kuder-Richardson's formula

$$r_{KR20} = \frac{k}{k-1}\left[1 - \frac{\sum_{1}^{n} p_i q_i}{s^2}\right],$$

where k represents the number of test items, p_{i} is the proportion of correct responses to test item i, q_{i} is the proportion of incorrect responses to test item i ($q_{\mathrm{i}} = (1 - p_i)$), n is the total sample size and s is the standard deviation. The reliability calculated for the test used for our research sample gained the value of

Table 10.1 Assignment of test questions for each area

	Question
Relationship between velocity and change of position	1, 2
Relationship between acceleration and velocity change	3, 4
Relationship between resultant force and change of velocity	6, 7
Relationship between resultant force and acceleration, $F = 0$, $F \neq 0$	5, 8, 9, 10, 11

$r_{KR20} = 0.51$, that is considered to be sufficient for evaluating a group performance (Helmstadter 1964).

Into the evaluation only those students were involved who answered both pre-test and post-test. Then the basic descriptive statistics was developed to show the main sample characteristics. For testing differences between pre-test and post-test the paired sample t-test was used.

Results of Research

Question 1: Is the learning scenario appropriate for the first class upper secondary school?
Based on the results of lessons' observation, interview with teachers, questionnaire answered by students and analysis of students' worksheets it can be concluded that the learning scenario can be implemented into regular physics lessons without significant problems. Students were capable to follow all the activities and fulfil all the assignments at reasonable level.

Question 2: Are students able to solve problems with the help of computer modelling tools?
Based on the analysis of the results of test on modelling it can be concluded that students are able to solve problems that they are familiar with (Assignment 1: car speeding up/slowing down, Assignment 2a: free fall). Their average gained score in these assignments achieved the value of 60% (Fig. 10.5). On the other hand, in

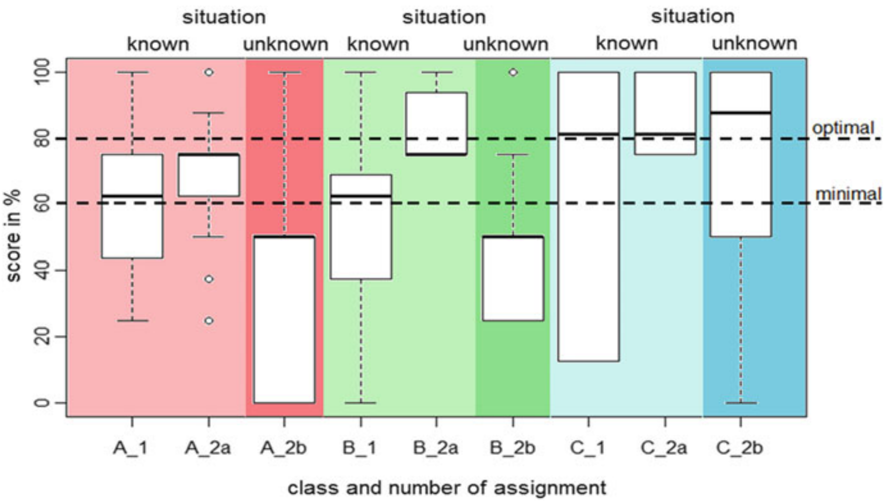

Fig. 10.5 Student's score is in assignments 1, 2 represented by box plot. The bottom and top of the box are the lower quartile and the upper quartile and the band inside the box is the median. The whiskers represent the minimum and maximum of all of the data and small circle represent outlier

Table 10.2 Basic statistical characteristics of the pre-test and post-test results

Class	A (1st grade, novice teacher) Pre-test (%)	A (1st grade, novice teacher) Post-test (%)	B (1st grade, experienced teacher) Pre-test (%)	B (1st grade, experienced teacher) Post-test (%)	C (4th grade, novice teacher) Pre-test (%)	C (4th grade, novice teacher) Post-test (%)
Sample size	25		26		13	
Mean	17.1%	21.8%	17.8%	34.3%	35.7%	45.5%
Median	18.2%	18.2%	18.2%	31.8%	36.4%	45.5%
Standard deviation	9.6%	9.1%	11.1%	17.9%	23.3%	24.9%
Standard error of the mean	1.9%	1.8%	2.2%	3.5%	6.5%	6.9%
p-value (paired t-test)	0.08		<0.001		0.15	

modelling the problem that students were less familiar with (assignment 2b: light ball fall), they were much less successful. As can be seen in Fig. 10.5, only 4th-grade students were capable to handle the problem of a fall influenced by drag force at reasonable level.

Moreover, when analysing the students' worksheets with their answers and conclusions, there were many problems identified in relation with interpretation of graphs and drawing conclusions from the results gained by modelling. These results were also confirmed by the test of conceptual understanding (Q3).

Question 3: What is the effect of learning scenario on the conceptual understanding?

This research question was answered analysing the results of pre-test and post-test of conceptual understanding (Table 10.2).

The table shows that the initial level of motion concepts of 1st grade classes is low. This is not surprising since students took the pre-test before learning about force and motion and they could use only the knowledge gained at lower secondary school that is quite limited considering the test content. On the other hand, the initial knowledge of 4th grade class was significantly higher ($p < 0.01$), even though we expected better results. Considering the effect of computer modelling, the significant difference between pre-test and post-test was proved only in the case of class B ($p < 0.001$). Neither the class A, nor the class C achieved significant improvement in the test results ($p = 0.08$ and $p = 0.15$). This result means that the experimental instruction affected the class B, while no effect was identified for class A and C. We suppose that there can be a strong influence of teacher who plays a key role in education. The teacher, even though well-educated in computer modelling, needs a good level of pedagogical content knowledge in order to achieve the learning goals, as can be seen in case of the class B.

In Fig. 10.6 the distribution of test results among the students of each of the experimental classes is presented. It can be seen that the distribution has moved slightly to the right towards higher achieved score.

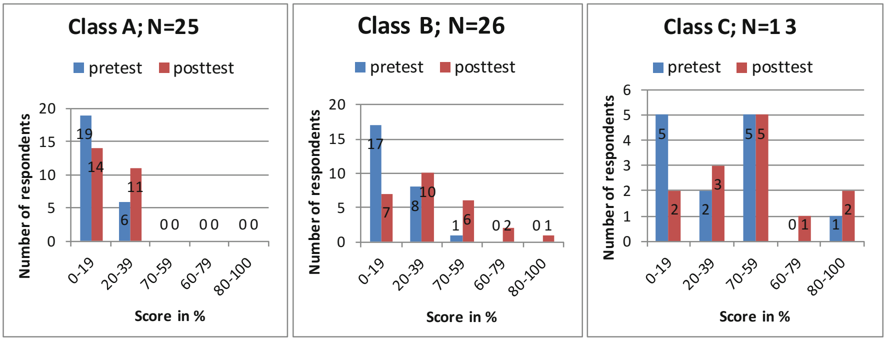

Fig. 10.6 Distribution of test results for each of the experimental classes

Discussion and Conclusions

The results show that the designed learning scenario is appropriate for learning to manipulate with models and develop simple models of motion. However, there are difficulties in understanding and skills connected with analysis and interpretation of the data gained from modelling. This is in accordance with the results of test of conceptual understanding taken by students both before and after experimental teaching. The test results showed significant improvement in only one of the three experimental classes.

Students in general had difficulties in interpreting graphs of different physical quantities describing motion connected with understanding the concepts of motion and second law of motion. From this research another interesting result emerged. The instruction in the class with positive learning gain was conducted by experienced teacher with good modelling competencies while the other two experimental classes were taught by novice teacher with excellent modelling competencies. This research outcome is in accordance with other research dealing with the role of teacher while implementing ICT tools into education. The results of other research shows that the role of the teacher in mediating the use of ICT is of crucial importance. Newton and Rogers (2001) emphasise that for effective use of ICT tools teacher should have operational skills (technical skills to manipulate software) and pedagogical content knowledge (Webb 2010) for ICT application. According to Webb, this is knowledge of how the wide range of technologies available may support the content to be taught and which pedagogical approaches are appropriate to be successful. The operational skills alone are insufficient to produce learning gains in students. As results of our research show, the novice teacher mastering operational skills at high level did not achieve the learning goals, likely because of the lack of pedagogical content knowledge.

Resulting from this research, another research round will be conducted with one experienced teacher who will teach both experimental classes with modelling and control class without modelling in order to minimise the number of parameters that could possibly influence the learning gains. The classes will be subsequently compared in order to show the effect of computer modelling scenario on students' modelling skills as well as conceptual understanding of the concepts of motion.

There is also more consistent approach to modelling needed over longer teaching period. There are opportunities for its implementation in other areas (oscillations, electricity) or even in other subjects such like biology, chemistry or geography that can be an interesting problem for the following research to deal with.

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Chapter 11
Introducing Preservice Science Teachers in the Development of Inquiry-Based Activities

Anastasios Molohidis and Euripides Hatzikraniotis

Introduction

Inquiry Based Learning: Theoretical Assumptions

Scientific inquiry refers to the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work (NRC 2000). As stated by NRC (NRC 2000) in inquiry based learning learners are engaged by scientifically oriented questions, formulate explanations based on evidence, evaluate their explanations in light of alternative explanations, and finally communicate justifying their proposed explanation. Therefore, teaching by inquiry, actually places the student in the role of the investigator, the owner of the problem. A number of studies have reported the benefits of inquiry-related teaching approaches, from the three domains of learning (e.g. White et al. 1999; Marx et al. 2004, etc.).

From a pedagogical perspective, the research findings suggest to support the teaching of science as inquiry so that students in compulsory education have the opportunity to be involved in relevant activities and develop the ability to think and act in ways related to scientific inquiry (Abd-El-Khalick et al. 2004). Thus inquiry is conceived as both a process and an outcome, aiming at engaging students in investigating physical phenomena as well as in several facets of scientific understanding. While science education research and several science educators suggest that inquiry-based approaches can be effective in facilitating students' conceptual, methodological and epistemological knowledge and skills, as well as enhancing their motivation and interest towards science and technology, in most European countries, including Greece, actual science teaching does not pursue inquiry (EU 2007).

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Table 11.1 Levels of openness of Inquiry in laboratory activities (inquiry continuum); adapted from Hegarty-Hazel (1986)

Level of inquiry	Problem	Experimental setup	Method	Results
0 Verification	Given	Given	Given	Given
1 Guided inquiry	Given	Given	Given	Open
2a Open guided inquiry	Given	Given	Open	Open
2b Open guided inquiry	Given	Open	Open	Open
3 Open inquiry	Open	Open	Open	Open

Introducing Preservice Teachers in Inquiry Based Learning

It appears that it is necessary to introduce inquiry based learning both in pre-service and in-service educational programs. Especially for pre-service science teachers (hereinafter PST, to be distinguished from "students", their future audience) inquiry based learning is one of the teaching and learning strategies that must be mastered as to be able to design inquiry based lessons which include most of the science process skills such as forming hypothesis, making observations, posing questions, planning investigations, interpreting data and discussing the conclusions (Anagnos et al. 2007; Lefkos et al. 2011; Elster et al. 2014).

While inquiry-based teaching can take multiple forms, the approach can be seen as a continuum from teacher-led to student-led processes. This continuum usually includes the most common strategies for teaching by inquiry: from "closed" to "open" inquiry. Blanchard et al. (2010) note that the "degree of inquiry depends on who is responsible for the activity."

Trying to bridge laboratory work and the opportunities for different types of learning outcomes, and therefore the way an inquiry approach is partially or fully approached, criteria can be used to classify practical activities into categories as shown in Table 11.1. The degree of openness of practical activities can be assessed in terms of whether the teacher or student decides the problem to be investigated, the equipment to be used, the procedure for setting up equipment and making observations and measurements and the conclusions to be drawn. At the lowest level of inquiry (Level 0 corresponds to the so-called "closed inquiry"), the problem to be investigated, the equipment to be used, the procedure and the answer to the problem are all given to the students by the teacher or by a worksheet (WS). At the highest level of inquiry (Level 3 corresponds to the "open inquiry"), the students are required to determine all of these for themselves. For the students the gradual transition from structured inquiry to more open inquiry, consequently to greater student autonomy, demands guidance from the teacher, so teacher should scaffold experiences—from highly structured to more open—by varying the amount of guidance, enabling students to come up with self-conceived conclusions (Eick et al. 2005; Lehtinen et al. 2016). Structuring can vary depending on the classroom context and objectives of teaching.

In the present study, we use web virtual labs (web VLs) as a "vehicle" to support PST preparing in inquiry based teaching. The web VLs are used in science teaching and represent real labs both in functionality and manipulation. As simulation, they can be used to investigate scientific phenomena as a part of inquiry based science teaching (de Jong 2006). They offer a chance for students to set up an experiment, perform it, change the experimental parameters and observe the effect.

Methodology

The Sample: The Profile of Our Students

The Laboratory of Didactics of Physics and Educational Technology in Physics Department in Aristotle University of Thessaloniki, apart from being involved in in-service science teacher professional development through various national projects, also provides sufficient and adequate studies to our students who intend to get involved in education as a profession. There are courses on Didactics of Physics and Educational Technology leading to a pedagogical and didactical efficiency. Our students are in their last year of studies and they have passed successfully eight compulsory experimental courses (such as Labs in Classical and Modern Physics, Optics, Electronics, etc.), before they attend the elective experimental courses that our lab provides (Didactics of Physics, Educational Technology and School Internship). We can say that our students are more or less experienced in laboratory work, although working with ready to follow strictly guided worksheets (WS), with a naïve approach in designing activities. Our sample in this study consists of 12 students equally distributed in gender and working in groups of two.

Design of the Course

The aims of the course are to provide students the appropriate knowledge and instructional designing skills in order to be able to design, develop, implement and evaluate lessons and integrated teaching scenarios in physics, addressing to high school curricula. In our course, the basic steps of inquiry are discussed and how to design and develop an integrated WS to support inquiry based activities is analyzed.

The course includes 10 two-hour lessons where PST design, develop, discuss, reflect and refine experimental activities based on the inquiry continuum model. During odd lessons the steps of inquiry continuum model are introduced (Fig. 11.1). The PST exercised in designing and implementing activities, reflecting and refining them as homework and sending them by email to the instructor of the course. Then, during the even lessons PSTs' work is analyzed and discussed, under the guidance of their instructor. The intended learning outcomes of the course vary from conceptual to procedural and meta-cognitive: PST should be able to distinguish the steps of an experimental teaching (conceptual) and to become aware of various ways of students' engagement (procedural). In addition, PST should come across with the

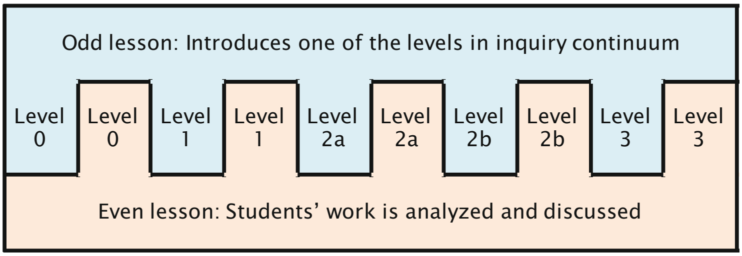

Fig. 11.1 Schematic representation of the course structure

scientific inquiry from two perspectives, namely, from the point of view of a researcher so to be experienced in various steps of inquiry and from the point of view of a forthcoming teacher so to organize activities in various steps of inquiry (meta-cognitive strategy/skills).

Web Virtual Labs: The "Vehicle"

Laboratory inquiry based activities may be implemented in real labs or in virtual counterparts. In our approach, we need PST to have unlimited access to a laboratory setting, even from home where they rethink and refine their design. We therefore have opted for a virtual (web-based) laboratory that has the feel and look of a real one. Virtual laboratories (VLs) have emerged as powerful environments which can successfully support experimentation and student activities, and, despite the limitations, offer, as educational environments, efficiencies over physical experiments and are not inferior to their real counterparts (de Jong et al. 2013). Furthermore, research points that the pedagogical design of activities for a lab are more important for learning outcomes than if the lab is "real" or "virtual". Especially, web based virtual laboratories (web-VLs) offer all the features of VLs and furthermore are accessible freely at any time over the internet, so they may break the natural barrier between the classroom, the laboratory, the school and the community and can support both formal and informal educational settings. The web-VLs we developed are three independent micro-world environments, in optics, heat and electricity, with realistic 3D representation of lab objects and appropriate functions for the simulation of relevant phenomena. The direct manipulation of the objects allows the user to compose experimental settings and fosters open inquiry activities and what-if investigations. A full description of the web-VLs and their functionality can be found elsewhere (Lefkos et al. 2011; Molohidis et al. 2016; etc.).

An innovative feature of the web-VLs is the existence of parallel components, which present multiple views of the phenomenon under study. The use of discrete worlds for representing the real and the symbolic entities is a main design strategy followed during the development of these environments and have been presented in previous papers (Hatzikraniotis et al. 2007; Lefkos et al. 2011). One component, the

"Cosmos" window, is a virtual laboratory, which represents, with visual and functional reality, the phenomena. Another component, the "Model" window, shows the symbolic representation of the experimental setup, is dynamically linked to the actual "labspace" and simulates the experimental setup in real time on the base of valid model-representations. As each action on the bench of the "Cosmos" is reflected dynamically in the "Model", a link is potentially established between virtual objects and scientific representations in students' mind. Research has shown that such affordances increase the students' conceptual evolution in complex situations (Olympiou et al. 2013; Taramopoulos and Psillos 2017).

The Inquiry-Approach Worksheets (WS)

For designing inquiry-based activities PST should be involved in selecting the problem in a context familiar to the student for the learning experience to be meaningful and represent authentic science. The WS in inquiry approach are tools that guide students as they plan and execute research, analyze data and draw conclusions. The student should wonder what variables may affect the phenomenon under investigation and what questions may be posed. Then the student should decide which equipment is to be used and which procedures are to followed. Finally, the student collect and analyze data (experimental evidence) and reflect upon the findings.

Different researchers use various terminologies to label the phases in inquiry-based investigation (Pedaste et al. 2015). We have adopted a five discrete phases model: student engagement, planning the experiment, performing the experiment, data analysis and communication and evaluation of the process. Each WS was structured on a template based on the above phases and each phase was clarified with questions like: *What am I going to investigate? What (in my opinion) will happen and why? What I plan to do? What will I need? What is the result? It was what I expected? Why did this happen?* etc. (Hackling 1998). In the early stages of inquiry continuum (Table 11.1) almost all of these answers were pre filled. As the inquiry advances from guided to open, the guidance given by the answers is gradually removed and space was given for students to answer. The structure of the WS template (phases and questions) was kept the same throughout the course, providing to PST a helpful scaffold *in the design* of activities based on the inquiry continuum.

The Research Question

Little research has been done on experiences of PST to design and incorporate inquiry instruction into their own teaching (Binns and Popp 2013). Therefore the purpose of this paper is to examine the learning of PST to design WS guiding students in inquiry instruction. The research questions that guided this research are:

(a) How do the PST evaluate the "vehicle" they have (web VLs) as a suitable tool in terms of utility and usability for the special reason that they use them?
(b) How do the PST perceive the inquiry continuum and how they implement the design principles of the inquiry continuum in WS?

Tools

The tools we used to collect data were:

- A 38-question questionnaire which assess the environment (web-VLs) and record the TLS self-evaluation,
- The WS that PST developed during the course (30 WS were collected and analyzed), from where we outline the improvement achieved according to inquiry continuum model, and
- The interviews with the PST taken at the end of the course, for the triangulation of data.

Questionnaire was statistically analyzed for internal consistency by Cronbach α, which is typically used in similar researches (Field 2009). The Cronbach α was found to be 0.786 (>0.7), which suggests that results are reliable despite the small number of PST.

Results

The PST in the course, having become familiar with the web-VLs in the first lesson, start to design WS, according to inquiry continuum model, aiming at involving their future students in a learning and experimental process. We asked them to evaluate the role of the web-VLs in their designing of the WS as a potential (what I think I can design with the web-VLs) and then we evaluate how they use the web-VLs in their WS, examining them.

Evaluation of the Web-VLs

Subsequently we present indicative results of the questionnaire, in three different clusters:

(a) The assessment of the PST as to the usability and utility of the virtual environment,

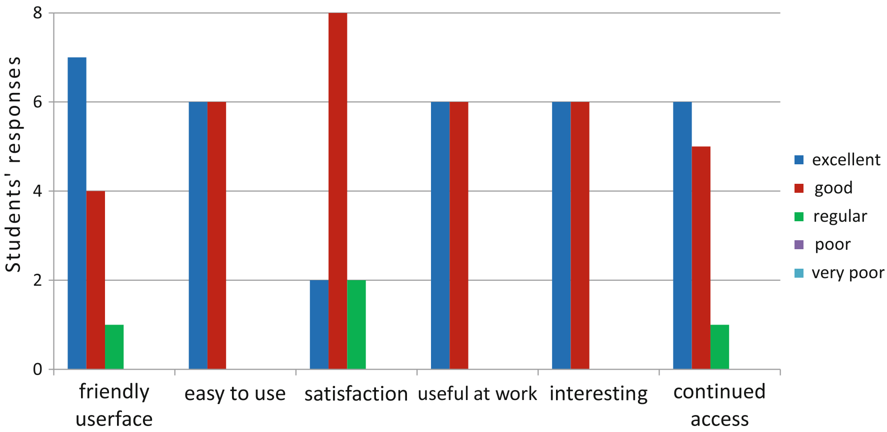

Fig. 11.2 Evaluation of six components in usability and utility dimension

(b) The assessment as to main characteristics of the virtual environment and the potential dimension they have,
(c) The assessment of what a teacher can do with the virtual environment.

a. Assessment of web-VLs

The assessment of the environment developed follows two axes which are usually taken into account in similar cases (Grudin 1992), usability and utility provided by the system to the user. The concept of usability concerns how easily one can obtain functionality and includes components such as learnability and satisfaction among others, while the concept of utility concerns the functionality of the interface.

According to the data of the histogram (Fig. 11.2), it seems that the web-VLs were evaluated from fairly to very positive in terms of friendly user interface and ease to use, two factors that determine how easily one learns (learnability) the environment. High are also the acceptance rates, as shown in the same figure, in satisfaction of the engagement with web-VLs and that of an interesting procedure provided by the environment which can be useful at work, three factors that determine the potential involvement of the PST and therefore the usability of the web-VLs. The unlimited access they have through web is also rated very positive, highlighting the web dimension of the environment.

b. Potential dimensions and characteristics of web-VLs

The realism of the various items in the web-VLs, as well as the direct manipulation of the web-VLs allowing the possibility to customize the experimental setup and to undo and redo functions as someone involved with web-VLs, is evaluated from fairly to very positive (Fig. 11.3).

The characteristic of web-VLs as capable of providing processes that support learning emerges (as they noted in the interviews: *I can repeat an experimental procedure, changing each time different parameters, without the stress of time consuming processes*). The usefulness of synchronized spaces (such as the model

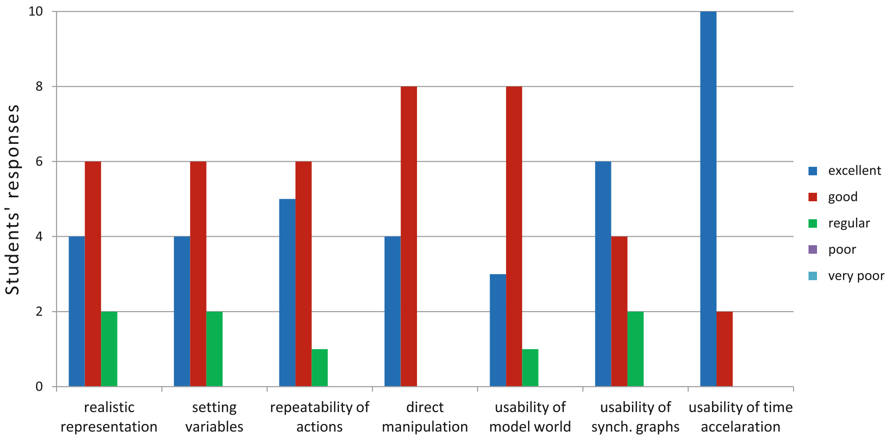

Fig. 11.3 Evaluation of seven components of main characteristics

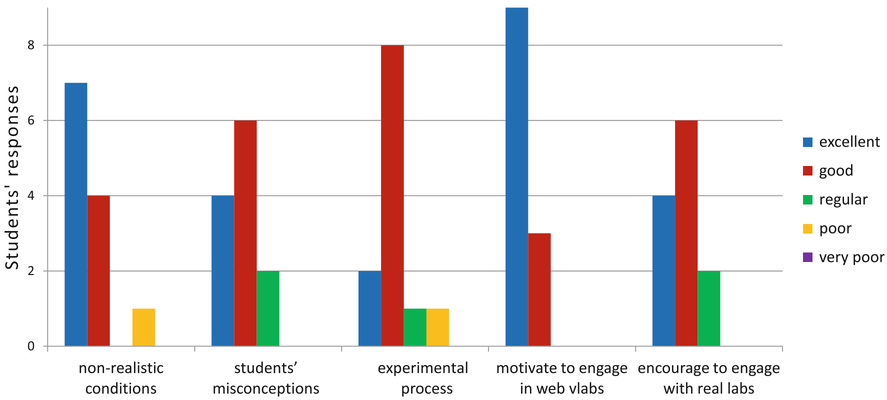

Fig. 11.4 Evaluation of five components of potential that web-VLs have

space and the graphs), as they give the chance of multiple representations, evaluated also positively as shown in the same figure. Finally the usefulness of various regulators (such as an accelerator of time) evaluated very positively. We may remind here that the PST are more or less experienced in laboratory work, as aforementioned, so one can easily distinguish the more positive evaluation at synchronized graphs (as the process of graphing is very common to them, they understood the potentiality of synchronized graphs) or at the regulator of time (as their experience is full of extensive experimental processes) compared to less positive evaluation at model spaces (as modeling is not a familiar process for them).

c. What pre-service teaches can do with web-VLs

The potential of the web-VLs in the designing of the WS evaluated positive by the PST, as shown in Fig. 11.4: they think that they can design experimental processes in nonrealistic situations, they think that they can take into account the alternative ideas that their future students have and so they can design special experimental processes to confront them and they think that they can design experimental processes aiming at the learning of experimental process per se. From the above quoted results it becomes obvious what PST consider that they can do with the web-VLs. Reviewing their scripts we can criticize if there is consistency: were their thoughts implemented in their worksheets? So, we may state that they:

(a) Utilize effectively the web-VLs to experiment and make observations where a real lab is inadequate, e.g. to study the quantity of the deposit salt during the heating and boiling of an amount of salt water, or
(b) Use the advantage of changing the temperature of the environment to extreme conditions e.g. to study the thermal equilibrium between two equal quantities of water at different temperature (e.g. 10 and 40 °C) but at unusual temperature of the environment e.g. 80 or −20 °C).
(c) Confront misconceptions, for example "objects that readily become warm do not readily become cold" (Lewis and Linn 1994) or "objects radiate and absorb at a dissimilar ease".
(d) Confront experimentally the fact that the boiling-point is an intensive property.
(e) Treat an experiment in a way that experimental objectives can arise e.g. to test the cooling of various refreshments choosing the parameters that enter into the phenomenon: the mass, the shape of the container, the walls of the container, etc.

The above findings from reviewing the WS defend the three left columns of Fig. 11.4: the PST do not only think that web-VLs can help at dealing with non-realistic conditions, confronting the students' misconceptions and treating the experimental process but they also proceed to implement these in their WS. As an example we can see in Fig. 11.5 (left) a provided experiment about thermal equilibrium of an amount of water (of 50 °C) in nonrealistic condition in a real lab: the environment is set up to −20 °C. The graph at right is the expected synchronized graph that the student following the instructions in WS can take and the one that he is going to interpret. While it is common the study where an amount of water is heated

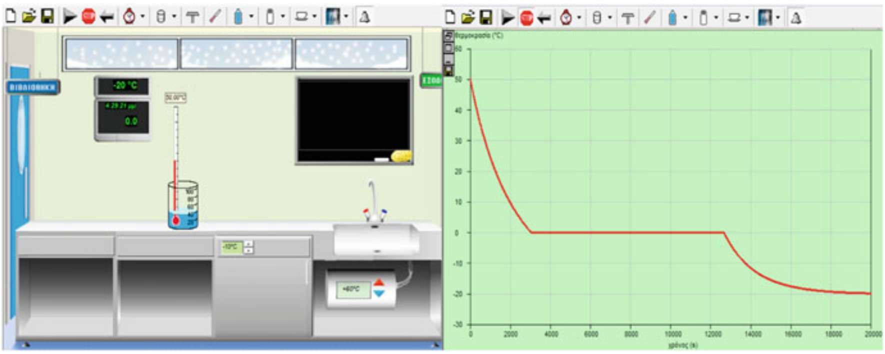

Fig. 11.5 An example of nonrealistic conditions in a real lab, left: the setup of the experiment and right: the synchronized graph

or cooled at room temperature, is not often cooling it in a workbench having a negative temperature, where change in the state of matter is encountered. All the above converge in that PST evaluate the web-VLs very positive in terms of usability and utility, not only by reporting that, but also as they use them to design activities in the developed WS. So we can say that the first research question is answered positively.

Evaluation of the WS

Answering the second research question, we note that they also implement the inquiry continuum in their WS. After introducing one step of inquiry continuum model in one of the lessons PST design a WS according to that step. So the PST not only were aware about that step of inquiry continuum model but also they practiced implementing their new knowledge into new WS. The evolution of WS is shown in Fig. 11.6: in the left, the WS is designed according to level 2a where the problem is stated and the equipment is given but the procedure and the answer are open, and,

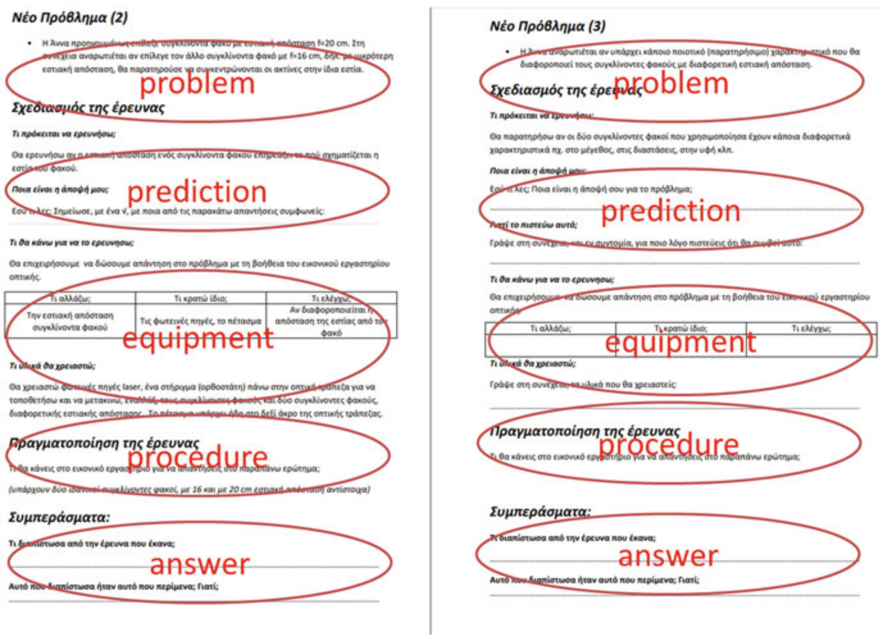

Fig. 11.6 An example of the design of the worksheets (WS): although the background text is in Greek, the implementation of inquiry continuum, which is the main point of this representation, is obvious. Left: WS according to level 2a and right: WS according to level 2b of the inquiry continuum. Note the difference under the term "equipment", referring not only to the equipment per se, but also to the experimental set up (control of variables): in the left WS is filled up, while in the right WS is blank

in the right, one page WS designed according to level 2b, where only the problem is given and procedure, equipment and answer are open.

At the interviews PST highlighted the importance and the usability of the course aiming at familiarization to design WS, so they can engage their future students in an experimental instruction according to the inquiry continuum model. Two aspects which describe well the overall impression of the PST, are: "*It was very useful to learn how to compose a WS. I'd never imagine that it could take so many forms*." and "*The WS we had used until this course was very guided so I thought that only this kind of WS exist, the 'cookbook' WS*." So we can say that the 2nd research question also is answered positively.

The intended learning outcomes are: PST to distinguish the steps of an experimental teaching and to become aware of various ways for students' engagement. In addition, PST should come across with the scientific inquiry from two perspectives, namely, from the point of view of a researcher so to be experienced in various steps of inquiry and from the point of view of a forthcoming teacher so to organize activities in various steps of inquiry.

PST consider themselves able to distinguish the steps of an experimental teaching (the 1st objective of the course), and they are sufficiently aware of various ways for students' engagement through WS (2nd objective of the course). Also they consider that they can design WS and organize activities in various steps of inquiry (3rd objective of the course). As shown in Fig. 11.7, PST self-evaluation have ranked positive ("high" and "very high") all the course objectives. PST ranked as "very-high" (9/12) the distinction of steps for an experimental teaching. This "very high" ranking was decreased (7/12) in the students' engagement in experimental teaching through WS and further decreased (6/12) in the design of WS in various steps of inquiry. Interviewing the PST, they attribute this declining "very-high" score to the few hours of practice, and to the fact that the WS they constructed were not

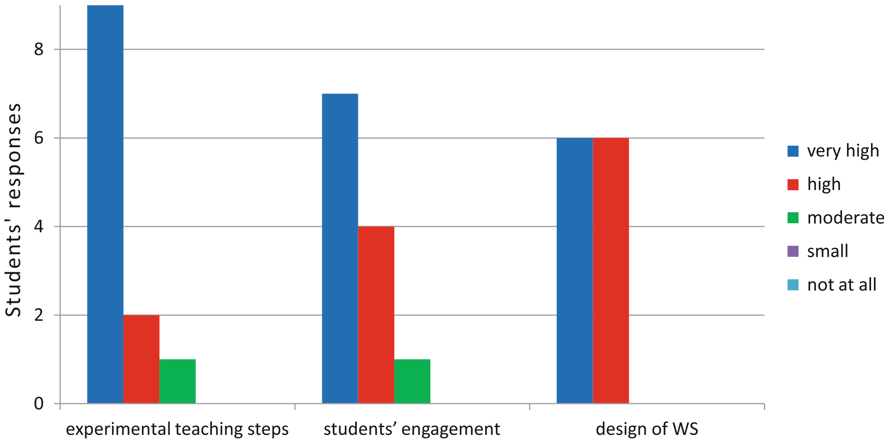

Fig. 11.7 Evaluation of the three objectives of the course

implemented in real (school) conditions in order to evaluate their effectiveness in practice.

Conclusions

In this work we propose a way for preparing PST how to develop inquiry based activities:

- The course is structured in 10 2-hour lessons, where PST are gradually introduced in the inquiry continuum levels,
- The teaching—learning scheme is composed of alternating introduction/homework/reflection lessons,
- As PST should have unlimited access to laboratory settings (even from home), we opted web-VLs that have the feel and look of a real one.

The course provides PST the opportunity to: gradually become introduced in the inquiry continuum levels and reflect and refine their own work, at their own places. Although the PST were inexperienced in designing WS at any method or strategy, much less according to inquiry continuum model, they managed to adopt the basic characteristics of web-VLs and design WS guiding their (future) students in inquiry instruction.

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Chapter 12
The Role of Information in Inquiry-Based Learning in a Remote Lab on Optical Spectrometry

Lars-Jochen Thoms and Raimund Girwidz

Introduction

Since Bohr discovered the relationship between optical spectra and the structure of atoms, spectrometry has served an important role in physics and chemistry. The analysis of spectra is a fundamental component for the understanding of wave optics and colour perception. Every student should have the opportunity to conduct his or her own optical emission experiments. Since spectrometers are expensive and require accurate calibration to obtain high quality spectra, the authors developed a remotely controlled laboratory on optical spectrometry. In this environment, six different customary light sources can be examined regarding emission spectra, the decrease of spectral irradiance with growing distance, as well as spatial characteristics of the radiation. In the following, essential educational aspects are discussed.

Experimenting in School

Experimenting is an essential part of physics and physics education (Duit and Tesch 2010; Hofstein and Lunetta 1982; Tesch an Duit 2004). This applies to every kind of demonstration experiments or student activity. Students in German upper secondary education recognize the crucial role of experiments, even though demonstration experiments dominate and student hands-on activities are rarely carried out (Baumert and Köller 2000). Demonstration experiments are often embedded in a teacher dominated, questioning-developing approach (Duit and Tesch 2010; Seidel et al. 2002). Student experiments are often constrained by precise instructions. However,

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instructional approaches that link theory and experiments and engage students actively should lead to a deeper understanding (Baumert and Köller 2000). The way of integrating experiments into the lesson plan determines the learning success (Harlen 1999; Tesch and Duit 2004). For the development of the learner's performance, not only the experimental time on task is critical, but also the total processing time, including preparation and review (Tesch and Duit 2004). Tesch and Duit (2004) assume that the large amount of time needed to carry out student experiments reduces the time for preparation and review in the classroom. They consider this as a possible reason, why student experiments do not generally lead to better performances (Hofstein and Lunetta 2004).

One conceivable option to relieve physics in-class teaching would be to conduct experiments as homework by means of a flipped classroom (cf. Crouch and Mazur 2001; King 1993; Mazur 1997). This would leave more in-class time for a thorough preparation and follow-up.

Four Levels of Inquiry-Based Learning

Banchi and Bell (2008) proclaim four levels of inquiry in activities with rising opening and withdrawal of predefined structure: confirmation inquiry, structured inquiry, guided inquiry and open inquiry.

- On the first level—confirmation inquiry—students confirm a principle through an activity when the results are known in advance.
- On the second level—structured inquiry—students investigate a teacher-presented question through a prescribed procedure.
- On the third level—guided inquiry—students investigate a teacher-presented question using student designed or student selected procedures.
- On the fourth level—open inquiry—students investigate questions that are student-formulated through student-designed or student-selected procedures.

Based on this classification, the authors developed a remotely controlled laboratory experiment on optical spectrometry with predefined set-ups selectable according to the class. This reduces the complexity of the lab activity for students. Students can carry out real experiments online. The experiment can be conducted by students remotely via the Internet. This allows ninth grade students (about 15 years old) to introduce themselves to atomic physics in a curricular valid way (Thoms and Girwidz 2015).

Before students perform the experiment, the experimental setup and the user interface for the operation of the trial should be known. Especially for inquiry-based learning, no additional mental load should be caused by a lack of familiarity with the new learning environment. Therefore, students receive pre-information regarding the experimental set-up and regarding the control of the experiment. Hereby the central research questions in this study arise:

- *Which* domain-specific knowledge should be offered to the students?
- *At what time* should it be provided?
- *How* should the information be presented?

In the following, implications for the design of the instructional material used in this study are derived from research on problem solving and discovery learning.

Influence of Domain-Specific Prior Knowledge on Discovery Learning

The idea of self-regulated learning takes cognitive and emotional perspectives of learning into account (e.g., Butler and Winne 1995; Schraw 1998). One intention amongst others is to foster interest (Krapp 1999, 2005), self-determination (Deci and Ryan 1993), or self-efficacy (Bandura 1997). Since self-regulation is necessary for effective intentional learning (Bereiter and Scardamalia 1989), learners should be able to self-regulate their learning process (Bransford et al. 2000). A suitable approach to foster self-regulated learning in physics education is discovery learning.

On the one hand, discovery learning can lead to a deeper understanding. On the other hand, learners may encounter difficulties during discovery learning (de Jong and van Joolingen 1998).

One feature of discovery learning is that domain-specific knowledge is accessed independently. Just this peculiarity—the lack of specific prior knowledge—is a factor for the difficulty of discovery learning, because students' ability to engage in self-regulated learning in turn depends on domain-specific knowledge (Brown and DeLoache 1978), what in fact stands in contrast to the initial idea of discovery learning.

Research on problem-based learning showed that learners with lower prior knowledge use less efficient problem-solving strategies less effective (Alexander and Judy 1988). This finding is transferrable to discovery learning (Lavoie and Good 1988; Schauble et al. 1991; Hmelo et al. 2000). This leads to the question, *which domain specific knowledge should be offered to students in a computer-based interactive learning environment inducing discovery learning?* Thereby, it must be considered that the knowledge of the meaning of variables per se is not productive, it is very important that students understand how variables are interrelated with each other (Lazonder et al. 2009).

The presentation of domain-specific knowledge *during* discovery learning stands in contrast to the initial intention of self-regulated learning. The question arises:

Should domain-specific knowledge be presented *before* or *during* a discovery-learning oriented unit?

Presenting domain-specific knowledge *before* a unit of self-regulated discovery learning is helpful (Leutner 1993). Presenting domain-specific knowledge *during* a unit is more supportive, especially for learners with low prior knowledge (Hulshof and de Jong 2006).

In a preliminary study, the information regarding the experimental set-up and the operation of that set-up was issued together with the instructional material. Observations made during the participants' experimental processing suggest that not all of the students have read the information attentively. These observations were confirmed in interviews with the students after the unit. Thus, the decision was made, to hand out the information as a pre-information five minutes before the instructional material and to advise the students to read the pre-information carefully. Afterwards, the cognitive load is measured and the students are asked whether they have read the pre-information attentively.

Hence, the decision is made, *when* to hand out the pre-information. The question remains, *which* information should be imparted to the students. More precise: *which kind* of information should be given?

Theories of Information

The term *information* is used in various ways across disciplines. Flückiger (1995) develops an interdisciplinary unifying concept of information. This should include all former theories of information and takes into account approaches from physics, cybernetics and information sciences. From this, Flückiger (1995, 1997) names and distinguishes two theoretical trends that initially seem incompatible: *structural-attributive* and *functional-cybernetic* theories of information. A third trend is the concept of *pragmatic* information (cf., Morris 1938; Weizsäcker 1971, 2014; Weizsäcker and Weizsäcker 1972) which has explicit relevance for the design and investigation of teaching and learning processes.

Based on these theories of information the instructional material is varied in the following study. So, these three tendencies in theories of information determine the three factor levels of the independent variable.

Text Difficulty

The amount and nature of the information presented has an unavoidable effect on the information-bearing medium. For example, the complexity of a text is decisively influenced by the information contained therein: Structural-attributive information can be separated well and organized in a point-like manner, while functional-cybernetic information by definition always functionally links structural units. Therefore, in the following study, the difficulty of the text must be controlled.

The analysis of the difficulty of the text can be restricted to surface characteristics or can be extended to the depth structure of a text. The evaluation by means of surface characteristics can be easily operationalized and objectivized. Different procedures take into account, for example, the number of letters or syllables per word or sentence (e.g., Bamberger and Rabin 1984) or count the word and sentence lengths (e.g., Flesch 1948) and form different quotients to compare. The difficulties caused by the depth structure of a text can, however, be difficult to operationalize. Nevertheless, there are extensive expert ratings based on operationalized criteria catalogues which allow a good estimate (e.g., Langer et al. 2011).

Since in this study the subjectively *perceived* difficulty of the text is of particular interest, this should be gathered with a self-rating scale.

Cognitive Load

The cognitive load is decisively determined by the task, the subject, and the interaction effect task $\times$ subject.

By definition, the *mental load* describes the contribution to *cognitive load*, which is caused by the task and the environmental conditions and is therefore independent of the subject. In contrast, the *mental effort* and the *performance* are determined by all three causal factors—the task, the subject, and the interaction effect of the task $\times$ subject (Paas et al. 1994). In the following investigation, the mental load caused by the text of the pre-information is determined. The mental effort in word processing is also measured.

In this partial study, a scale for the measurement of the perceived task difficulty is adapted for the measurement of the perceived text difficulty. The perceived task difficulty is a good measure for the cognitive load (Ayres 2006; Paas et al. 1994; van Gog and Paas 2008). Although perceived task difficulty is often seen as a measure of mental effort, it must be borne in mind that the perceived task difficulty and the mental effort are two highly correlated but different constructs (van Gog and Paas 2008).

To check for the model fitting, the following hypotheses are postulated:

H.1 The perceived text difficulty correlates positively with the mental effort.
H.2 Subjects distinguish between perceived text difficulty and mental effort.

In addition, the perceived depth of text processing (reading attentiveness) is measured.

Methods

To afford students inquiry-based learning in a remote lab experiment on optical spectrometry, pre-information on the experimental set-up and processing is offered.

Participants

In the quasi-experimental laboratory study presented here, 94 pupils (44% female) from four classes from three Bavarian high schools participated. Students were randomly assigned to the experimental conditions. In order to minify the potential influence of prior knowledge, the date of the study was set in a way that ensures that the topic was not taught in class before.

Instructional Design Based on Informational Theories

The implications that arise from the different informational theories become visible in the design of learning materials. The following three examples are excerpts from the learning material designed and used in this study and from part of the description of the experimental set-up. It should be noted that the information is reduced and simplified to target pupils of the ninth grade. The clarification follows later.

Structural-Attributive Information

Based on structural-attributive theories of information students receive information on the single parts of the experimental set-up:

> On the horizontal axis *is* the photon energy in electron volts (eV) and on the vertical axis *is* the acquired radiation energy in nano joules (nJ).

From a student's perspective, structural-attributive information serves to *orientate*.

Functional-Cybernetic Information

Taking into account functional-cybernetic theories of information, students get information on how the single parts of the experimental set-up function and how they interact with each other:

> *Here is* the acquired radiation energy in nano joules (nJ) on the vertical axis *plotted against* the photon energy in electron volts (eV) on the horizontal axis.

The functional-cybernetic information helps students to *link* parts of the experimental set-up with each other.

Pragmatic Information

Here, students get information on which actions can be conducted with the experiment and what significance each part of the experimental set-up has for the user:

> *For each value* of photon energy in electron volts (eV) on the horizontal axis, *you can read* a value for the acquired radiation energy in nano joules (nJ).

Pragmatic information should lead students to *act* in a proper way.

Text Difficulty of the Instructional Material and Mental Load

A particular challenge in the design of the instructional material is that the text difficulties of the variants should differ as little as possible. Of course, the number of the entities to be described increases from the structural-attributive description of individual things to the functional-cybernetic description of their connections. Hence, an increase in the necessary text volumes and thus the objective difficulty of the text cannot be avoided. It would also not be advisable to artificially increase the amount of text in the structural-attributive description, thus endangering the external validity of the investigation. Instead of the objective text difficulty, the subjectively perceived text difficulty is to be kept comparable.

Measuring Cognitive Load

The cognitive load was measured immediately after the pre-information has been read with a short questionnaire. This prompt measurement allows a good estimation of the cognitive load caused by the task processing (Paas 1992; Paas and van Merriënboer 1993).

The questionnaire contains four items with symmetrical seven-point subjective rating scales. Although the measurement of cognitive load with single-item self-rating scales is also criticized (Brünken et al. 2003), subjective rating scales represent a valid and reliable test instrument for cognitive load caused by the variation of the instructional material (Ayres 2006; van Gog and Paas 2008; Gopher and Braune 1984; Paas and van Merriënboer 1993; Paas et al. 1994).

In order to keep the questionnaire consistent, 9-point scales were rearranged to 7-point scales. The self-rating scale for the measurement of the perceived task difficulty by Bratfisch et al. (1972) was adapted for the measurement of the perceived text difficulty:

> Den Text empfand ich als … 1—sehr einfach … 7—sehr schwierig. [I perceived the text to be … 1—very simple … 7—very difficult.]

Paas (1992) has adapted the scale for the measurement of the perceived task difficulty by Bratfisch et al. (1972) for the measurement of the perceived mental effort. Marcus et al. (1996) shortened the scale from Paas (1992) to seven points. This scale was adapted to the German linguistic usage:

> Um den Text zu verstehen, musste ich mich . . . 1—sehr wenig anstrengen . . . 7—sehr stark anstrengen. [To understand the text, I had to make . . . 1—very low mental effort . . . 7—very high mental effort.]

For the measurement of the mental load caused by the subjectively perceived text difficulty, a scale was built based on the scale for the measurement of the perceived text difficulty:

> Der Text war . . . 1—sehr leicht zu verstehen . . . 7—sehr schwer zu verstehen. [The text was . . . 1—very easy to understand . . . 7—very difficult to understand.]

Additionally, participants responded how attentively they have read the pre-information:

> Ich habe den Text . . . 1—nur überflogen . . . 7—aufmerksam gelesen. [I have read the text . . . 1—loosely . . . 7—attentively.]

Results

Correlation Between Perceived Text Difficulty and Mental Effort

There was a significant positive correlation between the perceived text difficulty and the mental effort [$r = 0.586$, $n = 49$, $p < 0.001$]. The hypothesis H.1 is thus confirmed: The perceived text difficulty correlates positively with mental load.

Distinction Between Perceived Text Difficulty and Mental Effort

In order to test the hypothesis that students differentiate between perceived text difficulty and mental effort, a two-factor repeated measures analysis of variance was carried out with factors *subject* (factor steps: case number) and *item* (factor steps: perceived text difficulty and mental effort). There is a significant effect of the factor item on the measured value of the respective item on the 5% level [$F(1, 93) = 4.1701$, $MSE = 0.568$, $p = 0.008$]. The hypothesis H.2 is thus confirmed: The subjects distinguish between perceived text difficulty and mental effort.

Effect of Pre-information on Perceived Task Difficulty

A one-way between-subjects analysis of variance was conducted to compare the effect of pre-information on perceived text difficulty in structural-attributive, functional-cybernetic, and pragmatic conditions. There was no significant effect of pre-information on perceived text difficulty at the $p < 0.05$ level for the three conditions [$F(2, 91) = 0.268$, $MSE = 1.281$, p = 0.765].

Effect of Pre-information on Mental Load

A one-way between-subjects analysis of variance was conducted to compare the effect of pre-information on mental load in structural-attributive, functional-cybernetic, and pragmatic conditions. There was no significant effect of pre-information on mental load at the $p < 0.05$ level for the three conditions [$F(2, 91) = 1.485$, $MSE = 1.441$, p = 0.232].

Effect of Pre-information on Mental Effort

A one-way between-subjects analysis of variance was conducted to compare the effect of pre-information on mental effort in structural-attributive, functional-cybernetic, and pragmatic conditions. There was no significant effect of pre-information on mental effort at the $p < 0.05$ level for the three conditions [$F(2, 91) = 1.892$, $MSE = 1.445$, p = 0.157].

Effect of Pre-information on Reading Attentiveness

The participants read the pre-information attentively according to their self-rating ($n = 94$, $M = 5.84$, $SD = 1.102$).

Furthermore, there were differences to be noticed regarding the reading attentiveness between the intervention groups, that will be analysed in the following in an explorative manner (Table 12.1).

Levene's test for equality of variances was found to be violated for the present analysis ($p = 0.002$). Owing to this violated assumption, a Brown-Forsythe test was

Table 12.1 Means and standard deviations of reading attentiveness depending on pre-information

Pre-information	n	M	SD
Structural-attributive	32	6.25	0.762
Functional-cybernetic	31	5.84	0.779
Pragmatic	31	5.42	1.285

conducted to compare the effect of pre-information on reading attentiveness in structural-attributive, functional-cybernetic, and pragmatic conditions. There was a significant effect of pre-information on reading attentiveness at the $p < 0.05$ level for the three conditions [Brown-Forsythe's $F(2, 70.401) = 5.729$, $MSE = 0.942$, $p = 0.005$]. The estimated omega squared ($\omega^2 = 0.81$) indicated that pre-information accounts for approximately 81% of the variance in attentional reading for this sample.

Post hoc comparisons, using the Games-Howell post hoc procedure, were conducted to determine which pairs of the three pre-information means differed significantly. These results indicate that students with pragmatic pre-information ($M = 5.419$, $SD = 1.285$) had a significantly ($p = 0.009$) lower average score on the measure of attentional reading than students with structural-attributive pre-information ($M = 6.250$, $SD = 0.762$) as well ($p = 0.009$) as students with functional-cybernetic pre-information ($M = 5.840$, $SD = 0.779$). The effect sizes for these two significant effects were $d = 0.786$ and $d = 0.395$, respectively.

Discussion

Although the level of mental effort and the perceived text difficulty correlate positively, the subjects clearly distinguish between the two constructs. This finding supports the validity of the test instruments and also supports the fit of the model of cognitive load to the setting of this investigation.

In this study, the type of pre-information was not observed to have any significant influence on the perceived text difficulty, nor on the mental effort, or mental load generated by the text. Thus, the instructional material was successfully designed in such a way that the perceived text difficulty was kept constant through the variation of pre-information.

All in all, the students specify to have read the pre-information attentively. Furthermore, the kind of pre-information has a significant effect on the students' self-rating how attentively they have read the pre-information. The mean values of reading attentiveness were highest for the structural-attributive pre-information, lower for the functional-cybernetic pre-information, and lowest of all in the case of pragmatic pre-information. Of the total variation in average score on students' measure of reading attentiveness, approximately 81% is attributable to the type of pre-information.

The question of how the type of instructional material affects performance and knowledge acquisition then arises. In order to answer this question, greater in-depth analysis is necessary. In doing so, the variation in the self-rating of reading attentiveness should also be considered.

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Chapter 13
Web-Based Interactive Video Activities for Undergraduate Advanced Laboratories

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Introduction

Advanced laboratory experiments and projects can involve a high level of sophistication and complexity both in terms of concepts and instrumentation (Fig. 13.1). To ease the transition from the relatively simple lab experiments of introductory courses to advanced ones, we have developed a set of interactive web-based pre-lab activities. They are designed to provide an interactive lab-like environment that focuses on the essence of the lab topic, but is stripped of many of the complexities of the true lab experience. We anticipate that they will enrich learning and student enthusiasm in the advanced lab topics, provide a solid introductory framework to the physics, and lead to more meaningful experiences inside the laboratory.

The activities are built using software created in the LivePhoto Interactive Video Vignettes project (Laws et al. 2015). Interactive Video Vignettes are implemented using JavaScript and HTML5, so they run on tablets as well as laptop or desktop computers. *Vignette Studio*, a free, easy-to-use Java application being created by the project, allows instructors to make their own vignettes (Teese et al. 2016). Using its drag-and-drop interface, a developer moves pages into place on a workspace. Individual elements, such as images, videos, questions, video-analysis modules, graphs and so on can be dragged into place on each page. The user's input on one page can be echoed back on a different page, allowing users to compare their predictions to the results of experiments. Question-based branching can be set up, so each answer to a multiple-choice question links to a different next page. In this

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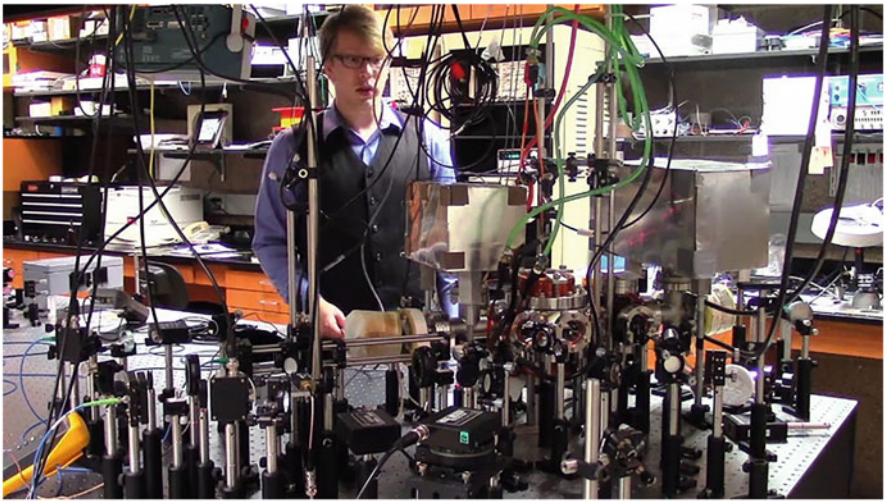

Fig. 13.1 The magneto-optical trap lab. Advanced labs are typically much more complicated than labs in introductory courses

way vignettes can provide remediation that is specific to the user's needs. *Vignette Studio* and its instruction are available for download (Teese 2017) so anyone can author vignettes.

The activities we have created focus on three topic areas that have been the foundation for student projects in the Bethel University physics department: (1) compressible fluid mechanics, (2) atomic molecular and optical (AMO) physics, and (3) plasmonics and nano-optics. In each activity, students carry out online video measurements and analyses of experiments pertaining to the test parameters they select. Students at Bethel University and other institutions used the activities while assessment data on student usage and performance was collected and analysed.

Examples of Activities

Ping-Pong Cannon

The ping-pong cannon, also known as an expansion tube accelerator, is a popular physics demonstration that captures the excitement of diverse audiences ranging from elementary school students to physics professors. With the cannon, a ping-pong ball is accelerated to speeds of approximately 300 m/s over a distance of 2–3 m using atmospheric pressure alone. At Bethel, student intrigue with the cannon has led to numerous undergraduate experimental studies and numerical simulations on the underlying physics behind the ping-pong cannon (Peterson et al. 2005; Olson et al. 2006).

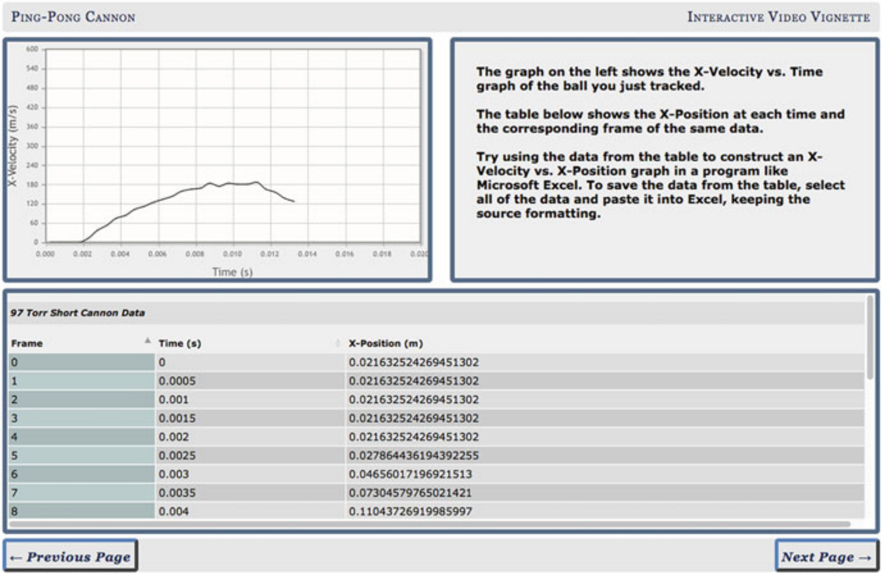

Fig. 13.2 A position versus time graph of a ping-pong ball moving inside a transparent cannon. The student user made the graph by video analysis on the previous page of the vignette

An advanced laboratory vignette describes the construction and basic operation of the Bethel ping-pong cannon and allows the user to study the behaviour of the ping-pong cannon under user-selected test conditions. The user can take frame-by-frame measurements by clicking on the ball in each frame of a high-speed video to display a velocity versus time graph of the ping-pong ball for the selected test conditions. Position versus time data is displayed in tabular form and can easily be copied into a spreadsheet for further data analysis (Fig. 13.2).

The conclusion of the activity provides the user with an opportunity to dig deeper into the compressible flow physics of and shock dynamics that are associated with a ping-pong cannon. Upon completion of the activity, most users will have learned that the underlying physics of a "simple" ping-pong cannon is much more involved than one might initially think.

Magneto-Optical Trap

The magneto-optical trap (MOT) uses three pairs of counter-propagating laser beams and a magnetic field gradient to trap atoms that have been slowed and cooled to less than 1 mK (Klemme and Hoyt 2012). Our vignette explains the basic features of the 7Li MOT at Bethel and lets the user make temperature measurements of the trapped atoms (Horstman et al. 2015). Several different types of temperature measurements can be made; here we use a time-lapsed video technique that images the atom cloud

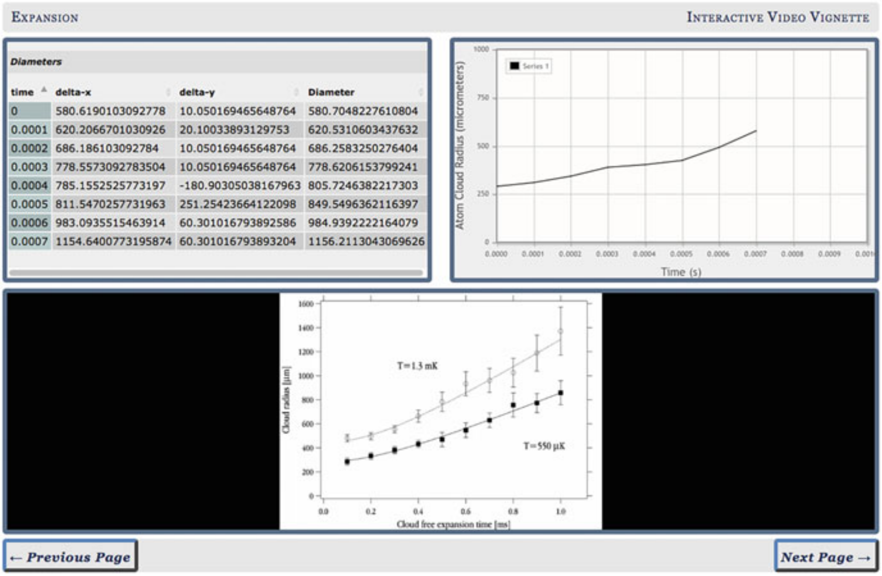

Fig. 13.3 A radius versus time graph of an expanding cloud in the MOT apparatus. The student user made the graph by video analysis on the previous page of the vignette. The measurements are used to find the atomic temperature

at various times via absorption of an on-resonance laser beam after the trap is turned off. The user of the vignette can click-and-drag across the atom cloud for several time delays (frames of the video) and plot the result to see the cloud's expansion (Fig. 13.3). Higher temperatures correspond to faster expansion. Careful Gaussian fits to the cloud and a theoretical fit to the data can yield an accurate measurement of atomic temperature. In our case, the user interacts with 7Li atoms at about 800 μK.

Brownian Motion

Microscopy is used heavily in nanotechnology related coursework and research at Bethel (Lindquist 2014). This vignette provides students a basic background on lighting, sample preparation, oil-immersion microscope objectives, and imaging of the motion of small (~1 μm) particles suspended in liquid. There are several different bead sizes—the smaller the bead, the more the Brownian motion. Students are asked to track the motion of a single bead and plot its (x, y) coordinate in time. After completing this exercise for the different sizes, students are asked to compare the different trajectories. Beyond providing a basic exposure to the behaviour of microscopic objects, the vignette also allows students to see how an experiment involving the microscope system is approached (Fig. 13.4).

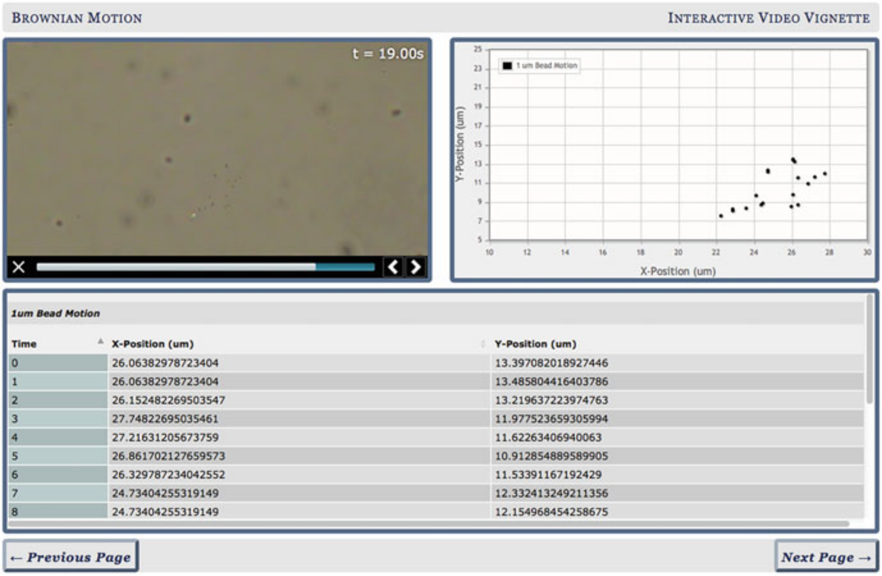

Fig. 13.4 By clicking on a particle in each frame of the video on the left, a student records its position in the y-versus-x graph on the right and the data table below it

Assessment

Classroom-based assessment concentrated on the effectiveness of an Advanced Laboratory vignette that examines the physics of a ping-pong cannon. The ping-pong cannon is a common introductory physics classroom demonstration that can be partially explained based on elementary air pressure concepts, but also has interesting physical complexities, such as compressible fluid dynamics and shock waves. Assessment occurred in the courses PHY292 (calculus-based introductory physics) and PHY422 (Fluid Mechanics) at Bethel University proceeding and following the vignette. One of the characteristics with the ping-pong cannon is the detachment of the tape from the cannon before the ball reaches the end of the tube. Before completing the vignette, the introductory-level students were reasoning through the problem to describe the tape detachment based on air, either air passing through the tube or some pre-existing air in the tube (33 and 40% respectively, see Fig. 13.5). After the vignette, students shifted towards reasoning about the role of shockwaves (78% of total responses) and only minimally reasoned about air alone (2%). This trend was also observable with the 400-level physics students, showing a shift from the 36% that originally reasoned about pre-existing air in the tube (0% after video). Nearly all students in the upper-level physics course ended their reasoning with the role shockwaves played (89%) whereas the introductory students maintained a greater spread in their final reasoning (Fig. 13.6).

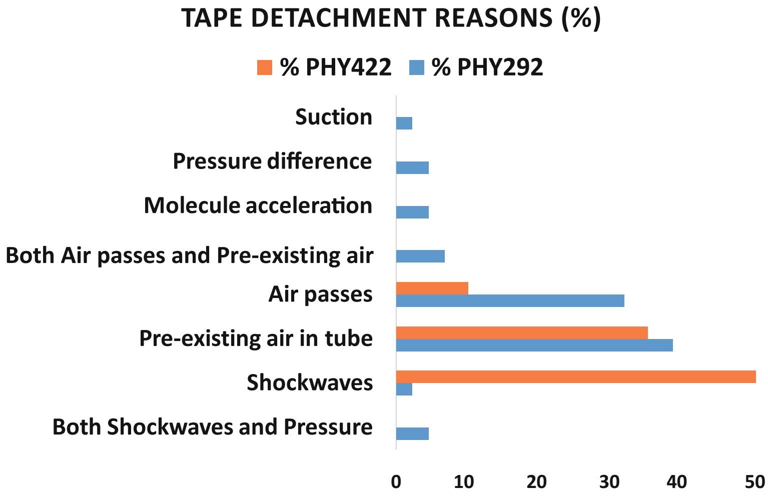

Fig. 13.5 Student reasons given before seeing the vignette assignment for the detachment of the end tape before the ball arrived at the end of the cannon. Student responses in two different courses (PHY422 advanced and PHY292 introductory) are compared

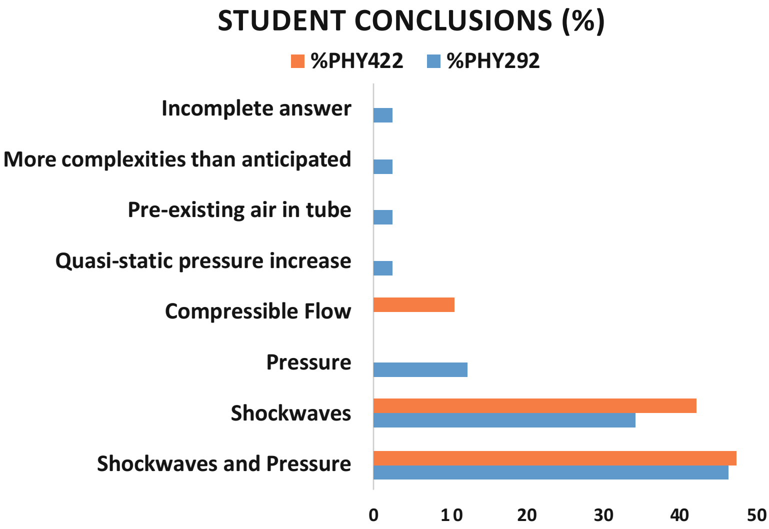

Fig. 13.6 Student conclusions after vignette completion about important effects in the ping-pong ball cannon. Student responses in two different courses (PHY422 advanced and PHY292 introductory) are compared

In completing the vignette, students were asked to estimate the exit velocity of the ping-pong ball based on the test conditions and to compare their prediction to the video-based velocity measurement. Interestingly, a significant percentage of the

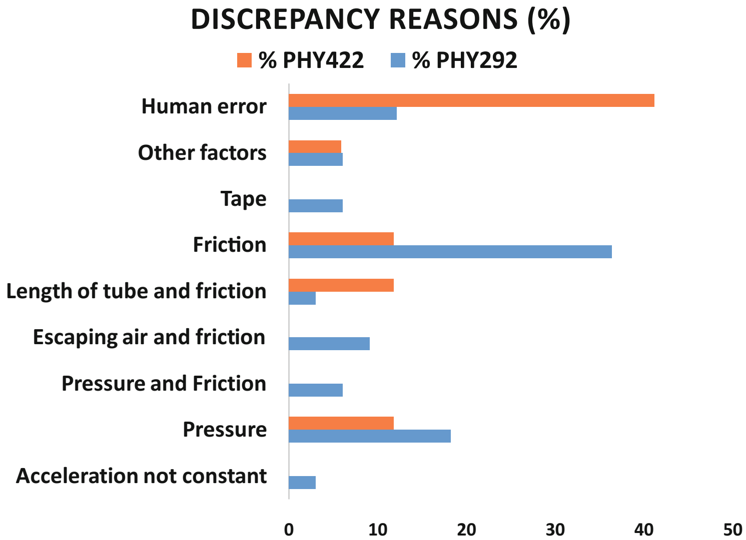

Fig. 13.7 Reasons given by students for discrepancies between their predictions and the results of their ping-pong ball exit velocity measurements. Student responses in two different courses (PHY422 advanced and PHY292 introductory) are compared

introductory level students (PHY292; 36%) demonstrated a pre-conception that the discrepancy between the predicted and measured velocities could be explained in terms of friction whereas only 12% of the PHY422 students listed this as a possibility. Interestingly, the PHY292 students had just covered this topic in class and could possibly have been working to apply this new understanding to a novel topic without further physics reasoning to know whether or not this application was realistic. In addition, upper-level students were more likely to attribute the discrepancy to human error than introductory students (Fig. 13.7). These responses suggest that physics students are responding developmentally to these questions. It is possible that the more expert-like one becomes in their thinking about the discipline, the more one realizes what they don't know. Upper level students could be displaying this phenomenon here when they identify human error as a possible way to explain the discrepancy. Alternatively, these students could be more novice in their thinking and be using human error as a "catch-all" to explain something when they are not sure of the reason. Overall, these results show a shift (Figs. 13.5, 13.6 and 13.7), identifying that students are moving closer to accurate explanations of the discrepancy after completing the interactive activity.

We also conducted a faculty survey at two physics meetings in 2015. The first (2015 Minnesota Area Association of Physics Teachers Spring Meeting at St. Cloud State University) served as a pilot survey and the data informed the development of the second data collection following a workshop on the vignettes. The workshop was at the 2015 Conference on Laboratory Instruction Beyond the Frist Year of College (BFY 2) at College Park in July of 2015. Results from these sessions show that faculty value all three components of the physics vignettes as essential (i.e., introductory video, data analysis, inquiry activity). Faculty found the level at which students engage with the videos to be high (mean = 1.36 + 0.67 (SD); where 1 is high; exceeding expectations), and were encouraged to use and develop their own vignettes. Some did suggest that the inquiry portion of the video give the students even more control by allowing them to design measurements that would help them identify which model best explains the discrepancy in the results. In addition, faculty reported that the vignettes were likely to enhance their teaching of concepts in the lab (1.67 + 0.78), effectively build confidence in students (1.83 + 0.58) and inspire physics students (1.92 + 0.9). Thus, the data show that these vignettes have the potential to be useful to other colleagues teaching physics.

Conclusions

The web-based activities developed in this project utilize interactive video to provide a means for immersing the student into the complexities of the advanced lab in a systematic, guided fashion, providing the student with preparation and an increased level of confidence for effective undergraduate engagement in the lab. The activities will be openly available at https://www.ComPADRE.org/ALIV/ to instructors and students engaged in the advanced laboratory. Additionally, the *Vignette Studio* software used to construct the activities is available as open source along with complete documentation, enabling other institutions to build activities based on their own advanced labs and undergraduate research, thus opening the doors of the advanced laboratory community to a broader audience. The activities provide a powerful depiction of advanced laboratory concepts as a web-based resource that is easily accessible to a broad public audience.

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Chapter 14
Smartphones as Measuring Instruments in the Physics Classroom: What Do Students Think?

Angela Oswald, Gerhard Rath, and Claudia Haagen-Schützenhöfer

Introduction

Smartphones are ubiquitous to modern life and many students use them daily for private purposes. However, the use of smartphones in education has been the subject of controversial discussions (e.g. Muuß-Merholz 2015). Educators in favour of using private mobile devices inside the classroom describe them as handy tools that students know very well. The “bring your own device” (BYOD) approach is per se not limited to smartphones, but has some special implications when applied to smartphones. For example supporters point out the motivational aspects a device mainly connected to leisure activity might bring to the classroom. Common applications are research of information and documentation of classroom activities, as well as interactive learning. For physical purposes built-in sensors make smartphones also potential measuring instruments. Both the physical quantities that can be measured using smartphones and the physics that makes smartphones work, provide technical arguments for their use in physics education. This discussion however is mainly centred around the educators’ perspective. The study presented in the following aims to change the viewpoint by asking what students might have to say about the smartphone as a tool for lab work and which beliefs they might bring to the physics class.

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Study

The study was conducted during three weeks in Nov/Dec 2015. It involved a series of experiments using smartphones and was complemented with some basic theoretical input during three consecutive physics lessons. The 25 participating students (17 male, 8 female) were aged from 14 to15 and had already used the smartphone in the physics classroom on different occasions. The experiments were conducted in groups of 2–4. Lab reports, written reviews and follow-up interviews formed the base for the qualitative analysis that focused on two aspects:

1. What are the students' beliefs about the smartphone as a measuring tool?
2. Which aspects do they address that may be relevant for planning learning paths based on smartphones?

The first set of experiments included a vertical jump force estimate using (a) the smartphone accelerometer (smartphone tied around the waist) and (b) the analogue "jump and reach" method. The latter translates jump heights into jump force in a simplistic model using the concepts of potential energy and work (see e.g. LEIFI 2016). The students stretch their arm and mark heights at a wall, when they are standing tall (neutral position), have their knees bent (jump start) and reach the maximum jump height. Jump force can then be calculated using upward acceleration length s (jump start to neutral position) and actual jump height h (distance neutral position to maximum jump height), as well as the jumper's mass (m) and gravitational acceleration (g) using $m \cdot g \cdot (h + s)/s$. Model and measurement process are not very sophisticated and are prone to inaccuracies.

The students were asked to document their measurements and answer some questions that compared the methods. Results were shortly discussed in the next lesson and some theoretical input was given on the smartphone acceleration measurement including a practical part. The concluding experiment was to calculate the average speed of a ball kicked at a wall (Vogt et al. 2015). This required measuring the distance with a tape measure and determining the time interval using an "oscilloscope" smartphone app, that recorded the sound peaks of the ball being kicked by the foot and the ball hitting a wall versus time. Again, students were asked to document their experiment. Their final task was to write a short review on the "smartphone as a measuring tool", based on their experiences and general ideas. Eight Students were later interviewed to discuss some of the stated ideas in a little more detail.

Results

Lab reports were kept short, but indicated that all groups managed to retrieve a numerical result from the jump and reach method, even though some results lacked the proper units or similar. The smartphone acceleration measurement required

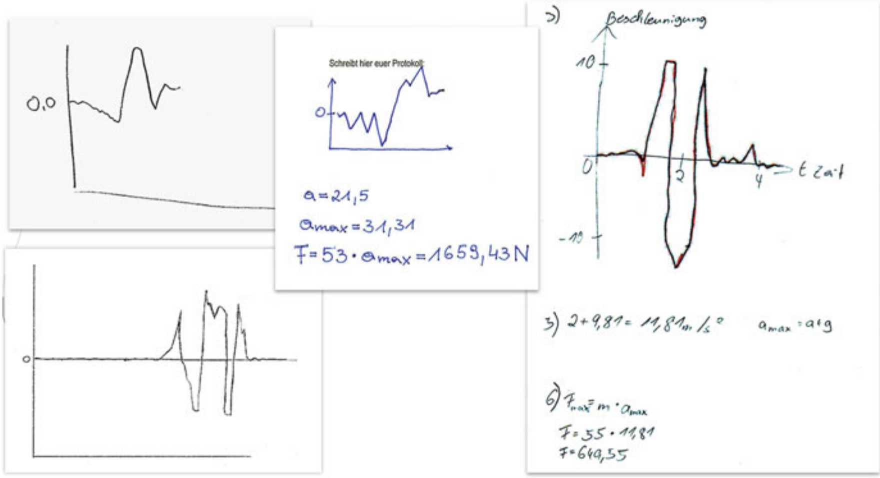

Fig. 14.1 Some samples of lab reports from the smartphone acceleration measurement. Many groups only copied the smartphone screen without any further attempt to identify the in the lab manual indicated value

reading the maximum value from a graph following an example in the lab manual. Only half of the groups managed to obtain the required numerical in this experiment; the other groups only attempted to copy the graph (typically without axes labelling) from the smartphone display (for some examples see Fig. 14.1).

Interestingly three out of the four groups that were not able to obtain the required numerical result stated to be "very satisfied" or "satisfied" with their measurement in a questionnaire. This may hint at the belief that a smart technical device has still provided the result and that the smartphone display may be interpreted as the final result anyhow. When asked to compare the analogue jump and reach method to the smartphone method, groups in favour of the smartphone method also state that the smartphone is more accurate, while humans are more prone to error. Groups which preferred the other method called the jump and reach method either more fun ("active measurement"), or claimed that a result is more easily obtained by using easily obtained values in a formula. One group stated that they distrust the smartphone as a measuring device and that it is not accurate.

The statements in interviews and reviews were centred around three categories: motivational aspects, assessments of smartphones as measuring tools and practical issues. Tables 14.1 and 14.2 provide an overview on the different and sometimes polarized views. There were students who stated that they liked the experiments, as well as there were students who disliked the smartphone experiments (Table 14.1), some of those hinting at difficulties experienced during measurements. When it comes to the smartphone as measuring device, students discussed a lot of different aspects like accuracy and reliability, where some quite opposing beliefs seem to exist (Table 14.2). Other students compared the smartphone to "regular" measuring instruments or discussed its variable usability in different contexts like school or

Table 14.1 Students' statements representing different opinions from written reviews and interviews concerning motivational aspects

The smartphone experiments were . . .	
. . . funny *. . . interesting*	*. . . boring* *. . . funny but not interesting* *I didn't like it so much, because sometimes things don't work.*
Would you like to do something like this more often?	
I would like to do something like this more often. *Yes, it's different.* *Yes, more often.* *From time to time.*	*Honestly, I've had enough of this.* *So-so, sometimes it is exhausting, when things don't work.*

Table 14.2 Students' statements representing different opinions on the smartphone as a measuring device from reviews and interviews

Accuracy	
The smartphone is better for jump force measurements, because *. . . it is more accurate.* *I like it [the smartphone], because it can be very accurate.*	The *Jump and Reach* method is better, because *. . . a smartphone can be inaccurate.* *The results are okay; sometimes not that accurate.*
Reliability	
The smartphone is better for jump force measurements, because *. . . humans make more mistakes than technical devices do.* *You do realize, when something completely wrong is displayed.*	*. . . because we don't trust smartphones.* *I would not use a smartphone for an important piece of work.* *These apps could just output anything.*
Comparison with [other] measuring instruments	
It is handier than big measuring instruments. *Yes, you can do physics measurements, but I still think that ["real"] measuring instruments are better.* *I would not really use a smartphone for something scientific.* *Something cheap is for sure not as good as a smartphone, but expensive measuring instruments are for sure better than a smartphone.*	
Does the context matter?	
Smartphones allow measurements for *"everyman", "hobby physicists"* *They are okay for school.* *For simple use a smartphone is probably better (handier), because it is one device that combines a lot of stuff.*	

science. Some statements hint at the belief that a smartphone is a very accurate measuring instrument per se, which can facilitate the measuring process and also take over part of the analysis. Others, however, question its reliability as it has not been built and tested for measuring purposes. Another interesting observation is that some students referred to the smartphone as an entity, while others differentiated between the smartphone and the apps. Many students pointed out practical issues, which should also be considered by teachers when planning lessons that involve smartphone activities.

How does this sum up with respect to the research questions? Even in this small sample, students express very different beliefs about the smartphone as a measuring device. One of three main ideas seems, that this fancy technical device is to be trusted per se. Statements like “the smartphone is (more) accurate” (something never investigated during the trial experiments) hint at this way of thinking. Also the opposing belief, that a smartphone is not built for measuring purposes and should not be trusted in this context (e.g. “these apps could just output anything”) is expressed in the trial class. A third group of students differentiates the smartphone’s capabilities in various measurement situations like science (“I would not really use it for something scientific”), school (“they are ok for school”) or hobby (they are useful for “hobby physicists”). The individual statements may of course be linked to success and failure during the measurements and the perception of the smartphone as an entity or a computer used by apps of varying quality.

Above is also relevant for the second research question. In order to keep the focus on the intended learning achievements, planning should take into account, that the perception of smartphones as measuring devices may vary widely even within a small group of students. Practical issues are similar to other BYOD situations. Some students explicitly expressed the need for more detailed instructions, others suggested that the apps should be installed and tested beforehand, so that the actual measurements work more smoothly. Although most students responded positive to the use of smartphones, one should not assume, a smartphone will automatically enhance motivation for all participants, as some critical remarks show.

Conclusion

This small qualitative study shows that students may have very different ideas about the smartphone as a measuring device. Some may have the idea that a smartphone can take over the complete measurement process and is per se reliable; others show a general distrust—both probably linked to a more general belief in the power of technical devices. However, some students of the trial showed a differentiated view by discussing a smartphone’s application in different context such as school or science. Students of the trial class had also made very different experiences (success to failure) during their measurements, often related to difficulties getting the apps to work properly (either caused by the smartphone/software or the user). Some asked for more assistance in the future, such as a very detailed introduction into the apps. This variety of views and skills may add an additional challenge to many aspects of BYOD implementation. It also emphasizes the need for in-depth planning of smartphone measurements and suggests making the smartphone, its purpose and limitations for the actual measurement process, part of the discussion.

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Part IV
Concepts and Lab

Chapter 15
Addressing Some Common Difficulties in Teaching and Learning Energy in High School

Michele D'Anna

Introduction

It is interesting to note how, albeit in different shades, the results of the countless studies devoted to the difficulties with energy teaching encountered by students (and teachers) converge substantially on the same aspects, regardless of whether the authors have experience in teaching or in science education research (Jewett 2008; Brewe 2002; Millar 2005; Swackhamer 2005; Doménech et al. 2007; Logman et al. 2009; Papadouris and Constantinou 2012; Papadouris et al. 2014).

In particular, a lot of studies focused on the difficulties connected with the concepts of energy *conservation* and energy *degradation* (Duit 1981; Duit and Haussler 1983; Daane et al. 2008, 2014); others investigated issues that, at least partially, cannot be considered specific to energy: the ontological conceptions of the students (Brewe 2011; Scherr et al. 2012), varying from conceiving energy as a substance-like fluid to recognizing it as an abstract quantity; the concept of energy in the language used by students and textbooks, in the everyday language or the use of models and metaphorical images (Lancor 2014); the relevance and the role of the historical development of the energy concept in teaching (Bevilacqua 2014); the development of tools to overcome the limits of an approach focused mainly on mechanics, allowing a correct interdisciplinary one (Ross 1993; Quinn et al. 2012; Dreyfus et al. 2014; Scherr et al. 2016); the relationship between theory construction and the epistemological and didactical role of experimental situations that are proposed in classroom (Sexl 1981; Bécu-Robinault and Tiberghien 1998).

My experience as high school teacher and teacher trainer made me conclude that in each of these particular points of view there is something valuable and useful: nevertheless, the outlined countermeasures remain excessively tied to the traditional presentation of energy, and therefore do not provide students with really effective

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tools to overcome the conceptual difficulties observed. Before starting with the illustration of my proposals, I'll also mention the chapter by H. Quinn *A physicist's Musing on Teaching about Energy* in (Quinn 2014), written from an unusual perspective, and with several considerations at a disciplinary level and a number of interesting challenging questions about their educational achievement. The concept of energy is present in many facets even outside of physics. Therefore, to be able to teach it, it is necessary to know and be able to discuss in detail each of these particular facets in their local significance, rather than seeking to impose a standardized solution, making the students lose the opportunity to build a coherent mental picture of their energy concept.

To start illustrating my proposal I refer to a work by Duit (2014), in which he presents, collects and systematizes the results of a large number of studies, introducing, on a first level, the conceptual frame from which my proposal will emerge. Summing up the general categories whose understanding seems necessary to solidly seize the concept of energy, Duit refers to four basic aspects and their interrelations: *energy transformation*, *energy transfer*, *energy conservation*, *energy degradation*. However, despite the fact that Duit initially reminds us that the concept of energy has many facets in both modern physics and other natural science disciplines, the subsequent analysis is essentially centred on the concept of "mechanical" energy. This is somewhat surprising and limiting. In those pages, to illustrate the inherent and essential interconnection between the various concepts of physical theory, emphasizing the necessity of a learning progression structure, he mentions a scheme for the understanding of the concept of "*Heat*", suggesting that in order to account for thermal effects that accompany a large part of natural processes—virtually all the so-called mechanical phenomena in which the dissipative effects of friction are only reduced and/or assessed as negligible—it is at least useful, if not even necessary, to introduce the concept of "*entropy*".

In this perspective, without a sufficiently broad conceptual framework, it is then not surprising that students struggle to come clear with the concept of *energy degradation*, a rather diffuse concept which is difficult to deal with, as every teaching person with some experience knows. Indeed, in spite of the ease with which it can be used in qualitative discussions, the structural difficulties are immediately apparent when students are asked to give an account of the quantitative aspects. The only way they can overcome them, is calculating the value of the dissipated energy as "missing energy", i.e. as the difference between the initial and final energy (usually both mechanical) of the system, taking energy conservation for granted. This is clearly an unsatisfactory situation and in the following I will try to present an alternative that allows—at least when it is possible to recognize and model the specific type of dissipative processes—to determine *directly* from the process features the value of the energy dissipated, as I will show next.

This approach obviously requires a slight expansion of the area of investigation, but it allows avoiding limiting a large part of the presentations on energy: indeed energy is *not* a topic by itself or a particular field of physics; energy is an *overcrossing concept* that permeates *all* the fields of natural phenomena, including therefore biology, chemistry and other natural sciences.

The Proposal and the Theoretical Background

In order to go beyond the assimilation of procedural knowledge essentially aimed at the resolution of exercises, learning the concept of energy can be effectively supported by focusing on some aspects which are rarely considered with the necessary coherence. In this perspective, the four points that I'd like to discuss envisage providing students with operative thought instruments which should permit them to better structure and manage the energy interplays at different levels of formalisation and complexity:

1. *A rigorous and systematic distinction between being constant and being conserved*: both from a disciplinary and didactical perspective, it seems interesting to have two different words in order to express the two following different aspects:
   - *Constant*, as the property of the value of a certain quantity (extensive or intensive) to be unchanged in time during a *particular* process occurring in a given physical system;
   - *Conserved* as a *general* property of certain extensive quantities, indicating the particular way in which their value, for *any* system and for *any* process, can change, i.e. *only through exchanges between the system and its surroundings*. To be *conserved* is then a characteristic of the physical quantity itself (and we actually know how to relate this behaviour to deeper structures of physical theory, like global and/or local symmetries and the Noether theorem)[1]

Although this distinction, to my knowledge, is still widely absent (yet) in textbooks and in the literature, I'd like to mention that it is addressed explicitly by H.G. Close in an appendix of his dissertation (Close 2005) as well as by D. Neuenschwander (2011) to the prologue of his book *Emmy Noether's wonderful theorem*. The didactical question is how to introduce this distinction at a basic level of teaching. My operative answer is to explicitly introduce the idea of *balance equation* for the different extensive quantities as soon as possible (both for *conserved* quantities and for *not conserved* quantities), i.e. a revisited version of the continuity equation holding for quantities such momentum, electric charge, energy, entropy, chemical amount. Notice that in its fundamental aspects this tool is used by every child since he/she starts to count marbles, coins, picture-cards, hens or rabbits.

In a first step it is possible to limit the examples to *uniform systems*, so that the model to be considered has no spatial distributions but only a *time* dependence. From the formal point of view the easiest situation is to consider processes of finite

[1]This situation is interesting also because, as pointed out years ago by Alonso (1994), the introduction of *modern physics* in the courses should not be done just adding some appealing topic at the end. Rather, a *modernisation* occurs introducing the fundamental results emerged in the research in more modern topics also in the classical fields: in this case the general and fundamental relationship between symmetries and conservations laws. This operation may require a deep rethinking of the conceptual structure both at a disciplinary and at a didactical level, but opens up to important new perspectives that can be of great help for our students.

duration, so that students are faced with a balance over a *finite time interval*. They should learn to manage the relation between the *change* ΔX_{syst} of the quantity X inside the system, the *exchanges* X_{exch} between the system and its surroundings and the *produced quantity* X_{prod} associated with processes occurring inside the system. Students should be aware how to operate with these elements at different levels: they should be able to describe the situations in words, with graphical representations of ΔX_{syst}, X_{exch} and X_{prod} in time and/or by a numerical relation:

$$\Delta X_{syst} = X_{exch} + X_{prod} \tag{15.1a}$$

Nevertheless, in order to give a more solid foundation to this tool, and to allow for the description of the general time evolution of a process, it is interesting to also simultaneously present an instantaneous version of the balance equation: here students encounter concepts such as the *rate of change* of the quantity inside the system at a given instant, *the total intensity of the flows* describing the exchanges between the system and its surroundings as well as *the production rate* at the same instant. Again, students should be able to describe the situations in words, with graphical representations of the three above mentioned quantities and/or by a numerical relation:

$$\dot{X}_{syst}(t) = I_{X,net}(t) + \pi_{X\,prod}(t) \tag{15.1b}$$

With these tools, students are then able to distinguish the specific characteristics of the states of the systems (and their changes) from the properties of the physical quantities, and can consequently distinguish and manage situations in which, in a given system, the value of a *conserved* quantity can change in time (for example: the increase of the momentum of a spring powered car[2]) or situations in which a *non-conserved* quantity remains constant (as the chemical amount of the reagents in a chemical reaction occurring in a reactor working at a steady state, or the entropy of a certain gas amount enclosed in a cylinder with a piston during a reversible adiabatic expansion) (Fig. 15.1).

The general relations (15.1a) and (15.1b) permits us to define simply and precisely what *conserved* means: for *conserved quantities*, as energy (but also electric charge in electricity, linear and angular momentum in mechanics, volume in hydraulics), there are no production or annihilation processes, so that a change of their values in the system is always connected with an exchange between the system and its surroundings. In particular, for energy the balance equation takes therefore the global respectively instantaneous form:

[2]It is interesting to note that students, looking at the accelerated toy car, naturally ask where the linear momentum comes from, as well as they are able to individuate the surface on which the car is moving as the second physical system involved in the mechanical exchange.

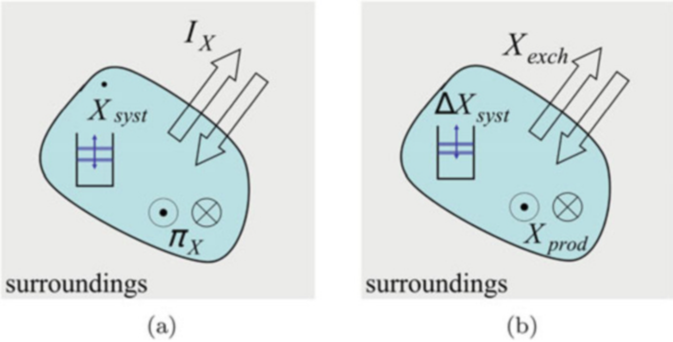


Fig. 15.1 Graphical representation of the general features of the balance equation: (**a**) the instantaneous form; (**b**) the global (or integrated) form

$$\Delta E_{syst} = E_{exch} \tag{15.2a}$$

$$\dot{E}_{syst}(t) = I_{E,tot}(t) \tag{15.2b}$$

It is worthwhile to note that these two equations have been obtained *not* as definitions, but as physical laws; this means that each term must be previously defined independently. In a teaching sequence it is of great importance to take care of these aspects: while the right side can be defined in a rather general way, the form assumed by the left side is totally dependent on the nature of the system under consideration, and can be written down explicitly only knowing the particular constitutive laws characterizing the system (like $E_{kin} = m\, v^2/2$ for the kinetic energy of a non-relativistic object, or $E_{elast} = k\, \Delta L^2/2$ for the potential elastic energy of an ideal spring).

2. The *systematic link to the production of entropy for all processes in which energy dissipation occurs*:

as evidenced by the previous considerations it is essential to stress this point: within the various energy interplays, students should be able to recognize and manage the dissipative processes, and—at least in the simplest cases, covering quite a large spectrum of situations—to be able to quantify both the energy dissipation rate $\mathcal{P}_{diss}$ and the entropy production rate π_S. While the relation between these quantities is quite general:

$$\mathcal{P}_{diss}(t) = T\,\pi_S(t) \tag{15.3a}$$

where T is the absolute temperature at which the entropy is produced, the expression for the rate of entropy production π_S depends on the particular dissipative process and on the system characteristics. It can therefore be made explicit only after all these elements are known, even if, as shown in the final section, there are some simple and characteristic situations that can be used, at least to some extent, to also model more complex systems.

With the two quantities $\mathcal{P}_{diss}$ and π_S, in principle, students are able to determine, for a given process, the dissipated energy E_{diss} and the produced entropy S_{prod}. Difficulties arise eventually from the mathematical side, but at a basic level it could be sufficient to work graphically, asking students to recognize and interpret, in a given process, the link between the area under the curve $X(t)$ in a given time interval Δt and the corresponding change $\Delta X(t)$ in the physical quantity, while the explicit calculation can eventually be required only in special cases (as in steady state processes, in which the integral reduces to a product):

$$E_{diss} = \int_{t_1}^{t_2} \mathcal{P}_{diss}(t)\,dt \quad [= \mathcal{P}_{diss}\ \ \Delta t] \tag{15.3b}$$

$$S_{prod} = \int_{t_1}^{t_2} \pi_S(t)\,dt \quad [= \pi_S\ \ \Delta t] \tag{15.3c}$$

In any case, rather than ability in calculations, the most important goal while introducing the concept of entropy production rate π_S is to make the students aware of the limits of energy "transformations", i.e. that generally a fraction of the energy released in a process, at the end is not energy of the desired form, but has generated a thermal effect. This is a general characteristic that can be enhanced introducing the *second law efficiency* ε as the ratio between the power obtained in the desired form and the power released by the process (see also point 3).

A second important advantage of the introduction of entropy production also lies in the possibility of giving a clearer view of the *second law* of thermodynamics, in particular clarifying the physical reason that implies that the *thermal efficiency* (or *first law efficiency*) η of a thermal engine, also in the ideal situation of reversibility (i.e. in absence of entropy production), is always necessarily less than 100%, a well- known result that historically caused no little ferment.

3. *The introduction of process diagram:* most of the theoretical considerations expressed above can be illustrated by a graphical tool allowing students to follow both the energy exchanges between the system and its surroundings, as well as the energy transfer (release and/or upload) occurring inside the system during a given process[3]. The basic idea is to schematically represent the system by a "rectangle" (defining automatically the surroundings), to introduce arrows which represent the various energy exchanges between system and surroundings, to represent also the energy carriers (in- or out-flow, production or destruction processes) as well as arrows for the released and uploaded power associated to the considered processes. In Fig. 15.2 some examples are reported.

[3]Process diagrams are of particular interest since in nature one process drives often another process, sometimes creating long chains. For a detailed introduction see for example Fuchs (2010).

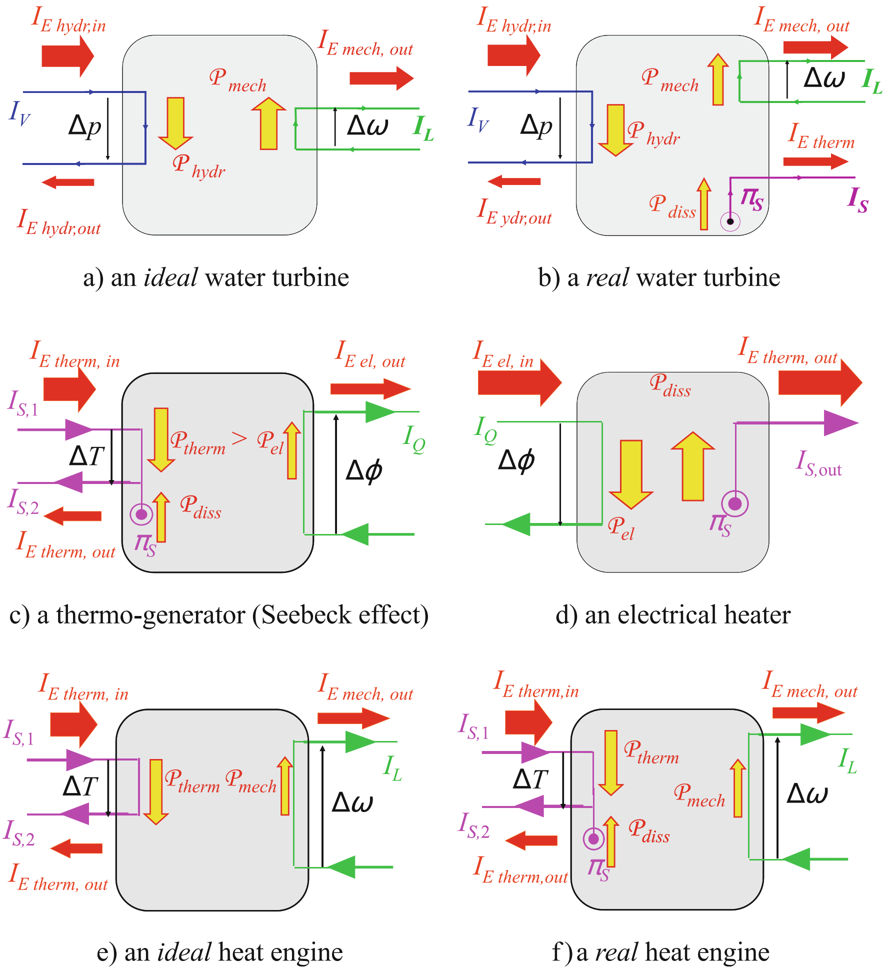


Fig. 15.2 Some examples of process diagrams representing schematically the *energy exchanges* between the system and the surroundings (big full red arrows) as well as the *energy transfers* occurring during the process inside the system (big edged yellow arrows), highlighting at the same time both the role of energy carriers as well as of the potential differences that can generate processes or that are generated in processes. In particular process diagrams permit to easily individuate the origin of irreversibility, evidencing the dissipative processes where entropy is produced. All the schemes represented here refer to a device operating in a steady state

4. *The introduction of fields as real physical systems that can store and transport energy*: as pointed out by Duit (2014), energy is a quantity defined *in a system*, so that, for example, the way we generally speak about the gravitational energy of a stone lifted to a certain height, saying: “the potential energy of the stone

increases" as the energy would "sit" in the stone, can generate some interpretation difficulties.[4]

The value of the internal energy U_{syst} associated to a given system in given conditions can always be correlated to *other* physical quantities that characterize the state of the system. We usually emphasize this by saying that the internal energy U_{syst} is a *state function* of the other variables of the system, so that any change in U_{syst} must be accompanied by a change of at least one other physical quantity that characterizes the system. This is obviously not expressed in the previous sentence about the lifted stone. In order to avoid this difficulty one is compelled to enlarge the system: the most popular solution is to say that by lifting the stone the energy of the Earth-stone system has changed. The goal is understandable and the idea is correct, but this way we only . . . increase the problem: what we said for the stone holds also for the Earth. In order to have a coherent picture of the situation, it seems necessary to introduce a third element. This can be done speaking explicitly about the (total) gravitational field of the system Earth-stone, thus introducing the idea that fields are real physical systems which can store energy. Even if the link between the potential energy and the field energy requires some care,[5] this picture can be of great usefulness for students. The difficulty is that in many cases the fields energy is not localized but extends in a quite wide region, so that high school students do not have the necessary mathematical tools to manage these situations. Qualitatively, through a certain number of experimental situations, it is nevertheless possible to introduce students to the idea that fields can store and exchange energy, and that the value of the exchanged energy can be determined looking at the changes in the positions of the sources of the fields. This "geometrisation" allows then to discuss qualitatively many interesting situations: for example, observing that in presence of attractive interactions the value of the potential energy generally increases when the distance between the sources is increased, it is possible to interpret gravitational, electrical and magnetic situations with "point-like" sources.

With a little more effort it is also possible to link this view to macroscopic systems, like a spring, where the stored and the released energy quantities are correlated as well to macroscopic changes in its geometrical shape. On this basis students are also able to make a connection with some results they know from their chemistry and biology courses: they can, for example, explain qualitatively why the process of solving a salt as sodium-chlorate in water is accompanied by a temperature decrease, or why in general in chemical reactions one can expect some thermal

[4]Probably not for those students who are happy to have a formula to enter numbers in, but rather for those who wish to understand, capture the inconsistencies and who therefore, unfortunately, often think *they* do not understand.

[5]As well known, only the "interaction term" of the total field energy can be interpreted as the *potential energy* of the system. However, in spite of what is considered by certain authors (see (Hilborn 2014), difficulties of this type do not seem to me a motivation for abandoning the idea of introducing fields as real physical systems already in high school.

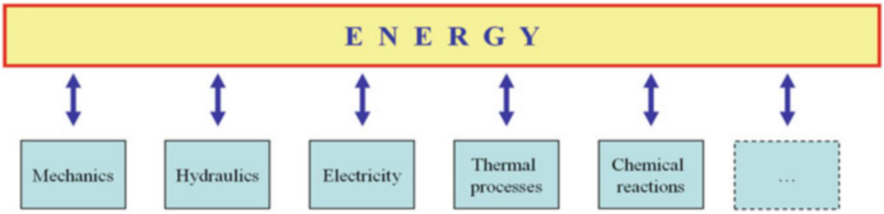


Fig. 15.3 Energy is the physical quantity introduced in science to link together areas of different nature, and therefore not directly comparable to each other, in order to accurately express (even in the quantitative aspects) the cause—effect relationship that we can observe time after time in the different processes

energy exchange with the surroundings (generally the solvent). They have in this way a slightly improved and coherent overview of their knowledge on energy.

To close this section, I will mention (without further commentaries, even if they may be useful) the way I use to communicate *a model for energy* to my students in the first year of high school: their challenge is to construct their competence in understanding the physical meaning of the different elements of the model and to use them in concrete situations. This is a relative long process: students need time and perseverance to work out several examples in the different physical fields (Fig. 15.3).

Energy is an extensive physical quantity that is characterized by the following properties:

- Energy can be stored,
- Energy can flow from a physical system to another,
- Each energy flow is always associated to the flow of another physical quantity (which can therefore be named energy carrier),
- During processes, energy can be transferred from a carrier to another carrier,
- To each process, it is always possible to asses a balance equation for energy,
- Energy is a conserved quantity.

Obviously, this is *not* the only way to introduce the energy concept, but it represents a synthesis of my teaching experience.

Experiments

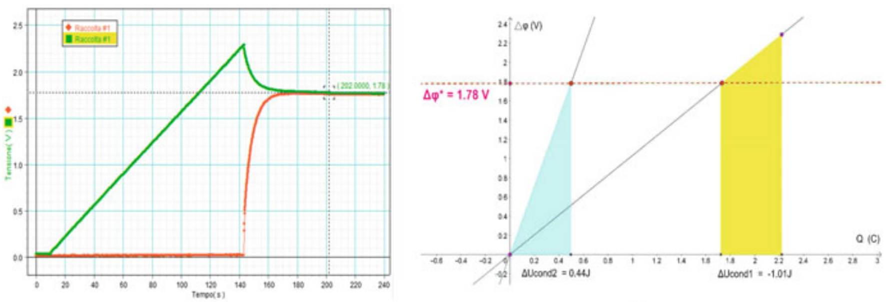
It is well known that the observing and/or performing experimental situations can help students to construct their own mental images in various fields of study: at the beginning, the basic quantities and their properties can be introduced through qualitative experiences, which help students to perceive the relationships between them; at a later time, after a deeper approach to a quantitative level all these competences can be used to validate conjectures and make predictions on the time evolution of a given system.

In an earlier GIREP conference (D'Anna and Rosenberg 2014) I showed a number of *qualitative experiences* whose aim was to show the possibility of interpreting different sub-fields of science by analogy (hydraulics, mechanics, thermodynamics, electricity and chemical reactions). For each sub-field, two types of experiment were described, showing: (A) processes *tending to equilibrium* as the consequence of a "difference" of an intensive quantity, driving the flow of an extensive quantity; (B) processes where, with an external intervention, the extensive quantity was pumped from a lower to a higher level, *creating a potential difference* that successively could act as a driving force for another process.

Here I can only shortly sketch the three experiments that I presented at the seminar and that permit to explore, foster and verify the properties of the energy concept, also from the *quantitative* side.

1. First I proposed an experience with two capacitors, that challenges students to prove the energy conservation also outside the mechanical context. Students should preventively be familiar with the concepts of electrical charge, potential difference and electrical capacity of the capacitor, as well as of energy stored in it. In the proposed experiment, initially only one of the capacitors is charged: when they are connected through a resistor, one measures the voltage vs. time as well as the current through the resistor until electrical equilibrium is reached. Students are then asked to determine the energy change associated to each capacitor in this process and to discuss the result from the point of view of energy conservation. This way they discover that the energy diminution of the first capacitor is greater than the energy increase of the second one (Fig. 15.4).

   This result may be surprising for those students who do not consider the process as a whole, but focus their attention solely on the capacitors. But it is easy to interpret remembering that the charge transport is connected to a dissipative process in the resistor: although they can determine the power dissipated in the resistor at any time, school students generally cannot integrate this expression



(a) (b)

Fig. 15.4 The capacitor experiment: (**a**) measured voltage vs. time during the charge process of capacitor 1 and the subsequently discharge process in capacitor 2; (**b**) the graphical representation of the process, permitting the students to perceive visually that the energy increase of capacitor 2 is less that the energy decrease of capacitor 1

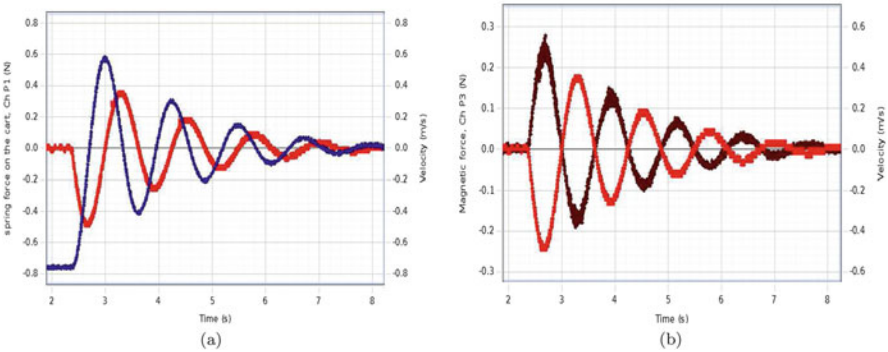


Fig. 15.5 The damped cart oscillation experiment: experimental results for velocity and force versus time: (**a**) between the cart and a spring force; (**b**) between the cart and the magnet force

in order to obtain the total amount of dissipated energy. Nevertheless, elementary or advanced numerical methods applied to the energy balance equation (as Euler's method, performed by hand, or the Runge-Kutta one, usually available within dynamic modelling software), make possible a *quantitative* verification of the energy conservation principle also for students not yet aware with calculus.

2. A second experience deals with a magnetically damped cart-oscillator, where the energy exchanges between, respectively, the cart and two springs and the cart and a magnet, are measured and modelled separately. This example aims to highlight how experiments, within the developed approach to energy, clarify the different roles played by the elastic and the dissipative forces in the energy exchanges (Corridoni et al. 2014).

   Figure 15.5 shows a typical experimental relation between velocity and force: Fig. 15.5a refers to the exchanges between the cart and a spring, and Fig. 15.5b to the exchanges between the cart and the magnet. The difference in the temporal structure is immediately apparent: while in the first case the two functions are out of phase by a quarter of a period, in the second case the functions are in phase opposition.

   Remembering that the energy flow is expressed at any time by the product of force and velocity, it is possible to clarify what happens by the energy exchanges: Fig. 15.6a shows the experimental proof that the energy balance of the spring-cart exchanges over a complete oscillation vanishes also in the case of damped oscillation, while Fig. 15.6b shows the energy dissipation through the magnet-cart interaction: a quantitative comparison with the initial value of the kinetic energy shows that *also* mechanical friction between cart and the track should be taken into account (Corridoni et al. 2014).

   Using a dynamic modeling tool, a more complete quantitative analysis, in which the sliding and/or viscous damping are distinguished, can be performed to obtain a detailed prediction of the various energy exchanges and to verify the compatibility of the whole model with energy conservation principle.

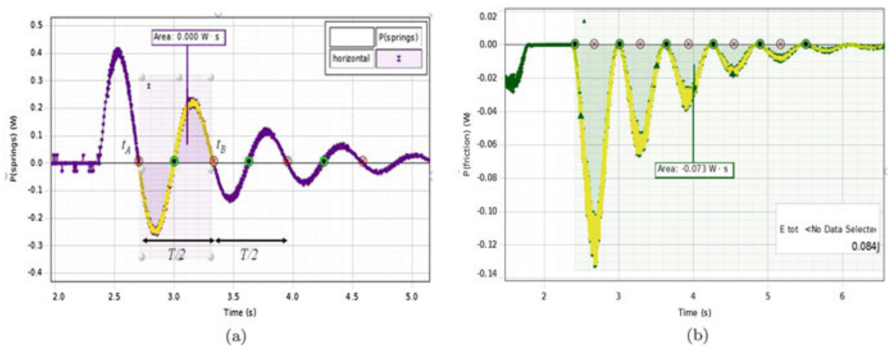


Fig. 15.6 Energy exchanges: (**a**) the energy balance of the spring-cart exchanges over a complete oscillation vanishes also in the case of damped oscillation; (**b**) the dissipation process

3. In a third group of experiences, the conservation of energy is tested quantitatively through a sequence of lab activities focused on friction processes, where at the end students can investigate quantitatively *also* the thermal effects of the occurring dissipative processes. A separate contribution in these proceedings (Corridoni and D'Anna 2016) reports on these experiments dealing with a sliding box, a magnetically braked cart and a rotating disc, respectively. In this sequence, starting from a situation in which students can only infer from the mechanical behaviour the presence of a dissipative process, step by step they progress to analyze a situation where, localizing the dissipative process in a little copper plate, it is possible to measure and model quantitatively the thermal effects (temperature increasing), connecting them this way to mechanical behaviour in a cause-effect relationship.

Conclusions

In order to face the recurrent and persistent difficulties experienced by both teachers and students in teaching and learning energy, the following four suggestions were proposed as starting point for the discussion in the seminar: (1) a rigorous and systematic distinction between being *constant* and being *conserved*, i.e. the distinction between the behaviour of a particular quantity during a particular process, and, on the other hand, a property of general character of certain extensive quantities; (2) the systematic link of the processes in which energy dissipation occurs with the production of entropy that accompanies all of them; (3) the introduction of *process diagrams* as graphic tools to allow students to follow both the energy exchanges *between* the system and its surroundings, and the energy transfer (release and/or upload) occurring *inside* the system during a process; (4) the introduction of *fields* as real physical systems that can store and transport energy.

For the first three aspects we already have conceptual tools, laboratory experiences and effective and proven teaching materials. Conveniently supported by an approach using analogies, these proposals allow students to gradually build a more solid and coherent conceptual framework. In particular, they appreciate the fact that they can recognize in a variety of contexts a common and transversal structure based on few basic ideas that gradually become for them useful tools for thinking, interpreting and making predictions, moving them away from the image of physics as a pool of formulas that must be known and applied mnemonically. About the systematic and coherent introduction of fields as physical systems, in my opinion, instead, basic research is still needed; it may be a non-indifferent effort, but it is also justified from an interdisciplinary perspective.

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Chapter 16
Teaching-Learning Sequences Using Low-Cost Experiments Aimed at Understanding of Concepts of Electricity

Věra Koudelková and Leoš Dvořák

Introduction

It is well known that students of various ages have problems with understanding of some basic concepts of electricity and magnetism. This fact has been verified repeatedly by conceptual tests like CSEM (Conceptual Survey on Electricity and Magnetism; Maloney et al. 2001), BEMA (Brief Electricity and Magnetism Assessment), DIRECT (Determining and Interpreting Resistive Electric Circuit Concepts Test) and others. Most of those tests were aimed at introductory university level. To reveal conceptual understanding of Czech high school students in the area of electricity and magnetism, a test CCTEM inspired by CSEM but adapted to high school level was developed some time ago (Koudelkova and Dvorak 2015). A survey using this test basically confirmed misconceptions known from literature; some details that differ might be caused by differences in how this topic is taught in Czech schools.

The next step is to try to overcome the misconceptions (which is a rather ambitious goal) or, at least, to help students to understand the relevant concepts in a better and more correct way. So, the paper describes four examples of teaching-learning sequences, which should help students to better understand some concepts of electrostatics. All experiments using in these sequences are low-cost, clear and not using "incomprehensible black boxes".

We use these sequences with high school students and in preservice teacher training too. Our experience with using these sequences is discussed at the end of the paper, including students' feedback.

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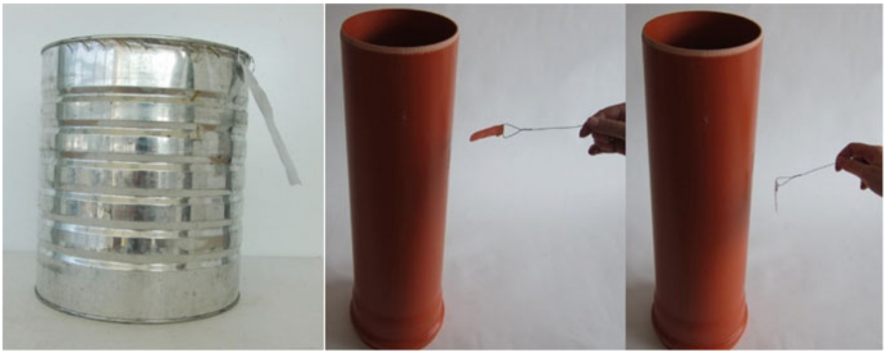

Fig. 16.1 Arrangement of the experiment—charged tin (left) and charged place (middle) and place without charge on a plastic tube (right)

Charge Distribution on Conductors and Insulators

The sequence has two main parts. The first is focused on the difference between charge behaviour on conductors and insulators, the second is concerned with different shapes of conductors and how conductors are connected with behaviour of charge on it in normal life.

The first part of the sequence reacts to the following misconception which was found using the test CCTEM: If we put some charge at one place on insulator, the charge disappears during a few second. Similar misconception was found in the test CSEM too, but it was not so strong.

During the first part of the sequence students compare behaviour of charge on a tin and on a plastic tube. As a plastic tube we use sewage tube which is similar in shape to a tin and can be charged. The charge on a plastic tube can be detected using small piece of aluminium foil fastened to a piece of wire (see Fig. 16.1).

During the first part of the sequence students discuss what will happen when we charge a tin and a plastic tube:

- at one place
- at two places
- at one place and wait for few minutes

After students' discussion in small groups their conclusions are verified by experiments.

The second part of the teaching-learning sequence (typically the second lesson) is focused on different shapes of conductors—students finds examples of Faraday's cages and tips in their normal life (for example a lightning rod, an alone tree in a field, a car during storm, mobile signal in an elevator. . .).

Fig. 16.2 Qualitative experiment: charged plastic straws repel each other

Coulomb's Law

The teaching-learning sequence starts with students playing with plastic straws charged by rubbing. Students see that charged straws are attracted to various surfaces. (This experiment was already described in Dvořák (2014).) In the following experiment students hold two plastic straws, again charged by rubbing, in their fingers as it is shown in Fig. 16.2. Students feel in their fingers the force by which straws repel each other [For some details, see Dvořák (2014)]. This qualitative—and "literally hands-on"—experiment reveals that charges can repel each other.

Then, a semi-quantitative experiment follows using a simple tool presented in Fig. 16.3. It can be used to discover how the repelling force depends on distance—or to persuade students that the force between charges is inversely proportional to the square of their distance, $F = k/r^2$, and not to their distance. (This is a quite common misconception. In tests, students often choose the answer that reducing the distance to one half results in the force getting two times greater.)

A tool for measuring the force consists of a plastic straw which can turn around a horizontal axis made from a pin; the upper part of the straw serves as a pointer. A part of the straw at its lower end is charged by rubbing, it is repelled by other straw the end of which is also charged. Of course, our charges are not point-like but the effect of that can be neglected in our measurements if the distance between straws is sufficiently large.

We can see that if the distance r is two times smaller the repelling force is four times larger.

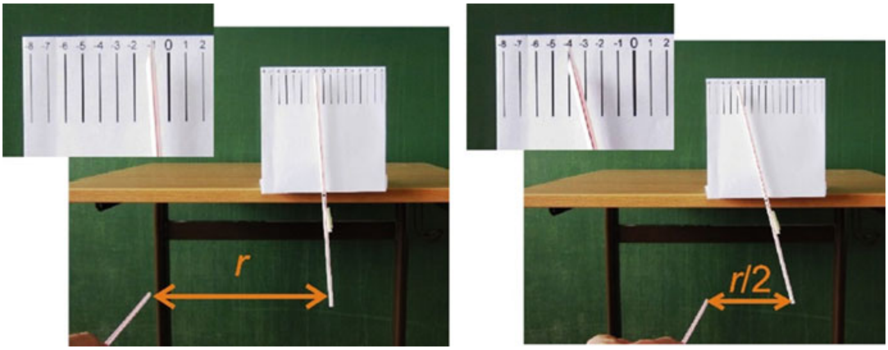

Fig. 16.3 Semi-quantitative experiment: a simple tool can reveal how force between charges depends on their distance

The same tool can also be used to demonstrate that the force is proportional to one of the charges: It is sufficient to repel the straw in our tool by two straws instead of one. (For brevity we neither show the photos of such experiment here nor discuss its details, precision etc.)

All three experiments mentioned here were used not only in teaching physics for high school students but also as introductory experiments in lectures on Electricity and magnetism for future physics teachers.

Electric Field and Electric Potential

Analogy Between Gravitational and Electric Field

The main idea of this teaching-learning sequence is to build concepts of electric field from the analogy with gravitational field. This approach is based on students' previous knowledges and experiences so it is more comprehensible for them.

In the first lesson, students discuss few tasks concerning a map and then they discuss similar task concerning a figure which looks similar, but it describes an electric field (see Fig. 16.4).

At the end of this activity students fill in the table where they compare terms concerning gravitational and electric field (see Table 16.1).

Examples of Other Tasks

The analogy can help students to better understand figures of field lines or equipotential lines—they are able to find charge if they only know the equipotential lines (see Fig. 16.5, left). Or, they are able to draw equipotential lines of homogenous field

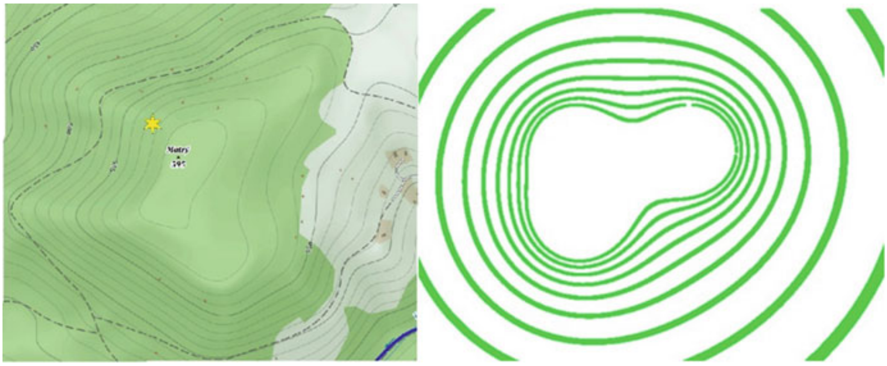

Fig. 16.4 A map and an electric field

Table 16.1 Comparison between gravitational and electric field

(A) Map—gravitational field	(B) Figure—electric field
Altitude	Potential
Contour line	Equipotential line
Altitude difference = height of a hill	Potential difference = voltage
Steepness of a hill	Electric field (intensity)
Fall line	Field line

Fig. 16.5 Where are charges? (left). Draw equipotential lines if the charges are at these places (right)

(they know only where the charges are, the term "homogenous field" was introduced after this task—see Fig. 16.5, right).

The analogy between gravitational and electric field can be used for quantitative tasks too. The concept of intensity of electric field is derived from the question "How to measure steepness of the hill if we could not see it?" One of typical students' solution is to put a small ball on a hill and to measure its acceleration. This solution can be simply made precise: better than acceleration is to measure the force which pushes the ball. So, in an electric field we will use a small charge instead of a ball and

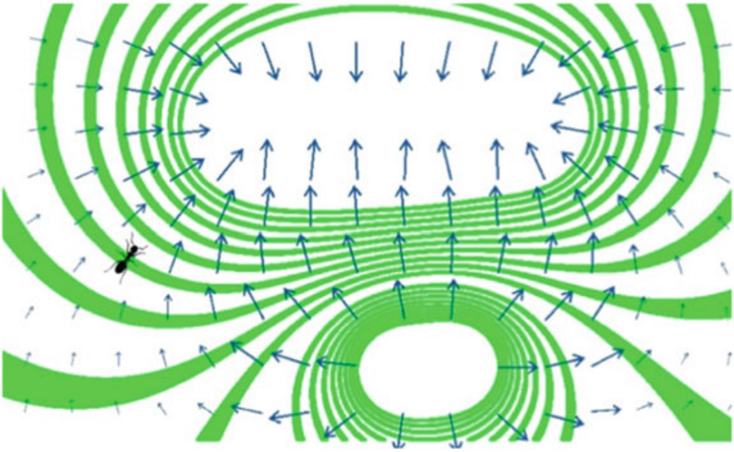

Fig. 16.6 An ant in an electric field

the intensity of the electric field can be described as a force which pushes this small charge. The concept of intensity of electric field is more comprehensible for students, if they can see “the ball on a hill” behind the formula $E = \frac{F}{q}$.

Ant in an Electric Field

This activity is focused on understanding the terms “intensity of an electric field” and “electric potential”. We used it for revision after holidays but it can be used for other purposes too.

Students have a few pictures of electric field with an ant somewhere in the picture (see Fig. 16.6) and a few texts in which “electric ant” describes what his surroundings look like. The task for students is to decide which field is described by which ant and if the ant describes intensity or potential.

As an example, the text which can be matched with the field in the Fig. 16.6 is: “There is a steep slope on my right side in front of me. The slope behind me is relatively gentle.” Because the ant describes only steepness of the hills, it speaks about intensity of the electric field.

This activity was very popular among students. They described it as uncommon and interesting and had comments such as “Wow, there is an ant. . .”. They asked to get some task with an ant in the test.

Fig. 16.7 The capacity of tins

Note

We use many figures of electric field in this sequence. All these figures are made from an applet where the field around point charges is calculated (We use this applet more dynamically too, not only for figures, of course). The applet is only in Czech now, but it can be translated into other languages.

Capacity and Capacitor

The teaching-learning sequence is focused on derivation of the term "capacity" and how a capacitor can be made. During the sequence we first build concepts of capacity. In the second part students make their own capacitors, which help them to understand how (and why) it is built.

Experiments in the sequence can be used as demonstrating experiments (with the laboratory work where students work on the second and third part of the sequence) or students can work in groups during the lesson. The length of the sequence is 1–2 lessons.

The first experiment is in the Fig. 16.7—there are two tins with different sizes which are charged to the same potential. After being disconnected, one of the students can try that the bigger one gives us bigger shock, so it is natural to conclude that there was more charge on it. It's simple for students to say that the bigger tin has bigger capacity. However, it is necessary for the teacher to emphasize that there was the same potential on both tins to avoid one of typical students' misconception which is that capacity is "how much of charge can be put to the conductor".

In the second part of the sequence students study different shapes of capacitors. They should dismantle bought capacitor and describe its parts. Then, they make two types of their own capacitors: made from two pieces of aluminium foil and cups (see

Fig. 16.8 Capacitor from cups (left) and from aluminium and plastic foils (right)

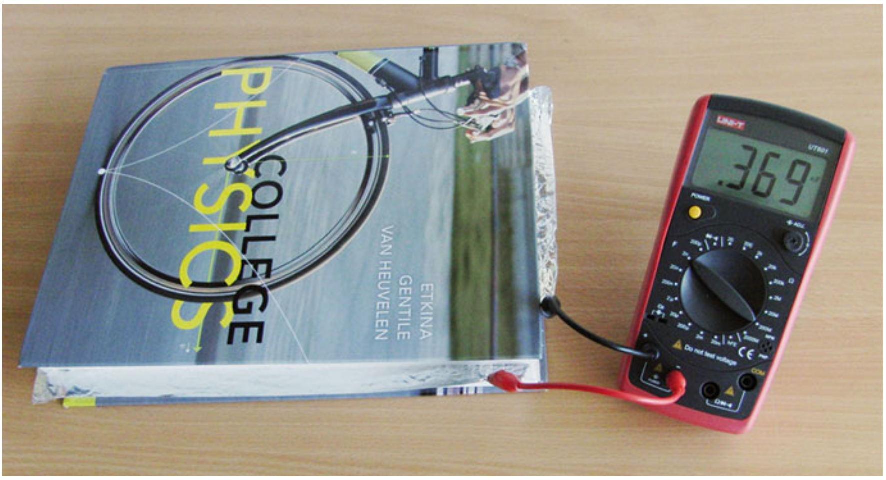

Fig. 16.9 Plate capacitor made from a book and a two aluminium foils. The capacity of this capacitor is approximately 0.37 nF

Fig. 16.8, left) or a model of a scroll capacitor made from two aluminium foils and a plastic foil (see Fig. 16.8, right).

We use a C-meter to measure capacity of students' capacitors. They can charge their capacitors too and compare the shock from the capacitor with the shock from a tin. So, they can understand the term "capacity" with their own hands.

Note: Because of safety reasons we use only 0.3 l cups or smaller. Capacitors made from bigger cups could have so big capacity that the shock could be painful for students.

The third part of the sequence is focused on studying parameters on which the capacity of parallel-plate capacitor depends. For this we use a capacitor made from a book inside of which there are two pieces of aluminium foil (see Fig. 16.9). It is possible to simply change the distance between aluminium foils (using different number of pages) or the area of the foil (halve one of the foils).

Students appreciate in these lessons that they are really hands-on. All students can touch capacitors, make them by their own hands and get a shock from them. Several months after these lesson most of the students remember, that a capacitor has two pieces of conductors and there is an insulator between them. Most of them also know that capacitor is used as charge storage and it is possible to put big amount of charge into the capacitor.

Feedback

One class undertook the CCTEM survey after using these teaching-learning sequences. There were only 22 students, so it is not enough, of course, for a reliable statistical survey but some conclusions concerning these sequences can be made:

- Results of this group of students were much better at least in some questions (normalized gain in the question focused on charge distribution is 77% compared with 23%—results of control group).
- They recognize capacitor as "device which is used for storage of charge" or "it is two pieces of conductor with piece of insulator between them".
- They describe potential as "how high it is" and electric intensity as "how steep it is".

After each teaching-learning sequence, students were asked to write some feedback. From these feedbacks it seems that students appreciate these lessons and evaluate them as a useful for them:

- "Overall, the topic as we did it was very attractive. It was great to look at it and even better to do it personally. Well, who would not like to get a shock from a capacitor made by one's own hands?"
- "Analogy with gravitational field helps me to understand it, because now I am able to imagine it better."

Although number of students is not enough to precise analysis of their results, it seems that described sequences help them to better understand few concepts of electrostatics and (which can be important too) are attractive for students.

Conclusion

Four teaching-learning sequences which can help students to overcome their misconceptions in electrostatics were described. The materials describing these sequences are prepared only in Czech so far. If you are interested in more detailed description of it or would like to use them, do not hesitate to ask the authors—the materials can be translated to English.

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Part V
Assessment for Learning Through Experimentation

Chapter 17
Inquiry Based Learning of Contemporary Physics Topics and Gifted Students

Mojca Čepič

Introduction

Although research has shown that giftedness or higher abilities are not hereditary (Subotnik et al. 2012), nevertheless, the share of identified gifted students from social and intellectual privileged families is much larger than from families with a underprivileged background (Ford 1998; Borland 2004; Freeman 2013). As the students are identified through various channels, reasons for that vary (Endelpohls-Ulpe and Ruf 2005; Kornmann et al. 2015). For example, teachers in Slovenia often identify gifted students on the basis of their excellent school results, on the basis of the results at various external competitions, however, the testing is also often demanded by the students' parents, who are aware of the importance of giftedness identification (Juriševič 2012; Košir et al. 2015). Such system is less inclined towards identification of students, who live in home environment not supportive of reading, and who are therefore less able to express themselves clearly, who live in home environment not supportive of learning and spending time on school chores, and live in home environment that does not value education in general (Borland and Wright 1994; Borland 2004; Cankar et al. 2016). Furthermore, identified giftedness does not guarantee its development. In addition, an individual needs a stimulating environment, possibilities for personal development and support (Gruber et al. 2008; Grassinger et al. 2010). Every gifted individual that does not have an opportunity to develop, can thus be regarded as lost capital for the modern society of knowledge. Identification of gifted students from underprivileged environments is therefore extremely important, because gifted students enrich the intellectual pool of society. Moreover, such identification also enables transferring among social groups for underprivileged individuals.

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Research focusing on students from underprivileged background is relatively rare (Ford 1998), even though educational politics are lately becoming aware of the importance of education for all segments of the society and of the impact education plays in the inclusion of all individuals into society (Borland 2004). International studies (OECD 2011; Sylva et al. 2011) have shown that a certain percentage of students, known also as "resilient students", is successful in school systems and achieve high performance, despite the unfavourable circumstances they experience at home. The percentage of resilient students varies from country to country, but it is higher in countries that offer more curricular content in science and other science related activities (OECD 2011). Therefore, it seems that learning science might be a privileged way for promoting intellectual growth and engagement of students from underprivileged backgrounds. Moreover, a properly adapted science education might assist in identifying gifted students from underprivileged background, so that they could develop resilience to negative influences of underprivileged personal background with proper assistance.

Inquiry based learning is a relatively new approach in physics education (McDermott et al. 2000; Harlen and Qualter 2009) that is derived from the scientific method. When approaching new problems, students acquire new knowledge in a similar way as scientists: they observe phenomena, measure various quantities, find patterns in acquired data, form tentative explanations and construct experiments for their verification. Based on evidence of proposed experiments, either they confirm the validity of explanation or they reject it and search for new ones (Etkina et al. 2006). Inquiry based learning is an approach, where gifted students are able to excel (Eysink et al. 2015) and is therefore more than appropriate for stimulating and supporting the development of gifted students. For acquiring new knowledge by inquiry based learning, specially designed experiments are required, which are appropriate for inclusion in regular school work as far as equipment availability and time-management are concerned, and at the same time yield evidence that leads to clear conclusions. Because inquiry based learning does not require specific academic skills as reading, writing, drawing, computer or mathematical skills, but is rather based on recognition of patterns in experimental data, drawing conclusions, and designing specific tests, it is suitable for students from all social groups, including underprivileged ones.

Processes leading to new scientific results require high intellectual abilities that are characteristic of gifted students (Ericsson et al. 2007; Eysink et al. 2015). Ability to effectively explore new phenomena, drawing immediate conclusions, implementing those conclusions in new circumstances, and/or transform them to analogous problems are all characteristics of giftedness and intelligence. Certain components important for effective research processes can be recognized as characteristic of mathematical-logical or of naturalistic intelligence (Gardner 2006). The characteristics of the quoted intelligence types or a combination of both do not satisfactory cover the giftedness in physics or science in general. Experimental verification for tentative explanation requires, besides good recognition of data patterns and abstract considerations, also consideration of irrelevant variables, negligible influences of various circumstances, and clever judgement of pro and contra arguments for the relevance of results in regard to tentative explanation.

Existing research in this field is rare (Eysink et al. 2015) and detailed literature review shows that research of giftedness in science is more focused on social questions than on specificities of gifted students and their approaches to learning science.

Successful implementation of the scientific method for acquiring new knowledge requires excellent capability of observation, efficient identification of patterns in obtained data, inference of possible cause and consequent relations, ability to form explanations, and ability to verify those explanations. High level of abstract thinking, characteristic of gifted students, is a prerequisite for planning verification of hypotheses, especially for new explanations and for generalization of conclusions. Therefore, it is reasonable to expect that gifted students differ from other students in inquiry based learning of science, and the activities for the identification of the gifted therefore base on this approach.

Giftedness in science is only one manifestation of general giftedness of an individual; however, it is expressed and thus can be recognised under specific conditions. Carefully designed experimental activities for inquiry based learning of science can be included into regular school work. Proper design manifests in activities appropriate for the whole spectrum of students' abilities, from guided research for weaker students, to open-ended problems for high-able students. Individual's giftedness is revealed through open-ended problem inquiry. When followed by a relevant protocol, it could allow for identification of gifted students, even those, who might have remained unidentified by other instruments of identification.

Criteria for identification of talents in sport or music are already well defined (Ericsson et al. 2007). So are the instruments for measurements of individuals' creativity, literacy, spatial perception and mental abilities in general, commonly used for identification of the gifted (Harder et al. 2014). Unfortunately, those instruments are not adjusted for identification of gifted students in underprivileged social groups. If the family does not support school chores, reading, drawing and other intellectual activities relevant for success in school, it is more than possible that a gifted student would not excel at those instruments. Even if such student is potentially identified as talented by her/his teacher, she/he would often not be interested or even able to obtain good results in abstract standard testing, because such intellectual activities are not valued at home (Borland 2004). As such, other tests for giftedness identification are needed.

In this contribution we discuss a preliminary theoretical framework for identification of gifted through inquiry based learning of contemporary topics in physics. Contemporary topics are characteristic in absence of preliminary knowledge. Students from different social backgrounds have an equal, almost non-existent preliminary experience and knowledge (Pavlin et al. 2011, 2013). Moreover, this means that learning results in these topics cannot be influenced by prior experience and knowledge. Because initial conditions are thus independent of students' background, teachers may rely on actions of students that are related to acquiring entirely new knowledge.

The suggested framework should be considered as a theoretical prediction that remains to be tested. It is focused on two aspects: (a) the expected characteristics of gifted students that could be revealed through inquiry based learning activities, and (b) properties and design of activities based on contemporary physics topics that allow for characteristics typical for gifted students to be revealed.

Giftedness in Science

In psychology, a behavioural characteristics of superior students is an important and thoroughly studied issue. They are divided to several categories, for example Renzulli et al. (2013) suggest teachers to asses students' learning, creativity, motivation, leadership, artistic, musical, dramatic, communication with respect to precision or expressiveness, planning, mathematics, reading, technology, and science characteristics in order to recognize strong areas of their students. Unfortunately, behavioural characteristics in science is among lesser developed and several criteria are rather criteria for motivation and interest on science than on scientific superiority. Physics teachers and researchers in physics education would quote characteristics of students superior in science without hesitation. The physics teacher and lecturer considers a superior and gifted if he or she shows the ability to

(a) Recognize patterns in given sets of data;
(b) Recognize possible relations among variables;
(c) Form tentative explanations for the observed phenomenon using their knowledge;
(d) Suggest an experiment to test the reasoning;
(e) Use the experimental data to reject the reasoning;
(f) Form a new explanation if the initial idea is rejected;
(g) Consider effectively indirect cause and effect relations;
(h) Consider effects of various variables on the same phenomenon;
(i) Distinguish among more and less important influences of variables;
(j) Describe phenomena symbolically and use those descriptions for support of explanations;
(k) Generalize the conclusions based on studied examples.

To our best knowledge, these intuitive criteria were not used in characterization of giftedness in science yet. We were not able to find any tests or activities designed to systematically target or stimulate students reactions within categories A to K given above. Therefore, one has to conclude, that although "giftedness in science" is used as a term on some occasions, it is not established as a category through systematic studies, yet.

Inquiry Based Learning Units in Contemporary Physics Topics and Giftedness

Gifted students or individuals have been identified already for centuries. Systematic identifications of gifted individuals and development of approaches for their promotion, however, is discussed more extensively only in the last few decades. Giftedness is not defined unequivocally (Gardner 2006; Harder et al. 2014) and definitions of criteria for its identification are still discussed (Borland 2004; Juriševič 2012; Harder et al. 2014). Even the research community focusing on giftedness and other related phenomena has not yet reached an agreement on basic definitions of giftedness and even the question whether giftedness is innate or not and how it could be reproducibly measured is still discussed (Ericsson et al. 2007; Ziegler 2007). One of the most problematic issues is the lack of researchers' objectivity. In this regard, one might highlight the unclear differentiation between giftedness and skills that may in certain circumstances mimic giftedness; uncertain equivalence of identification of the same individual as gifted by different means and different assessors; inconsistency in changing criteria of giftedness through time; the role of deliberate practicing and so on.

Although the research identifies some settings, where the identification is relatively objective, that is, repeating assessments yields the same results and its prediction is relatively accurate, they are limited to sport and chess where supervisors' or coaches' decisions may be confirmed against actual competitions. For example, measurements of specific physical tasks like reaction time, coordination, flexibility and similar, hints that an individual has predispositions for development in a certain sport discipline. In spite of a talent, everybody knows that even more important for the success of an individual is his/her motivation, working habits, focus etc. Similarly, in music talented children are identified very early. Identifiers are clear: having a good ear and a sense of rhythm accompanied by love for music. Practicing itself cannot substitute those innate abilities no matter how extensive it is. On the other hand, again everybody knows, to become a good musician, years of an extensive practice are inevitable.

To develop a talent in sports and music, supervisors and mentors are role models for their protégées. Coaching in sport is mostly a second career after retirement from an active participation in competitions. The ability, knowledge and experience of a coach is usually far above the trainee level. Therefore, it is natural and obvious for students to follow the guidance of an experienced person with much higher level of proficiency. Similarly, music teachers have all finished music high schools, academies, most of them performed on stages at various levels etc. Their gifts and proficiency were proven already by acceptance to the music academy as almost all of them have rigorous entrance exams. Therefore, the student works with her/his role model on everyday basis.

Unfortunately, the regular school lacks the role models. Highly gifted individuals rarely develop their career as the school teachers. Even for rare examples of highly gifted students that decide on the career of a teacher in the regular compulsory school, they are often not aware of their talents or the society does not value them as such. Gifted students in a regular school rarely find a teacher able to think beyond the standard teaching frame, have a reach personal experience of looking on problems in an “unusual non-traditional” way and asking “strange” questions. Regular teachers sometimes cannot even follow the reasoning of a highly able students, who easily consider various causes and several consequences of a discussed phenomenon at the same moment. Therefore, teachers have to be trained in identification of gifted students and later on support and development of their abilities. Finally, teachers should be aware that almost in every classroom a student or two are more gifted than the teacher himself in general and they should accept this as an opportunity and not as an threat for their authority.

Besides the testing in sports, only one example of purposely designed testing that has proven a predictive value was found in the literature. In studies conducted in chess (Ericsson et al. 2007 and references therein), researchers have designed a set of specific positions of chess pieces on the chessboard. The archived moves of world champions in those situations were analysed and compared with the moves of chess trainees. It turned out that more trainees performing similar or exactly the same moves as champions become successful chess players than trainees making other, usually more elementary moves. The method was highly predictive with this respect.

Inquiry based learning of science is similar to a chess game in some aspects. Former predictions and consequent actions are later tested during the game development. The outcome of the game is usually not known. In inquiry based learning, students meet new phenomena, they observe them, measure some quantities they find important and are asked to discover patterns in the measured data. They form possible explanations and test them with purposely designed experiments. From experimental results students conclude if the tentative explanation survived the test and is possible as an explanation or it should be rejected. The whole process aims to systematically establish the circumstances researchers are faced with while investigating the unknown phenomena. Students’ approaches in inquiry based learning that recreate such circumstances can thus be used for identification of giftedness, regardless of students’ personal, social, intellectual and economic background.

A Unit Example: A LCD and Additive Colour Mixing

In this section an example of an active, relatively simple inquiry based learning unit on liquid crystals display colours is presented, which may be used for initial tentative identification of gifted students, also students from underprivileged background having weaker academic skills like reading, writing and drawing. Specifics of the activity related to the indicators of giftedness are emphasized.

A detailed explanation of the liquid crystal display function is presented in Chap. 3 (Čepič 2014). Here the physics of liquid crystals display is only briefly discussed. The display consists of long thin light tubes and several layers of plastic sheets with purposely designed properties providing uniform illumination of the rear

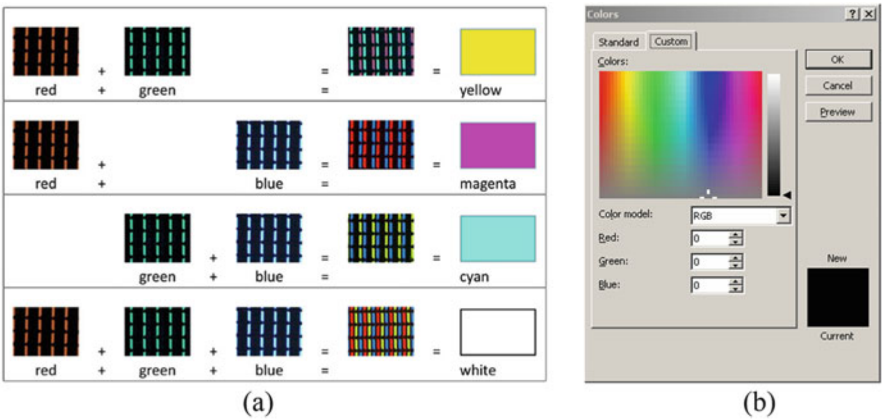


Fig. 17.1 (**a**) Colour math for display colours. (**b**) The tool for numerical definition of colours

side of a display, and the liquid crystal filled between two conductive glasses laminated by crossed polarizers (Planinšič and Gojkošek 2011). The pattern of the conductive layer on the display glass allows to address each constituent part of the liquid crystals display—a pixel—independently. The special structure of the liquid crystal between glasses rotates the polarization of light after passing the rear polarizer for 90°. This polarization direction coincides with the transmission direction of the second polarizer. The light is fully transmitted. The structure of the liquid crystal changes, if voltage between the two glasses is applied. The unit of a pixel is transparent if no voltage is applied. If the voltage is larger than a certain threshold, few volts usually, the pixel unit is non-transparent or dark. For voltages in-between, the pixel's unit is semi-transparent, the light is partially absorbed and variability of the transmission is called the grey levels. Each pixel usually consists of three unit[1]: the red, the green and the blue. Each unit of a pixel is addressed independently and for obtaining the colours red, green or blue colour filters are added to each unit of the pixel.

To determine the colour on the screen the function "palette" or "background colour" available in any word processing or graphical program is used. The brightness of each colour is defined by a number between 0 (dark) and 255 (completely transparent, bright). By changing this number, the brightness of considered part of a pixel (red, green or blue) changes and the colour that appears on the screen changes as well (Fig. 17.1). The colour on the screen is defined by three principal numbers from 0 to 255.

The activity aims for students to learn that three elementary colours of different brightness form any colour on the screen. In addition, based on experience, students

[1]Pixels in more recent displays often have more units than three. Additional white unit of a pixel is added for increased brightness. Such displays can still be used for the activity, but the colour settings has to be appropriate.

construct additive colour mixing rules and are able to predict the colour from the palette numbers.

Let us briefly resume the structure of the active unit, and consider possible indicators of giftedness related to activities of students. The unit consists of four activities in which students

Activity 1: Learn to use a digital microscope.

Activity 2: Observe colours on the screen using a digital microscope.

Activity 3: Relate colours to their numerical values given in "palette"

Activity 4: Recognize magnified parts of the original screen picture.

Each activity allows for several indications of possible giftedness of a student. In addition, activities do require good observation, inference and ability of forming predictions, but extensive reading of instructions is excluded. Let us consider the activities in more details. Identification letter from A to K from the list of identifiers given the 2nd Section are marked besides the activities.

Activity 1: Using a Digital Microscope

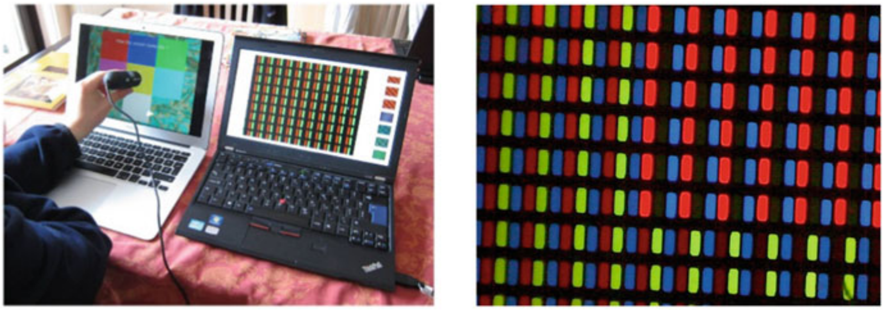
Students receive elementary instructions: Which program uses the microscope; How to connect the microscope to the computer; How to focus the lenses in order to get a clear image of the object on the screen.

Students usually grasp the idea quickly and start to investigate various objects and their surfaces. Some students try to observe almost everything, some are happy with basics, observing a few objects like skin, cloth, paper, for example, and their motivation is lost. As a curiosity, in particular the curiosity about science is one of the specific characteristics of gifted students the teacher may identify, this activity usually serves as the first indicator. Potentially gifted students often

- Suggest and independently observe various objects, which even teacher often did not consider as interesting (leads to or due to A and B).
- Find two magnifications for near objects without being instructed (A–D).
- Discover a role of a microscope as a camera for distant objects without needing a hint (A–F).
- Are very persistent in using the microscope for various investigations (a general indication of giftedness).

Activity 2: Observe Colours on the Screen Using a Digital Microscope

For this activity an additional portable computer, an LCD screen or a tablet with two images prepared in advance is needed (Fig. 17.2). As the first image the teacher prepares a photo that has areas of different colours. Especially appropriate is a photo



(a) (b)

Fig. 17.2 (**a**) Observation by a digital microscope of a computer screen on the left is shown on the computer screen on the right. Two computers allow for easier performance of screen observation than using a single one. (**b**) The puzzle: Which part of the picture in 2(a) is shown in 2(b)?

that includes woods, grass and sky, and a wide rainbow over them. The second image should consist of three series of coloured squares like in Fig. 17.2a. The first row consists of red, green and blue square, the second of yellow, magenta and cyan square, and the third of grey, brown and light orange square. Students use a digital microscope to observe various areas of the first photo before proceeding to the second image. After recognizing that three colours only are present, they proceed to the second image, observe the coloured squares with the digital microscope and the teacher helps them to understand the additive colour math (Fig. 17.1). However, gifted students are usually quicker than others and need less guidance in this process. They are able to

- Quickly recognize that three colours form all colours observed at the screen (A–F, K).
- Form the additive colour math rules even without explicit observation of squares (A, K).
- Predict how saturation and hue depend on the brightness of pixel parts (A, K).

Activity 3: Relate Colours to Their Numerical Values Given in "Palette"

The third activity introduces numbers in the colour palette as parameters that describes the brightness. The larger is the number for a specific pixel colour, the brighter the corresponding colour. The number ranges from 0 to 255. The goal of this activity is that students are able to recognize the colour from a given number and vice versa; students are able to predict the numbers for a specific colour. Students in general are able to reach the goal, however different students spend very different amounts of time on acquiring enough experience for successful prediction of colours with various hue, brightness or saturation. However, an indication for a gifted student is

- A quick adaptation to numbers and transformation of numbers to colours and vice versa (A–F, K).
- An easy prediction that red colour becomes light red by adding blue and green (K).

These activities were implemented for a group of around 30 teenagers, the participants of the Youth Summit in May 2016 that was organized in parallel to the ICIE (The International Conference on Excellence, Creativity, and Innovation in Basic and Higher Education) in Rijeka, Croatia (Čepič 2016). Two additional tests were for the group of the first year students of the program for prosperous physics teachers (20 students) and for the elective subject called Interesting physics for younger students available to students of all programs at the University of Ljubljana, Faculty of Education (around 30 students). In each group one or two students only were able to suggest the approach to change the pure red colour to the light red and even less were able to locate the most difficult magnifications on the original image. These tests have served to verification of the clarity of instructions and the time requirements, therefore no thorough studies were made.

Activity 4: Recognition of Magnified Parts of the Picture in Their Original Version

The last part is used for an active conclusion and recollection of the unit learned. Teacher prepares few images. Images start from geometrical objects having elementary red, green and blue colours only and increase in complexity regarding colours. The magnified parts of the pictures also increase in complexity. The teacher starts with magnification of a simple part of the picture by asking: from where is this part of the picture. One example is given in Fig. 17.2b. Magnified parts of the picture increase in complexity as well. The parts are taken from areas with continuously variation of the colour, but they could be rotated in addition.

The activity could be performed as a game and it is used for additional evidence in an identification process. A good spatial orientation is often used as an independent indicator of giftedness, this activity actually focusses on its demonstration. For gifted students one could expect

- A quick recognition of picture parts for introductory magnifications (K).
- Recognition of more complex magnifications with respect to colours by applying the previous experience regarding colours, brightness and numbers (K).
- Recognition of magnification even when its orientation is not the same as in the picture without additional hints (K).

All activities have in common that no preliminary knowledge is necessary for achieving the goals that is to find the rules for colours at the screen and to understand the structure of the screen. As newly acquired knowledge is immediately used in new situations, the whole activity although it is simple and straightforward, provides indication for giftedness. Observation of students' actions is simple and straightforward. Indicators for giftedness are relatively clear.

Conclusions

The paper discusses problems related to identification of gifted students and is focused on detection of students from underprivileged background. The theoretical consideration of contemporary physics topics in education for identification of giftedness is discussed. In contemporary physics topics, especially if they are taught by inquiry based learning approach, students are equal with respect to the prior knowledge and experience, and the lack of academic skills does not obscure actions of students as the regular schoolwork at standard topics does. Therefore, students lacking academic skills and prior knowledge, which is common for students with underprivileged background, may express themselves and excel in activities. An observant teacher can focus her/his attention on students' actions, questions and suggestions indicated for each activity. However, evidence from a single observation is not enough, but it may draw the attention of a teacher to a specific student, yet not recognised for his/her talent. The teacher further attention and support may result in improvement of student's efforts later.

Another issue already mentioned in this paper is that students with the lack of academic skills have worse results measured by standard instruments then they should have according to their abilities (Borland and Wright 1994). Activities of the type suggested in this contribution are appropriate for an individual case study of actions of the potentially gifted student. The student that shows interest and motivation in science in spite of low results in regular school chores should be invited to perform activities individually in order to her/his actions and responses should be assessed with respect to criteria a–k proposed in this paper. If the teacher's observation detects a student's good ability in drawing conclusions and using very recent information in new and different circumstances, a further support to student for development of his abilities she/he cannot develop at home is advisable.

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Chapter 18
The Development and Pilot Testing of the Measurement Tool of Skills Level Development in the Lower Secondary Physics Classroom

Katarína Kríšková and Marián Kireš

Introduction

One of the aims of the educational reform in Slovakia from 2008 was to focus rather on the competencies and skills than on the knowledge. The national curriculum was changed; the topics and their order were adjusted. The number of physics lessons (as well as for other science subjects) was changed—unfortunately, the number of lessons was lowered. The main idea of the reform was not to memorise the knowledge but rather to develop the skills helpful to survive in the twenty-first century world. By the change, the way of teaching, learning and organising the lessons had to be changed. To fulfil the idea of the skill development, the pupils themselves had to be actively involved in the classes. In the physics education, this can be simply made by conducting an experiment by pupils themselves, where various skills can be fostered. Pupils seem to be pleased by this—experimenting resembles game more than learning. On the other hand, teachers have to think how to assess such activities. It is hard for them as they are not assessing only the knowledge. The assessment of the skills involves much more opportunities for teachers and pupils but also the problems and limitation teachers meet. Because of that, we tried to create the tool for the skill measurement. The process of the skill measurement tool in the form of pen-and-paper test is described in detail.

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Skills Test

The education focused on the skill development requires the change in the teaching methods. The teacher should not talk and explain only, but rather lead pupils to find their own explanation, to inquire, to ask, to be active and responsible for their own education. The change has to reflect also the way of the assessment of pupils' work (Harlen 2013). Because of that, the various tests were developed. The tests focus not only on the knowledge but rather on the skills that can be used in various situations mainly in real life.

To assess skills, various methods can be chosen. Skills may be assessed within practical work, where one can directly see how they are used while solving a practical problem. However, the practical assessment methods require not only the sufficient amount of the equipment but also the time for testing the whole class. On the other hand, the pen and paper test are often used to assess the skills as it is a quick and easy way to collect the data.

There are many of the tests developed to measure skills developed in science. The most known are: Test of integrated process skills (TIPS) (Dillashaw and Okey 1980; Burns et al. 1985), Test of integrated Science process skills (TISPS) by Beaumont-Walters and Soyibo (2001), or the Scientific inquiry Literacy test (ScInqLiT) by Wenning (2006). These are written assignments assessing various skills. The tests are suitable mainly for higher secondary pupils that have some scientific knowledge. The tests are predominantly designed in the multiple-choice format and are easy to evaluate.

Purpose

By studying the literature, national curriculum and physics textbooks, we decided to focus on the development of three particular skills. These are: making predictions, following directions and working with data tables. The skills are to be developed in the lower secondary education physics lessons. Skills can be easily developed via experiments and hands-on activities.

Before the test development, the national pedagogical documents were studied and analysed. The analysis was conducted in these steps:

1. The study of the national curriculum with the focus on the skills,
2. The study of the textbooks activities and their potential for the skills development,
3. The debate with experienced teachers,
4. Reselection and the definition of the skills' level,
5. Study of skill tests available.

By studying and analysing the national curriculum (SPU 2015) we found the minimal requirements for skills to be enhanced in the lower secondary education. The national curriculum states skill fostering is the essential part of the education.

Skills to be enhanced in the physics education are connected mainly to the inquiry, but there are also interpersonal skills mentioned. Although there is no list of specific skills to be developed, the formulation of the requirements is definite.

Physics textbooks (Lapitková et al. 2010a, b, 2012a, b) available in Slovak republic are written in the way to support the pupil's practical work. The textbooks reflect the aim of the national reform. The textbooks contain a lot of practical activities by which skills can be fostered. However, the skill development is not emphasised. The activities have a form of the leaded inquiry—the problem and the instructions are stated. Pupils are lead to learn through experiment, to discover new phenomena and to construct their own system of knowledge. To make it properly, the various skills are needed. Looking at the selected skills we can see that:

- Making predictions—not required in most of the activities, a few activities ask to predict the outcome at the beginning of the activity, (mainly in the form of the answer to the question), guess of the measurement outcome is more common,
- Following the directions—quite each activity has written instructions, the instructions are understandable, often supported by the picture/scheme, some activities request to design own instructions (in higher years),
- Working with data tables—data tables prepared for the measurement, a few activities request to design the suitable data table.

After the analysis, the debate with physics teachers was prepared. The aim of the debate was to find out what teachers think about the issue, how and if they develop the skills and how they assess it. The teachers are partially acquainted with the issue. Teaching methods are based on the inquiry and practical work of pupils. They see the importance of the skill development. However, they do not know how to assess it. They use tests and written assignments focused on knowledge. Therefore they demand the skills measurement and assessing tool suitable for determining the skill level and the progress of development. The formative assessment can be easily done by rubrics, monitoring of pupils' work, self- and peer-assessment. As the practical work is the principal part of lessons, it should be the part of, not only the support to the final assessment. In the discussion, teachers stated that they may try to estimate the pupil's skill level by the observation of pupil work during the lessons. However, there are more than 20 pupils in the class, so it is impossible to estimate the skill level of whole class at once. The demand for the skill level determination is, therefore, important for them.

By defining the selected skills we determined the skill level. Skill level determination was based on the literature (SAILS FP7 project), personal experiences and experienced teacher recommendations. Each skill has four levels of development, ordered according to the difficulty of the enhancement (Table 18.1), the first level is the base of skill every pupil is able to acquire.

Before selecting the appropriate skill test to be chosen, the determination of the attributes of the test was done. However, these stated the limitation for skill tests

Table 18.1 Skills and their specification level

Skill	Specification level	
Making predictions	P1	Differentiate prediction from the general statement
	P2	Prediction as an answer to the question
	P3	Filling in the incomplete prediction
	P4	Formulate the predictions
Following directions	D1	Reading with the comprehension
	D2	Following specific directions
	D3	Rewriting/reformulating the given instructions
	D4	Write the directions/instructions
Working with data tables	T1	Reading the information from the data table
	T2	Filling in the data table
	T3	Modification of the data table given
	T4	Designing the data table

available. Because of that, we decided to develop the measurement tool that fulfils the following needs:

- Suitable for the lower secondary education,
- Tested pupils that have no or a little knowledge of physics (and science in general),
- Focused on the selected skills,
- The informal way so it does not resemble the examination,
- Not developed for a special curriculum content.

Because of the specified requirements, the items in the test should not be focused on the physics problems and phenomena. The tasks should be formulated in the way the pupils are able to understand without any scientific knowledge. Problems in the test should have a lot in common with the pupils' experiences and situations as authors assume solving such tasks is more interesting for pupils that tasks disconnected from the pupil's life.

The Measuring Tool

The developed measuring tool has a form of written assignment. Authors decided to use pen and paper format because of simplicity of data collecting, administration and the evaluation. The measuring tool is suitable for the lower secondary education pupils. The tasks are inspired by the real-life situations pupils either have experienced before or it is possible they will experience. The tasks test the application of the skills learned by the experimentation. The developed measurement tool is focused on the selected skills mentioned above.

The test contains eight items; some of them are divided into 2–3 subtasks. Four of the tasks are designed in the format of choosing the right answer—one of them is multiple-choice, the others have one correct answer. The remaining four test items are open questions.

The first item is called the Candle. The original task focused on the graphs skills is from the test MFTest—SPS (Temiz et al. 2006). We redesign the task so it is focused on the data tables primarily. The main point of the task is to design data table and fill it with the appropriate information shown in the picture. The item has tree subtasks ordered according to the level of difficulty. At first, pupils are asked to list information they can read from the picture given. Next subtask is to design the data table suitable for the information. The data table should have the basic attributes—rows and lines, heading with the quantities and units stated. At last, the designed data table has to be filled with the values read from the picture.

The second item focuses on the predictions (Bilgin 2006). As the pupils may not know what the prediction is, its definition is stated at the beginning. By this, we want to avoid incorrect answer because of not having the knowledge. The question asks to choose a statement that may be the prediction. The statements are formulated in the way that may lead to think they can be tested somehow and stated if it is true or not. The main idea is that the prediction is the statement about the future action, so the statement with the past time information and the general statements about the snowman are not suitable for the definition of the prediction.

The third task is called The Timetable. The task was designed on the basis of the task from Czech national examination for 5–6 years old pupils (CERMAT 2006). The original task was reformulated to the school environment and a recording data table with the information given was added. The task is to read the timetables given and decide which one is correct according to the information given. Information given is formulated in the way one, two or none of the timetables is excluded.

Task number four, Merry-go-round (CERMAT 2006) is dedicated to the following directions skill. The map of the city part is given. There are four descriptions of the journey from one place to another. The task is to choose the correct way from the given ones. When reading with comprehension and following the written direction correctly, the journey is easy to find.

Next task focuses on the skill making predictions. The task is adapted from the tests (Wenning 2007). The task has the multiple-choose format.

The TETRIS game is the sixth test task. The item is designed by the authors. The task is inspired by the homonymous computer game. It measures the following direction skills. The aim is to move the objects to the given place; draw its final position and write the instructions for the movement. At the beginning, the explanation of the game is written and the example showed (Fig. 18.1). The example of the object movement helps pupils to comprehend the movement and its symbolic notation. The task (Fig. 18.2) is designed in the way so there is no incorrect placement of the object. Pupils can decide with which object they start and where is will be placed. The order is not as important as the drawing of the final position and the writing down the process of the placement.

The item no. 7—RECIPE is also focused on the following directions skill. The item is designed by the authors. The handwritten recipe for the cake is given (Fig. 18.3). The task is to list the ingredients and rewrite the process. By writing

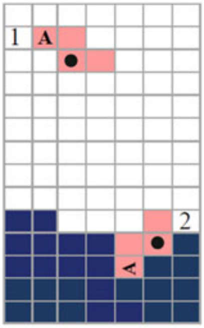
6. Tetris game

Tetris is an electronic game in which you try to place the objects so that you fill the whole row. The objects can be moved to the right, to the left, rotated and released down.

Example:

The object was moved from position1 to position 2.
The steps of the movement are written:

Steps	Symbolic notation
Object A is moved 3 boxes to the right.	→ → →
Object A is rotated in the direction of the arrow.	↶
Object A is released down to position 2.	↓



Annotation: *When rotating the object, the part containing the point does not change its place.*

Fig. 18.1 Task no. 6 The TETRIS game instructions

Move three objects so that you fill in as many rows as possible.
Write down the procedure of the movement by using symbols (→, ←, ↶, ↷, ↓)
Draw the final position of the objects.

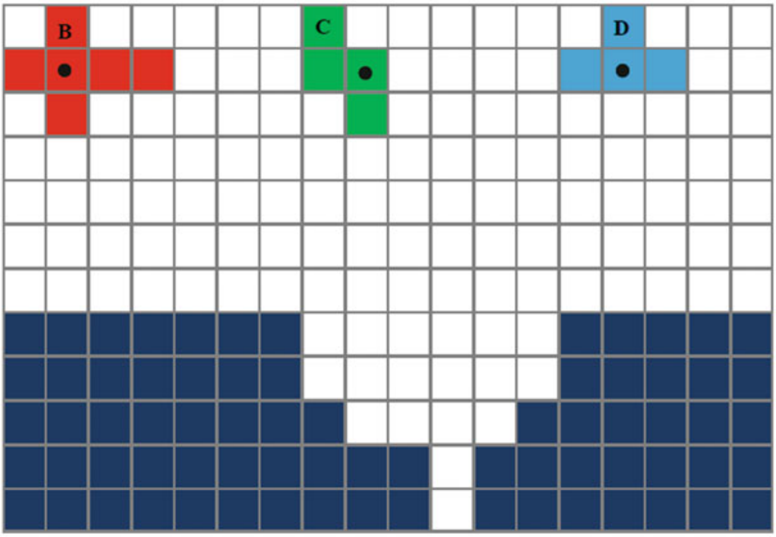


Fig. 18.2 Task no. 6 The TETRIS game task and working place

the list of ingredients we can see the level of the reading with comprehension skill. By rewriting the process in the order, we can see if and how the following direction skill is acquired. The order of the process is important although first few steps can be shifted without making mistakes.

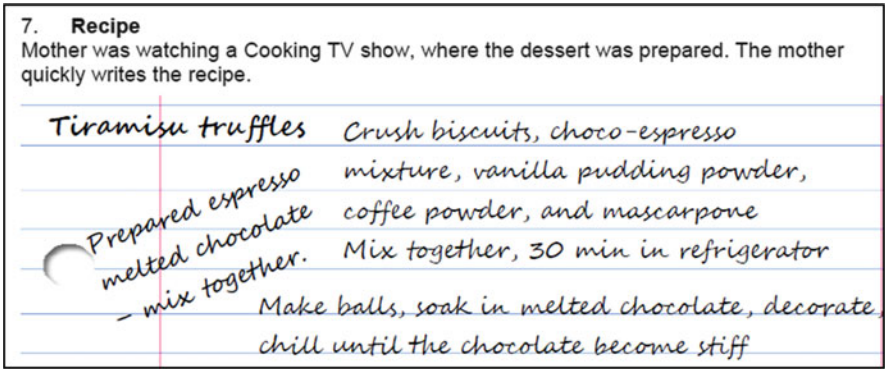


Fig. 18.3 Task no. 7 Recipe

Table 18.2 Test tasks and the skills they focus on

Task	Task name	Skill	Specification
1	Candle	WORKING WITH DATA TABLES Reading with the comprehension (D1)	Designing the data tables (T4) Filling in the data tables (T2)
2	Snowman	MAKING PREDICTIONS	Differentiate the prediction from the general statement (P1)
3	Timetable	WORKING WITH DATA TABLES	Reading the data tables (T1) Filling in the data tables (T2)
4	Merry-go-round	FOLLOWING DIRECTIONS	Following the specific directions (D2)
5	Old flashlight	MAKING PREDICTIONS	Understanding the concepts of the prediction (P1)
6	The TETRIS game	FOLLOWING DIRECTIONS	Write the directions (D4)
7	Recipe	FOLLOWING DIRECTIONS Reading with comprehension (D1)	Rewriting the directions, direction order (D3)
8	Experiment	MAKING PREDICTIONS	Understanding the concept of the predictions (P1)

The last test item is called the Experiment. The task is from the test NoSLiT (Wenning 2007). The task focuses on the making predictions skill.

Table 18.2 contains the list of skills the test items focus on. One can see there are more skills needed within one task. The skills cannot be separated. However, in the course of the evaluation, this had to be taken into account as misuse of these skills may lead to an incorrect answer. In the table row specification, skills are specified by a level of skill development.

Pilot Testing

Pilot testing was conducted in order to find out if formulation and the design of the test items are correct. The testing was conducted in June 2016 with a group of 25 pupils from year 8 (13–14 years old). The test was administered by their physics teacher. The time for completing the test was 45 min, although pupils were able to complete the test in a shorter time.

Within the pilot testing, the possible responses were observed. That helps us to distinguish the skill level more precisely and to find out potential groups of mistakes pupils may do. By the evaluation of pilot tests, we can state the minimal acceptable skill level.

By the administration and the pilot testing, we can see that:

- Administration can be done by the teachers (they do not need any detailed instructions),
- The use of language and formulation is understandable,
- The test is suitable for the lower years of the lower secondary education,
- The maximal time-length of the test is 45 min,
- There is no need of special equipment.

The evaluation of the pupils' tests was done with the intent of finding the skill level. The skill level may be stated by the correct answers as well as the analysis of the written procedures.

Findings

While marking the test, the analysis of the responses was made prior to finding the most common mistakes pupil made in the test. These mistakes can help us to find the problems and the misuse of the skill pupils had. The mistakes repeated by a large group of pupils could be considered as the misconceptions keeping the skill development from the progress. The mistakes can also point out the skill level that is not enhanced appropriately. The test was evaluated and the responses were analysed with intent to find not only the limitations of the test but also to find the skill level according to the pupil's responses.

Table 18.3 contains the expected responses for the open questions and the most common mistakes pupils made. By looking at the mistakes we can see the problems pupils have at solving tasks. One can assume the problems arise because of the low skill level achieved. The analysis shown is made for the open question task—first two focuses on the working with data table skill, the remainders are focused on the following direction skill.

We can see that pupil have some problems with the designing the data table, namely missing the data table headings (there are no physics quantities written and their units) and the table contains redundant rows and lines, although the designed

Table 18.3 Expected responses and the most common mistakes for open questions

Tasks	Expected responses	Most common mistakes
1a	List of the physics quantities and their change	Incomplete list Redundant information (the speed of change, the wax evaporating, change of the shape, ...)
1b	Designing the data table	Redundant rows and lines No heading Designing the graph
1c	Filling in the data table	Using words Units in each cell
3	Reading the information from data tables Filling in the data tables	Correct notation in data table Incorrect notation in excluded timetable row excluded timetable row not filled in
6a	Move three objects according to the rules given	Object not moved Disallowable movement
6a	Write the directions	Direction not written Incorrect number of side arrows
6b	Draw the final position of three objects	Final position of one object not drawn Final position sketch, objects cannot be distinguished More objects were drawn
7a	Write the list of ingredients	Ingredient is written two times Missing Ingredient
7b	Write the process (instructions)	Change of the order Missing step in the process Extra steps (cooking pudding with milk)

data table should fit the information given. The most common mistake found in the first task was the graph plotted instead of the data table designed. Therefore we assume the pupils do not acquire the highest skill level (D4—Designing the data tables).

The making predictions skills tasks were focused on the lowest level (P1—distinguish the prediction from the general statements). The percentage of all the tasks focused on the skill was high (in average 81%). By that, one can assume the skill on the level stated is fostered in an acceptable way and it is acceptable for the transition to the higher levels.

The following direction skills test items focus on different skill levels. The D1 level (reading with the comprehension) was tested by task 1a (Candle) and 7a (The Recipe). The Merry-go-round task tested the level (D2—following specific directions), The Recipe task tested the level 3 (D3—rewriting/reformulating the given instructions) and The TETRIS game tested level 4 (D4—write the directions/instructions). While the task 1a gained the average percentage 72%, the task no 7a gain less than 50%. By this, we can see the pupils have some problems with the reading with the comprehension. That can affect the successfulness of the other tasks. The percentage of the D2 level item was 60%, the percentage of D3 was even lower—only 16% of the responses were without any mistake. Twenty percent of the responses were correct at the D4 level task. From this, we can assume the skill is not fostered in the levels D3 and D4. The level D2 of the skill should be improved more.

The working with data tables skill was tested on these levels—D1—reading the information from the data table, D2—filling in the data table, D4—designing the data table. The T1 task had them average percentage 78% that indicates the skill level development is acceptable and pupils can foster higher levels. The level T2 cannot be evaluated, as the tasks were formulated in the way the T1 and T2 overlapping. By looking at the answer analysis we can assume the level is developed on a moderate level, although it should be strengthened more with the aim to eliminate the mistakes. The highest T4 level was assessed by one task. The percentage was low—only 32% of pupils had correct and complete answers. More than half of the answers contained the data table designed, but only 32% had also the correct heading with quantities and their units stated. The T4 skill level is therefore not fostered appropriately.

Conclusion

The designed measuring tool was pilot tested in June 2016 at the sample of 25 pupils of year 8 (aged 13–14).

The test contains three items focused on the making prediction skills. The average percentage chained was high. One may assume the skill is developed on an appropriate level. From the evaluation, we can see pupils are able to distinguish the prediction out of the other statements at the base of the information given. To test the higher skill level (P2—prediction as an answer to the question, P3—fill in the incomplete prediction and P4—formulate the predictions) it is recommended to use open question type.

There were two test items focused on working with data tables skill. The items contain more subtasks focused on various skill levels (reading the prepared data table, filling in the prepared data table, designing the data table). From the evaluation of one can see pupils do not have a problem to fill in the data tables (level T2), although there are some mistakes that need to be eliminated. Because of that T2 level needs to be strengthened. The T4 level (designing data table) is not fostered appropriately. Some of the respondents design the graph instead of the data table. That may indicate they are not used to design the data tables because the graphs are more often used in physics.

Following directions skill was tested by three items, although it can be tested indirectly by evaluating of following the tasks in the whole test. One of the items was in the form of a single-choice question, the others were open questions. The tasks focus on the different skill level (D1—reading with the comprehension, D2—following the written direction, D3—rewriting/reformulating the given directions, D4—designing the instructions). According to the evaluation, one can see the skill is not developed at the appropriate level. Pupils had problems with rewriting the instructions. The recommendation is to emphasise the skill more.

The designed test is intended to be used in a study focused on the skill development with the aim to determine the skill levels and its progress. By pilot testing, we can see the test can be used for the skill level determination. The suggestion toward the test improvement is to extend the test by adding more tasks focused on the selected skills. The question should be in the open question form. Another recommendation is to make the test evaluation easier, so the test can be used by the teachers themselves.

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Chapter 19
Assessing Student's Conceptual Understanding in a Laboratory on the Measurement of the Planck Constant

Massimiliano Malgieri, Pasquale Onorato, and Anna De Ambrosis

Introduction

Experimental activities focusing on modern physics topics have a high value in education, both at high school and undergraduate level, as they allow students to observe and measure consequences of theoretical concepts which may otherwise remain too abstract for them. One common choice is the measurement of the Planck constant, either from the linear relationship between frequency of incident light and stopping potential in the photoelectric effect, and from the linear relationship between the threshold potential and the light frequency of LEDS with different colours (Precker 2007). The two activities may complement each other (Checchetti and Fantini 2015), in the sense that the first one shows that light can be absorbed in "lumps" of energy $E = h\nu$ by an electron to make a transition from a lower to an upper energy level, while the second shows that light can be emitted in the form of photons with energy $E = h\nu$ by electron making a transition from an upper to a lower energy level.

At the University of Pavia we are carrying out a long term project of education to quantum physics for both high school students and teachers (Malgieri et al. 2014, 2017; Onorato et al. 2015). In the context of the Italian PLS—Piano Lauree Scientifiche, and we realized a composite laboratory activity revolving around the measurement of h using the two methods described above.

We tested the activities with a final class of the Italian Liceo Scientifico, composed of 16 students, 10 male and 6 female, and we designed a structured post-test to

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assess their effectiveness in helping students understand basic quantum concepts. Although overall encouraging, the results show vast margins for improvement, especially regarding students' understanding of the connection between microscopic and macroscopic quantities and, more generally, the longitudinal integration of new knowledge with far reaching concepts of physics such as energy and power. Based on such indications, we designed an extension of the activity with LEDs based on the observation and study of the relationship of emitted light intensity to both voltage and current, and the evaluation of the external quantum efficiency.

Experimental Activities

Measurement of Planck Constant Through the Photoelectric Effect

Theoretical aspect on this topic were introduced by the teacher in class, before the laboratory activity. The photoelectric effect was studied using the PASCO AP-9368 *h*/*e* apparatus used for the undergraduate laboratory, consisting essentially of a vacuum photodiode and a mercury gas vapour lamp to whose output slit a diffraction grating is applied, so that the different colours of the discrete spectrum of Hg can be separately directed towards the vacuum photodiode. The activity is divided in two steps:

- By using a variable transmission filter, the stopping potential (in this case, the potential difference at the terminals of the vacuum diode after electrical equilibrium is reached) is shown to be independent of the intensity of the incident light.
- By directing light of different colours to the intake of the vacuum photodiode, students measure that the stopping potential is instead dependent of the frequency of incoming light. The dependence is verified to be approximately linear, and the value of h is estimated.

The treatment of the dependence of photoelectric current on the intensity of incident light is necessarily qualitative with the apparatus adopted: students observe that, by increasing the light intensity through a variable transmission filter, the capacitance associated to the vacuum tube takes more time to charge and adjust to a stable voltage level.

Measurement of the Planck Constant from the Turn-On Voltage of LEDs

The LED activity was preceded by a theoretical discussion of the diode and LED models, which touched both a semi-classical picture of the device, based on the build-up of a charge distribution in the n-p junction depletion zone, and a schematic quantum depiction of the electron being first promoted to the conduction band energy and then, upon reaching the active region, dropping to the valence band again following collision with a "hole". The procedure for measuring the Planck constant involved the following steps:

- Using the PASCO PS-2115 voltage-current sensor, the *I-V* characteristic curve was measured by students for four LEDs up to a maximum current of 50 mA. The LEDs were Kingbright water-clear package diodes of red (640 nm) yellow (590 nm) green (560 nm) and blue (470 nm) colours. In the circuit they were in series with a 470 Ω resistor.
- The threshold voltage V_{th} for each LED was estimated by using the standard procedure of interpolating the *I-V* curve with a straight line when its slope stabilizes, and taking the intercept between such straight line and the *V* axis.
- The data obtained were then displayed using MS Excel on a new graph reporting the LED peak emission frequency, taken from the house datasheets, on the horizontal axis and the estimated bandgap energy $E_g \approx qV_{th}$ (where q is the electron charge) on the vertical axis. The data was fitted to a straight line crossing the origin of coordinates, with the estimated value of the Planck constant corresponding to the slope of such line.

Test Instruments and Results

The assessment test was conducted in class about 10 days after the lab activity. Students did not conduct other physics activities on these concepts at school between the lab and the test, and were informed that the test would count as an assessment for school grading. The test was composed of two parts; the first part was to be filled by each one of the students individually; for the second part, which consisted of two problems of some complexity, students were re-divided, in the classroom, in the same groups used for the experimental activities.

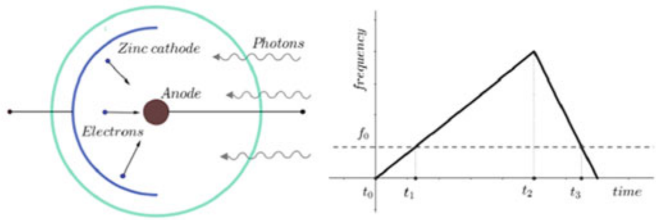
Individual Questions

The individual part of the test was composed of four questions, two of which (Figs. 19.1, 19.2, Tables 19.1 and 19.2) were multiple choice items with explanation, and two (Figs. 19.3, 19.4, Tables 19.3 and 19.4) multiple choice only. The first two questions were adapted from the literature (Oh 2011).

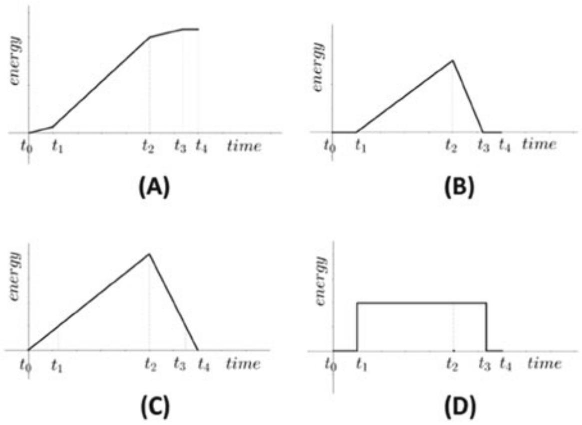
Small Group Problems

The questions to be solved in small groups were in the form of problems; we hypothesized that by communicating among them in the small group, students could overcome some of the difficulties of the proposed items. This part of the

Question 1. A vacuum photodiode (figure below, left) similar to the one used in the lab, is illuminated with electromagnetic radiation with a frequency slowly varying in time from zero to a maximum value as shown in the figure below, right.



Which one of the following graphs best represents the time dependence of the maximum kinetic energy of the electrons emitted from the photocatode (when the graph shows zero kinetic energy, electrons are not emitted)?



Explain your reasoning.

Fig. 19.1 Question 1, inspired by Oh (2011)

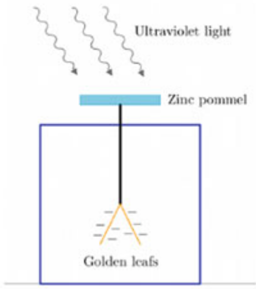
questionnaire was not only meant for assessment purposes but also with formative aims, as part of the educational process (Figs. 19.5, 19.6, Tables 19.5 and 19.6).

Discussion

Results from Individual Questions

The activity on the photoelectric effect was effective in helping students understand the photoelectric as a threshold phenomenon, and the meaning of the relationship $E = h\nu$. Out of 16 students, 14 chose the correct answer B in Question 1, and the

Question 2. In the experiment represented in the figure below, a gold leaf electoscope is initially charged with a small negative electric charge, so that the gold leaves diverge. The upper pommel of the electroscope, which is used for charging and discharging it, is a plate made of zinc, a metal capable of producing photoelectric effect.



If the zinc plate is illuminated with ultraviolet light, the zinc emits electrons and gradually the electroscope is discharged, so that the gold leaves become nearer and nearer until they eventually adhere one to each other.
Suppose that the ultraviolet light lamp, which emits light at a fixed frequency, can be used at different intensity levels. Is it true that, if the intensity of the light which illuminates the plate is higher, the gold leafs close faster, while if the intensity is lower, the leaf close slower?

True **False**

Explain your reasoning.

Fig. 19.2 Question 2, inspired by Oh (2011)

Table 19.1 Results for question 1

Type of answer	Number of students (N = 16)
Answer B (correct)	14
Of which with correct explanation	14
Answer C (no threshold)	1
Answer A (integration-like process)	1
Answer D (on-off process)	0

Table 19.2 Results for question 2

Type of answer	Number of students (N = 16)
Answer "true" (correct)	6
Of which with correct explanation	6
Answer "false"	10
Incorrect explanation based on the idea that electron flow only depends on frequency	10

explanations for the correct choice were typically exhaustive and well-articulated. For example, one student wrote:

Question 3. The light emitted by a LED diode is produced essentially:

a. From thermal agitation of the atoms which constitute the LED
b. From photons emitted by electrons continuously accelerating
c. From photons emitted by electrons making a transition from a lower to a higher energy level
d. From photons emitted by electrons making a transition from a higher to a lower energy level

Fig. 19.3 Question 3

Question 4. The emission of light form a LED only happens when the the potential difference goes beyond a certain threshold (which we measured in the lab) because:

a. The threshold is the potential difference which allows the LED to heat up enough for emitting visible light.
b. The threshold is the potential difference which allows electrons to be expelled from the material the diode is built of, thus emitting photons.
c. The threshold is the potential difference which allows electrons to be excited to a higher energy level, from which they fall back to a lower energy level, emitting photons.
d. The threshold is the potential difference which allows the material the LED is built of to capture free electrons from the air, emitting photons.

Fig. 19.4 Question 4

Table 19.3 Results for question 3

Type of answer	Number of students (N=16)
Answer “d” (correct)	15
Answer “c”	1

Table 19.4 Results for question 4

Type of answer	Number of students (N = 16)
Answer “c” (correct)	14
Answer “b”	2

> Below the threshold frequency no electrons are emitted, and observing the initial graph we see the threshold frequency is first reached at t_1 and then it is returned upon in t_3. Thus, the graph will have energy equal to zero in the time intervals before t_1 and after t_3. Between t_1 and t_3, energy will be proportional to frequency in consideration of the law E = h f, and in particular it will increase between t_1 and t_2 and decrease between t_2 and t_3 as it is in figure (B).

Indications from Question 2 are less encouraging, as a majority of students (10 out of 16) did not understand the relationship between photoelectric current and light intensity. Students providing the wrong answer always over-extended the correct concept that the kinetic energy of electrons only depends on the frequency of incident light, concluding that also the flux of electron from the golden leafs could not depend on the intensity of incident light; for example one student wrote:

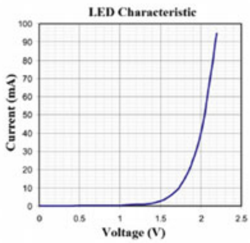
Group question 1. An experiment is performed with a photocell having a potassium photocathode. The photocathode is illuminated with monochromatic light. For certain wavelengths of the incident radiation, electrons are emitted from the photocathode. Some of them are able to reach the anode even when it is connected to a lower potential than the cathode. However, this happens until the potential difference between cathode and anode is lower than a threshold value, called stopping voltage. The stopping voltage is measured for some values of the incident light wavelength. Results are reported in the following table:

Wavelength [nm]	579	562	546	491	436	423	405
Stopping potential [V]	0.14	0.20	0.27	0.53	0.84	0.91	1.06

1. Identify the two quantities, connected with the experimental data, between which the theory predicts a linear relationship, and represent such relationship in a graph.
2. Derive form the graph the minimum energy necessary for extracting an electron from potassium (extraction work).
3. Determine the maximum wavelength of the incident radiation above which no electron is extracted (photoelectric threshold for potassium).

Fig. 19.5 Group question 1. The item was proposed in the Italian Olympics of Physics (AIF 2016)

Group question 2. A red LED diode, which emits predominantly at a wavelength $\lambda = 640nm$, has the following current/voltage characteristic:



Assuming that its *external quantum efficiency* (ratio, expressed as a percentage, of the number of photons emitted in free space to the number of electrons injected in the LED) is 0.01%, what is the total power (measured in W) of the light emitted by a LED if it is kept at a voltage of 2 V?

Fig. 19.6 Group question 2

Table 19.5 Results for group question 1

Type of answer	Number of groups (G = 5)
Correct answers to all three questions	1
Correct answer to question 1 only	2
No correct answer	2

Table 19.6 Results for group question 2

Type of answer	Number of groups (G = 5)
No correct answer	5

> Light intensity does not determine the quantity of electrons which are freed, rather the frequency of light determines it.

Six students instead demonstrated understanding of the ideas that (a) light with higher intensity contains more photons; and (b) the number of incident photons is proportional to the number of emitted electrons, one such answer is for example:

> The greater the light intensity, the more photons it contains. The number of photons contained in the light beam is directly proportional to the number of electrons emitted with the photoelectric effect.

Part of the problem may lie in the way such issue is dealt with using the PASCO *h*/*e* apparatus. In fact, using such equipment, students observe the relationship between light intensity and current only indirectly, by estimating the time required for fully charging the vacuum photodiode's capacitance at different levels of light intensity, rather than directly, by measuring a current. This also introduces new theoretical elements in the explanation of the phenomenon (i.e. requires a robust intuitive understanding of the capacitance concept) which may produce additional difficulties to students.

Most students answered correctly the multiple choice questions on the mechanism of light emission from LEDs (15 students out of 16 for Question 3, and 14 out of 16 for Question 4). Besides providing an independent measurement of h, the LED experiment and the discussion preceding it was used to introduce the general ideas that (a) electrons can occupy different energy levels and (b) electrons can operate a transition between a higher and a lower energy level by emitting a photon of energy $E = h\nu$, where E is the energy difference between the levels. Based on multiple choice questions only, students seemed to have acquired these basic ideas.

Results from Evaluation in Small Groups

Contrary to expectations, group based evaluation did not help students overcome the difficulties posed by complex problem, and provided some evidence of low motivation, such as the noticeably lower overall quality of produced written answers with respect to the individual test. Further research may be required to understand whether these shortcomings can be overcome by providing increased motivation, or by removing some other adversely influencing factor. For example, group evaluation may in future be moved from the classroom to a different setting (e.g. one of the school labs) were students may be encouraged to communicate more.

In Problem 1 of the group test, only one group could effectively re-apply all the ideas related to the photoelectric effect discussed and practiced in the lab, about 10 days afterwards; while two groups applied them partially.

Problem 2 of the group test proved to be beyond the capabilities of students. Only one group attempted a partial solution: they identified the value of current corresponding to a voltage of 2V from the graph, and computed the energy of each emitted photon through the Planck formula, but were unable to proceed further.

The problem required to connect several ideas in an integrated perspective; students' difficulties may lie in either one of them, or in their combination:

- Deriving the number of electrons per second crossing the LED from a value of current intensity,
- Deriving the number of photons emitted per second from a value of emitted power,
- Understanding the I-V characteristic curve
- Understanding the relationship between power and energy

Extension of the Led Activity

In order to overcome the limitations of the activity with LEDs highlighted in the test, an extension of the activity was designed, revolving around the study of the intensity of light emitted as a function of both voltage and current, and the estimation of the quantum efficiency of the LED (Kraftmakher 2011). The main focus of the activity was in helping students relate microscopic quantities, such as the number of photons emitted by the LED and the number of electrons injected in the active region, to macroscopic, directly measurable quantities such as current and light intensity.

Before proposing it to high school students, the activity was tested with a group of 10 undergraduate students enrolled in a course (preparation of educational experiences) belonging to the specialization in teaching for both the Physics and Mathematics degrees. The activity develops as follows: first, based on a Predict-Observe-Explain approach, students have to predict the shape of the light intensity versus voltage curve. Then they measure it, by using both a PASCO PS-2106A light sensor and a PASCO PS-2115 Voltage–Current sensor. After having tried to explain the measured curve, they are asked to compare the light intensity versus voltage curve to the current intensity versus voltage curve (see Fig. 19.7) and advance a hypothesis for the relationship between light intensity and current.

Students then directly observe the light intensity versus current characteristic (Fig. 19.8) which is found to be with sufficient approximation a relation of direct proportionality. More exactly, the relation is typically found to be linear up to at least 15–20 mA before starting to slowly decrease its slope, and with an intercept on the horizontal axis near zero, typically at about 1 mA.

Both the theoretical grounds for light intensity being predicted as directly proportional to current intensity, and the possible reasons for the observed departures from linearity are discussed with students. Then, students obtain a linear fit for the light intensity versus current curve in the range of 0–20 mA. The slope m_{lx} of the linear fit obtained is transformed from photometric to radiometric units by providing students with an approximate factor, depending on the LED used, and the distance the measurement was performed, to find the light intensity to current ratio in W/A rather than in lx/A, according to the following formula:

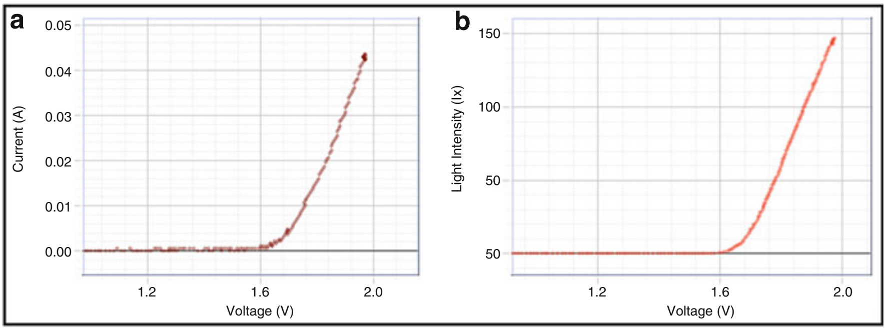


Fig. 19.7 Current versus voltage (**a**) and illuminance (in lx) versus voltage (**b**) curves for the Kingbright WP710A10SRC/E Super Bright Red LED. Light intensity is measured on the LED axis at about 8 cm from the LED capsule

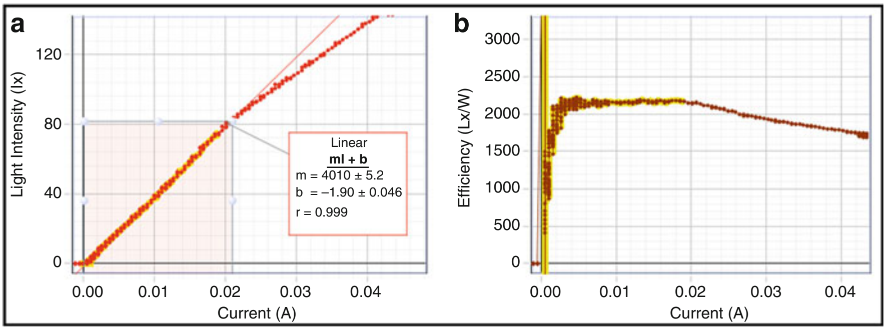


Fig. 19.8 Illuminance versus current (**a**) and efficiency in lx/W versus current (**b**) curves for the Kingbright WP710A10SRC/E, measurements in the same conditions as Fig. 19.7. The graph (**a**) also shows the linear interpolation of the data in the range 0–20 mA

$$m_W = m_{lx} \cdot F(d) \tag{19.1}$$

The expressions for the $F(d)$ provided to students are in Table 19.7.

The values provided in Table 19.7 come from an integration of the luminous efficiency curve on a small range of wavelengths (obtained from the half-width-half-maximum value of the LED spectrum in the factory datasheet) around the LED peak; and also contain the simplifying assumptions that the LED emission is purely Lambertian (multiplication by $\pi\, d^2$ rather than $4\,\pi\, d^2$ for a uniform emitter). These topics are only touched by passage with students, and if desired can be delved more in depth later. The activity from here proceeds to the objective of evaluating the *external quantum efficiency*.

In fact, the coefficient m_W is easily interpreted as the ratio of the total luminous power P, expressed in W, emitted by the diode in free space, and the current intensity I injected in the active region, in the zone of maximum efficiency of the LED,

Table 19.7 Results for group question 1

LED type	Peak wavelength (nm)	Factor F(d) (W/lx)
Red	660	0.035 π d^2
Yellow	590	0.002 π d^2
Green	557	0.0015 π d^2
Blue	465	0.024 π d^2

i.e. before the slope of the light intensity versus current start decreasing. But the following relations also hold:

$$P \approx n_\gamma h\nu \tag{19.2}$$

Where n_γ is the number of photons emitted in free space per unit time and ν is the frequency corresponding to the peak emission wavelength, and

$$I = n_e q \tag{19.3}$$

Where n_e is the number of electrons per unit time injected in the active region, and q is the electron charge. Then it follows that

$$\frac{n_\gamma}{n_e} \approx \frac{P}{I}\frac{q}{h\nu} = m_W \frac{q}{h\nu} \tag{19.4}$$

The activity is concluded with a discussion of the reasons why the external quantum efficiency computed should not be considered equivalent to, and is in fact significantly lower than, the internal quantum efficiency, i.e. the number of photons produced in the active region for each injected electron. In particular, we highlight the role of total internal reflection from the semiconductor (n = 3.4–3.7 depending on the type of substrate used) to the epoxy dome (n = 1.4–1.5) and connect it to the non-uniform, Lambertian-type emission pattern of the device.

The preliminary trial with undergraduate students was satisfactory, in that students were effectively engaged in the activity and generally found it interesting and not particularly difficult. The measured external efficiencies were compatible within error with those which can be computed from the LED datasheets for yellow and green; for the red and blue diode results were in lesser agreement because of the very large uncertainty in the factor $F(d)$ at the sides of the luminous efficiency curve, but still of the same order of magnitude as the correct one.

Conclusions

A laboratory activity centered on the measurement of h with two different methods, and the investigation of the photoelectric effect and the LED device, seems to have a large educational potential in helping students understand the basics of quantum physics. However, according to our results, in the design of the activities particular care should be taken of some problematic issues.

Students may have difficulties in connecting the laws relating macroscopic quantities such as current intensity, voltage, irradiated and electric power, to a model involving microscopic entities such as electrons and photons. According to our results, students do not seem to have specific problems in associating the Planck law to an individual photon-electron interaction; however, both in the photoelectric effect and in the case of LEDs, their difficulties lie more in understanding that the number of such interactions in a given time is conceptually connected to the values of current and light intensities.

In order to contribute to overcoming these difficulties, we propose to extend the activity with LEDs with a direct measurement of the light intensity emission as a function of current and voltage end the evaluation of the external quantum efficiency. Besides helping connect the microscopic and macroscopic description of the LED, this could favour a better understanding of the concepts of power and energy, improve the understanding of the one-to-one relationship between electrons and photons also in the case of the photoelectric effect, and finally open the route for other interesting considerations, such as those related to energy saving.

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Part VI
Low-cost Experiments and Inquiry

Chapter 20
Effectiveness of Learning Through Guided Inquiry

Dagmara Sokołowska

Introduction

It is difficult to point out an exact moment of the first appearance of inquiry instruction in science education, but the concept of inquiry-based teaching (IBT) emerged in early 1960s (Bruner 1961; Schwab 1960). The fundaments of the method originate from constructivist and experiential learning ideas of Jean Piaget (e.g. in Jervis and Tobier 1988) and Lev Vygotsky (2004), as well as works by Jerome Bruner (1960) and the idea of progressive education promoted by John Dewey (1897, 1916, 1920, 1933).

At least a few models of inquiry-based science education (IBSE) have been developed so far (McDermott et al. 1996; Brown et al. 2006; Milne 2010; Harlen 2013), all of them emphasizing an active role of learners and the learning process involving critical thinking and reasoning, development of skills and procedures employed by scientists, as well as cooperative and collaborative work. The learning process takes place in repeated cycles of scientific inventory (Martin et al. 1997; Reiff et al. 2002; Bybee et al. 2006; Harlen et al. 2012) and at different levels, distinguishing a certain degree of learner's independence from teacher instruction, i.e. openness in the teaching through inquiry (Schwab 1962; Herron 1971; Colburn 2000; Buck et al. 2008; Faulconer 2016).

Teaching through inquiry has been advocated in science education for decades (Hakkarainen 2003). Furthermore, since the beginning of the twenty-first century it has been promoted very intensively in the USA after a publication by National Research Council (NRC 2000) and across Europe after publication of so-called Rocard's Report (Rocard 2007), and many projects (e.g. ASSIST_ME, Fibonacci, ESTABLISH, SAILS) have ever since been funded by the EU to support IBSE

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dissemination at all levels of schooling. Yet the implementation of the method is slow and frontal teaching of science and learning of science confined in textbooks still prevail (Song and Kong 2014; SECURE Recommendations 2013). Even if inquiry activities are practiced in the classroom, they seem to be mostly teacher-directed (Asay and Orgill 2010).

Among many obstacles related to school environment, classroom management and teaching habits, like timetabling, access to equipment, and safety concerns (Baker et al. 2008; Anastopoulou et al. 2012; SECURE Recommendations 2013), teachers point out in particular unfamiliarity with adequate assessment tools and express their own reservations related to the concern about students' learning outcomes as measured by standard exams (Tan and Caleon 2016). Thus securing the acquisition of basic knowledge during implementation of IBSE (Harlen et al. 2012) seems to be one of the most important factors determining the success of this method in a schooling system (Miner et al. 2009), even though the method itself is generally perceived as a teaching approach that develops mainly practical research skills and not so much as a vehicle for learning science content (Asay and Orgill 2010).

Intensive research on effectiveness of teaching and learning through inquiry has been carried out since 1980s, but the scope of the majority of individual studies is local, based on small samples (Cairns and Areepattamannil 2017) and they focus on limited ages (Song and Kong 2014; Kukkonen et al. 2014; Varma 2014), although meta-analyses are also published from time to time (Bredderman 1983; Hattie 2008; Furtak et al. 2012; Lazonder and Harmsen 2016; Cairns and Areepattamannil 2017). The research considers different inquiry approaches (levels of inquiry) and study the impact of inquiry teaching and learning on affective and cognitive domains. All studies researching the influence of inquiry instruction on affective domain find positive associations between inquiry and dispositions towards science, such as interest in and enjoyment of science learning (Cairns and Areepattamannil 2017) and attitude towards science (Rissing and Cogan 2009), regardless of the science subject and the learners' age. At the same time there is no agreement between researchers about the impact of teaching through inquiry on the increase of scientific knowledge, encompassing in particular content knowledge and process skills, as compared to more traditional, direct teaching. In his book on synthesis of meta-analysis Hattie (2008, p. 209) reports small effect size of the impact of IBL on achievements related to science content and a larger effect for science process outcomes, found in meta-studies in period 1983–1996. A number of more recent studies (e.g. Varma 2014; Kim et al. 2012; Cervetti et al. 2012; Song and Kong 2014; Kukkonen et al. 2014) indicate significantly greater gains in content knowledge and science understanding in primary school learners taught through inquiry as compared to the control groups. No difference between inquiry and traditional groups was found by Cobern et al. (2010) in science classes in middle schools; modest learning associations with an amount of inquiry saturation resulted from research synthesis done by Miner et al. (2009) at the same age, while at the same time Witt and Ulmer (2010) found inquiry appearing to be more effective than traditional teaching in increasing middle-school student academic achievement. The study by Cairns and Areepattamannil (2017), drawing data from PISA (2006) revealed that inquiry-based science teaching was significantly negatively related to science achievement among 15-year-old students from 54 countries across the world. It is worth to notice that the lack of consensus in the above-mentioned studies may, among others, derive from different approaches to inquiry as regard the details of the employed inquire activities and the degree of learners' independence from teacher instruction, which make the direct comparison inadequate. Nevertheless, the overall picture emerging from the research shows the trend of decreasing of the effectiveness of learning through inquiry with age (Hattie 2008). Quite common is also a research-based conclusion that minimal guidance in open inquiry fails on acquisition of science content knowledge (Kirschner et al. 2006) and that inquiry-based learning can be more effective than other instructional approaches as long as students are supported adequately (Lazonder and Harmsen 2016; Furtak et al. 2012).

Among a rich spectrum of resources on research on the effectiveness of teaching through inquiry, it is difficult to find results regarding medium- or long-term effects. Those few available in the literature report longitudinal impact of inquiry mostly on student's attitude towards science and interest in science careers (Gibson and Chase 2002; Knox et al. 2003). Marx et al. (2004) studied a group of students from middle schools participating in a learning program spanning 3 years and found out statistically significant increases on content knowledge test scores for each year of participation. Long-term retention of knowledge is reported by Metz (2008) concerning statistics knowledge acquired during introductory biology classes incorporating inquiry-based investigations. Thus it is visible that little attention is paid to the medium-term and long-term retention of learning outcomes through inquiry, probably mostly due to the considerable difficulties in access to the students, encountered in a longer period of time (Knox et al. 2003).

In order to address this gap we proposed the study on the retention of the effectiveness of development of conceptual understanding and acquisition of scientific knowledge 6 months after implementation of a series of ten lessons of teaching through guided inquiry in science lessons provided in ten classes of 4th–6th grade students. The intervention was a part of the project Academic Center of Creativity. Two research questions were considered: (1) what was the pupils' learning achievement, in terms of some inquiry process skills, conceptual understanding and content knowledge, just after the inquiry intervention? (2) what was the retention of a learning achievement in inquiry-based lessons over the span of 6 months (medium-term retention)?

Context of the Study

The study presented here was a part of a project Academic Center of Creativity (ACC) which received funding from the European Union under European Structural Funds in 2015. The aim of the project was to implement a series of guided-inquiry activities and to research to what extend such implementation is feasible and advisable, as well as to investigate the effects of implementation on pupils' learning outcomes and their attitudes toward science.

The intervention consisted of design of instructional units, teacher workshops, and classroom practices in ten classes of four different primary schools participating in the project. Schools were invited on the basis of previous cooperation in other educational projects (Fibonacci, SECURE, Swietlik), taking into account their characteristics like localization, size of the school, statistics in national exams and the place they had at that time on the list of school ranking. That resulted in the selection of two rural and two urban schools, ranked 6–8 in official school ranking on scale 1–9, where lower number means lower overall achievement of the school. All activities took place during the summer semester of the school year 2014–2015, except for one test meant to measure the longitudinal effect of implementation, which was delivered after summer vacation in the same calendar year.

The guided-inquiry based learning units were designed by the project research group, consisting of members of academic staff and Ph.D. students from the Faculty of Physics, Astronomy and Applied Computer Studies of the Jagiellonian University Krakow, Poland. The units were based on physics and chemistry topics, specific for science curricula of 4th–6th grade of primary school in Poland at that time and encompassed each topic as a whole, so no additional lessons were needed to meet the curriculum demands for the selected topics. Two tools were prepared in each unit, namely worksheets for pupils and respective guides for teachers. In addition to inquiry investigations, worksheets for students were supplemented with tasks for scientific reasoning, most of them containing different representations (graphs, diagrams, pictures, tables etc.)

Prior to the intervention in-service science teachers, teaching classes participating in the project, were trained on inquiry-based method in theoretical and practical manner. The workshops for teachers encompassed some of the units prepared for their classes, as well as the introduction to assessment strategies appropriate for teaching through inquiry. Four sessions of 5-h meeting were organized. For all five teachers involved the training was their first experience with inquiry based method.

In addition to that, we invited to the project also five students, undertaking at that time the pedagogical preparation for pre-service science teachers at our faculty. They took part in six separate 5-h workshops on teaching through inquiry and during the training they met in-service teachers participating in the ACC project. The idea was to connect in-service and pre-service teachers in pairs that would result later on in cooperative work on inquiry lessons in the project. Thus the subsequent implementation of teaching through inquiry was done by pre-service teachers in the classes of in-service teachers who took the role of observers of the teaching intervention involving their own pupils.

Implementation of inquiry spanned 5–7 weeks in March and April 2015 and took place in all classes at the same time. It was the first contact of learners with the method of teaching through inquiry. Each class was provided with ten lessons of guided inquiry, the approach in which the teacher sets up a problem to investigate and provides resources, and students select procedures and conduct experiments, collecting the data and drawing research-based conclusions (Colburn 2000; Banchi and Bell 2008). We chose this approach to inquiry, as evidence shows it to be the most appropriate and giving the best impact on students' learning (Kirschner et al. 2006; Lazonder and Harmsen 2016; Furtak et al. 2012). The classes met pre-service teachers once again in the last 2 weeks of the school year (June 2015) and took part in additional 2–4 h of open inquiry (Colburn 2000; Banchi and Bell 2008), conducting investigations prepared in advance by pupils themselves on science topics they were interested in. Every hour of implementation was observed by at least one researcher who took notes on the process of implementation, problems and obstacles.

Research Design

During the intervention several measures of the processes and their influence on affective and cognitive learning domains were employed (two questionnaires for pupils, observations in classes, pupils' worksheets). All above measures provided data on perception of implementation and implementation details, analysis of which is beyond the scope of this paper. The core instrument implemented in order to enable the measurement of learners' acquisition of knowledge through guided-inquiry was the test T1 administered in April 2015, just after completing the series of the guided-inquiry lessons. Three different tests were designed for each grade due to differences in science topics covered by the curricula specific to these grades (Table 20.1). Pupils were retested with use of exactly the same tests 6 months later, in October 2015, in order to collect data to study the medium-term retention of conceptual understanding and scientific content knowledge acquired through guided-inquiry. The first tests were announced to the pupils a week before they were held. The second set of tests was unannounced, so the learners were not induced to make any additional effort to prepare for it.

The tests for all ages encompassed a variety of questions: multiple choice and open-ended questions, tasks involving reasoning and scientific inference, tasks requiring explanation of phenomena or observation, as well as one task of preparing the experiment (consisting in putting forward the hypothesis, choosing adequate materials and tools, and designing the experiment plan). Most of them were based on different visual and mathematical representations: graphs, diagrams, pictures, tables, charts, maps etc., recognized as those which, when used in learning and assignments,

Table 20.1 Topics encompassed in ten lessons of a guided-inquiry instruction during the implementation

Grade	Topics
4	1.Water and its phases 2. Weather constituents 3. The Sun over the horizon and seasons
5	1. Matter
6	1. States of matter 2. Mixtures 3. Light and shadow 4. Mirrors and lenses

help constructing multiple mental representations (Schnotz and Bannert 2003) and foster different types of cognitive processes (Ainsworth 2006). It is worth to notice that all types of representations included in the tests had been also introduced into in pupils' worksheets and practiced during the guided-inquiry based learning implementation and in homework tasks.

Results

The guided inquiry-based intervention involved 170 pupils out of whom 161 participated in the first test and constitute the sample for the study of short-term effectiveness of learning through inquiry, while 140 pupils participated in the second one. One 6th class consisting of 10 students took part only in T1 due to difficulties in reaching particular students in the Autumn after they finished grade 6 and left the school. Two tests, T1 implemented in April 2015 and T2 organized in October 2015, were administered to the other nine classes. Only 131 pupils took both tests and they constitute the sample for the study of the medium-term retention of learning outcomes, in terms of some inquiry process skills, conceptual understanding and content knowledge gain.

We studied the overall results as well as compared the results between genders. We have also divided all pupils participating in the study into three groups of different abilities, assigned on the basis of pupils' semestral grades achieved in science subject prior the implementation of the inquiry-based learning method in their classes. Level 1 (L1) constitutes pupils achieving grades D and C (average scores below 70%), Level 2 (L2) comprises learners attaining grade B (average scores 70–80%) and Level 3 (L3) constitutes pupils achieving grade A and A+ (average scores above 80%).

The Shapiro-Wilk test statistics indicated that the results of both tests, T1 score (S1) and T2 score (S2) are not normally distributed in most of the separate groups under study (including the entire sample), so below we report only the medians (*Mdn*) and interquartile ranges (25–75 % percentiles) or mean ranks (R_{mean}) of the results and we compare the groups, using non-parametric tests.

The median for test T1 was found to be $\mathrm{S1_{Mdn}} = 60\%$ and can be juxtaposed with the median of an overall semestral performance of the learners, $P = 70\%$, encompassing the results of all tests, assignments and other activities. The Mann-Whitney test statistics indicated no statistically significant difference in achievement in groups of boys ($N = 91, \mathrm{S1_{Mdn}} = 60\%$) and girls ($N = 70, \mathrm{S1_{Mdn}} = 58\%$) at the level of $p < 0.05$ ($U = 3038$, $Z = 0.5$, $p = 0.617$), see Fig. 20.1. On the other hand the results obtained by learners belonging to different ability groups differed significantly as indicated by the Kruskal-Wallis test statistics, $H(2, N = 161) = 23.84$, $p < 0.0001$, with greatest value for group L3 ($N = 48$, $\mathrm{S1_{Mdn}} = 77\,\%$, $R_{mean} = 56.6$), lower value for group L2 ($N = 66$, $\mathrm{S1_{Mdn}} = 61\,\%$, $R_{mean} = 82.3$) and the lowest value for group L1 ($N = 47$, $\mathrm{S1_{Mdn}} = 47\,\%$, $R_{mean} = 103.2$). Further pairwise comparisons (two-tailed) indicated statistically significant differences between

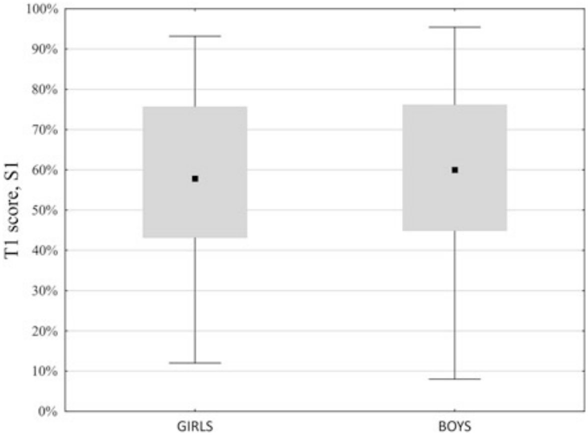

Fig. 20.1 Box-and-whisker plot of T1 results for group of boys ($N = 91$, black square indicates median, $S1_{Mdn} = 60\%$) and girls ($N = 70$, black square indicates median, $S1_{Mdn} = 58\%$). Grey boxes encompass interquartile ranges (25–75% percentiles) and whiskers represent min-max values

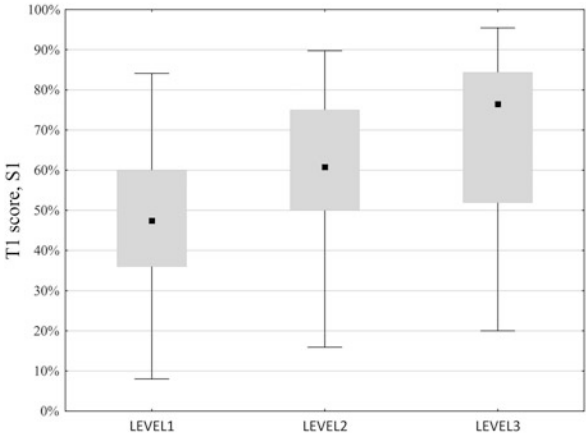

Fig. 20.2 Box-and-whisker plot of T1 results for L1 ($N = 47$, black square indicates median, $S1_{Mdn} = 47\,\%$), L2 ($N = 66$, black square indicates median, $S1_{Mdn} = 61\%$) and L3 ($N = 48$, black square indicates median, $S1_{Mdn} = 77\%$). Grey boxes encompass interquartile ranges (25–75% percentiles) and whiskers represent min-max values

results in group L1 as compared to the results of group L2 ($p = 0.011$) and L3 ($p < 0.00001$), and no statistically significant difference between groups L2 and L3 ($p = 0.054$). Figure 20.2 presents the box-and-whisker plot of the S1 medians in three ability groups.

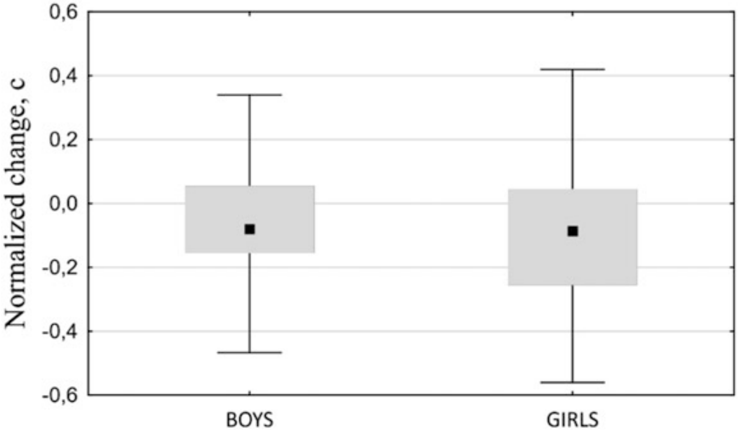

Fig. 20.3 Box-and-whisker plots of normalized change for group of boys ($N = 68$, black square indicates median, $c_{Mdn} = -0.079$) and girls ($N = 63$, black square indicates median, $c_{Mdn} = -0.086$). Grey boxes encompass interquartile ranges (25–75% percentiles) and whiskers represent min-max values

In order to characterize the change of an individual's learning gain over a period of 6 months we employed so called normalized change factor (Marx and Cummings 2007), given by the following:

$$c = \begin{cases} \dfrac{S2 - S1}{100 - S1} & \text{for } S2 > S1 \\ \text{drop} & \text{for } S2 = S1 = 100 \text{ or } 0 \\ 0 & \text{for } S2 = S1 \neq 100 \text{ and } 0 \\ \dfrac{S2 - S1}{S1} & \text{for } S2 < S1 \end{cases} \tag{20.1}$$

where S1 and S2 are individual's performance in (T1) and (T2), respectively (given as a percentage). According to the Shapiro-Wilk test statistics the normalized change is also not normally distributed in most of the groups under study. The median of a normalized change value for the whole sample over the period of 6 months including 2 months of summer vacation, was found to be $c_{\mathrm{Mdn}} = -0.086$, (indicating 8.6% of loss or 91.4% of learning retention).

In order to compare the normalized changes achieved by boys and girls, we used U Mann-Whitney test (double-tailed), which indicated no statistical significant difference in normalized change between boys ($N = 68, c_{Mdn} = -0.079$) and girls ($N = 63$, $c_{Mdn} = -0.086$) at the level of $p < 0.05$ ($U = 1952, Z = 0.87$, $p = 0.38$). Figure 20.3 presents a box-and-whisker plot of the normalized change for both groups.

Since the distributions of the normalized change are normal only for L1 and L2, we compared the normalized change factor using a non-parametric Kruskal-Wallis one-way analysis of variance by ranks (ANNOVA Kruskal-Wallis test). The

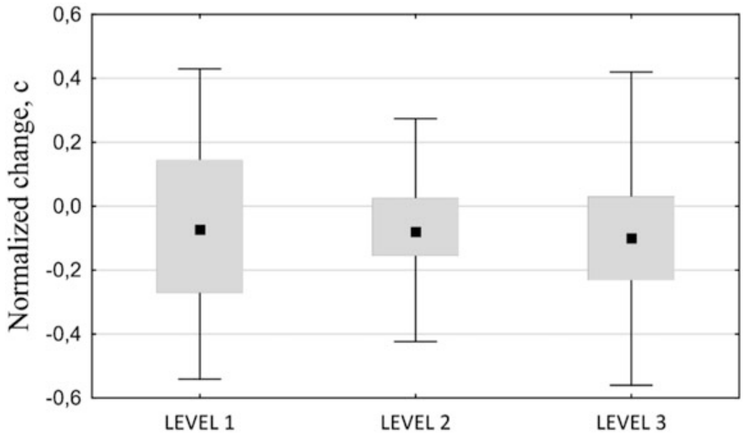

Fig. 20.4 Box-and-whisker plots of normalized change for L1 ($N = 38$, black square indicates median, $c_{Mdn} = -0.072$), L2 ($N = 55$, black square indicates median, $c_{Mdn} = -0.08$) and L3 ($N = 38$, black square indicates median, $c_{Mdn} = -0.099$). Grey boxes encompass interquartile ranges (25–75% percentiles) and whiskers represent min-max values

statistics result, $H(2, N = 131) = 0.224$, $p = 0.894$ indicates no evidence of stochastic dominance between the samples, so we conclude that there is no statistically significant difference of a normalized change across three ability groups (Fig. 20.4).

Conclusions

The main purpose of this research was to examine the impact of a 10-h-long guided inquiry-based intervention on the pupils' learning gains in science, in terms of some inquiry process skills, conceptual understanding and content knowledge. The implementation was part of a 10-months project, having its time and span limitations. Care was taken in selection of schools, taking into account diversity in their characteristics, like localization, size of the school, their statistics in national exams and the place they had at that time on the list of school ranking. Yet the selected sample of learners was not too big and we could not fully compare the learners' achievements in inquiry-based approach with their prior performance in science, since apart from the study with use of our research instruments, we were only enabled to access information about the semestral grades of the learners. Furthermore, it was not possible to work with an equivalent class of learners who were following the same curriculum but without the inquiry-based approach. This limits any comparative claims we can make from this study.

We were interested in the results achieved by the learners just after the guided-inquiry intervention (short-term effectiveness) and in the retention of the learning gain over the span of 6 months (medium-term retention). Comparison was made between boys and girls, as well as between pupils belonging to different ability groups, assigned on the basis of pupils' semestral grades achieved in science subject prior the implementation of the inquiry-based learning method in their classes. Since most of the scores in groups occurred not to be normally distributed (Shapiro-Wilk test) presentation of the results was limited to medians, interquartile ranges (25–75% percentiles) and mean ranks and the statistical analysis was performed with use of non-parametric tests, thus further limiting the statistical inference.

Examination of the findings for scores obtained in test T1 by the learners participating in the study (Fig. 20.1) reveals that the guided inquiry-based approach results in similar performance of boys and girls, thus not favoring any gender. On the other hand learning through inquiry did not change the rank of low-, medium- and high-achievers in science, as revealed by the results of comparison of test T1 scores between different ability groups (Fig. 20.2). The overall median of T1 scores was found to be $S1_{Mdn} = 60\%$, similarly to the learners' overall performance in science, $P = 70\%$, (which presents the average assessment of all tests, assignments and other activities the learners took part in during the semester prior to the implementation).

Medium-term retention of a learning achievement was studied with use of a normalized change factor. The data analysis revealed an overall 91.6% median of retention of learning achievements over 6 months after guided inquiry-based intervention, which is surprisingly high. Since no statistically significant difference was found between genders and between three ability groups, it seems that the guided inquiry-based approach resultes in similar retention of learning achievements for all pupils.

Thus, having in mind all the limitations of the study, we can conclude that the guided inquiry-based intervention in a group of 170 primary school pupils resulted in a short-term learning outcomes similar to the learners' prior achievements in science (taught traditionally), and that a quite high rate of medium-term retention of learning achievement was common for all pupils, not favoring any gender or ability group. Nevertheless, further study would be desirable to increase the significance of these findings.

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Chapter 21
A Non-classical Acoustics Teaching Lab Supported by BYOD and Inquiry-Based Learning

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Introduction

The scientific educational scenario is nowadays populated by several apparently appealing opportunities disclosed by novel technologies. Their presence alongside traditional educational activities, however, must be careful evaluated in order to avoid that the improvements in didactic and learning qualities, typically mentioned as one of the core benefits brought by technological advancements, would represent neither a pedagogical risk nor a false myth.

A series of key elements must be considered:

1. The availability of portable devices with considerable technological capabilities amongst students and teachers;
2. More broadly, the daily technological scenario where students and teachers live when they are outside schools;
3. The technological offering within didactic coursework.

As for the first aspect, it has been already assessed by several studies how mobile devices are incredibly diffused amongst students, especially younger ones. Since the early 2010s, mobile devices have become students' inseparable friends for their non-educational activities so that a "technology addiction" can be clearly highlighted amongst them (Raman and Pramod 2014).

The diffusion of mobile devices in young users was already well known, due to the motivational factors supporting this scenario, ranging from dependent and

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compulsory behaviours (Hooper and Zhou 2007) to emotional and instrumental ones (Ishii 2011). However, nowadays the diffusion is so spread that "*mobile devices are not just landline and computer substitutes but have become personal extension for the Millennial Generation students*" (Ahmed 2012).

As a direct consequence, a considerable amount of educational activities has started to embed portable electronic devices as possible didactic supports in the recent years, under the broad definition of mobile learning (Pachler et al. 2009; Traxler 2010).

However, despite numerous efforts, relevant gaps still exist between technology-intensive activities that students perform outside their schools and the level of technology available within the educational offering they receive daily (Wu et al. 2012). This has been recently confirmed by the Pearson Student Mobile Device Survey (Harris Poll Interactive Online Inc. 2015), according to which, students:

1. Would like to use mobiles more often in the classroom (Elementary Schools, ES: 72%; Middle Schools, MS: 66%; High Schools, HS: 54%)
2. Show a predominant usage of smartphones (ES: 53%; MS: 66%; HS: 82%)
3. Also show a high and growing usage of tablets (ES: 78%; MS: 69%; HS: 49%)
4. Believe in the didactic effectiveness of mobiles (overall: 90%)
5. Believe mobiles make learning more fun (overall: 89%)
6. Believe mobiles are more suitable to their learning behaviours (overall: 82%)
7. Believe mobiles can improve their learning outcomes (overall: 81%)
8. Believe they know mobiles better than their teachers (ES: 62%, MS: 72%; HS: 77%)
9. Attend few schools where mobiles are provided for every student (overall: 19%).

But how this positive attitude of students towards mobile devices, intended as profitable supports along the educational path, and how this evident limitation of schools in providing an adequate number of technologically-advanced portable devices can be actually tackled? And, at the same time, how mobile devices have actually proven to be effective in this field?

Several educational paradigms have been proposed and already analysed so far, ascertaining an undoubted usefulness for mobile devices in education, provided that the corresponding risks are clearly highlighted and coped with accordingly. In this research work, we have referred to two of these paradigms. On the one hand, the Bring Your Own Device (BYOD) paradigm is based upon the conception students can introduce their personal electronic devices into their learning experiences with a significant increase in learning effectiveness (Afreen 2014). This is particularly evident in STEM (Science, Technology, Engineering and Math) disciplines, where modern mobile devices offer powerful computational and networking capabilities. On the other hand, the Mobile Crowd Sensing (MCS) paradigm allows leveraging mobiles also as effective sensing stations, thanks to their rich set of built-in sensors (Ganti 2011), thus making them suitable for laboratory-oriented educational activities.

We believe that a proper combination of the BYOD and MCS paradigms can help overcoming current financial and logistic limitations in laboratorial didactics, which are normally due to high buying and maintenance costs for equipment as well as to the need of skilled personnel for lab assistance activities. Moreover, we also believe in mobiles as suitable technological drivers for engaging students more effectively in Inquiry-Based Learning (IBL) activities (Abd-El-Khalick et al. 2004), which promote the active participation of learners in problem solving.

Amongst the possible Laboratorial Didactic Experiences (LDEs) that can benefit from the adoption of MCS and BYOD, we have selected the acoustic domain for several reasons. First, the study of acoustic and sound propagation mechanisms usually falls outside the scope of the majority of scientific laboratories in middle and high schools. Second, the constantly increasing attention of the public opinion towards noise pollution, especially in urban scenarios, represent a significant additional element of interest. By involving students in studying these topics, a better awareness of the noise-related health issues can be achieved as well.

Therefore, we describe in this paper our IBL-based LDE in acoustics, which addresses students from middle and high schools into IBL-based LDEs and exploits MCS and BYOD paradigms. A technological platform has been developed for allowing students to participate in sound monitoring campaigns and acoustic-oriented lab activities.

The paper is organized as follows: Section "Adopted Technological and Educational Paradigms, Strategies and Approaches" summarizes the educational relevance of the BYOD paradigm and IBL strategies. Section "The Platform" presents the developed platform. Section "The Laboratorial Didactic Experience (LDE)" provides a detailed overview of the proposed LDE. Section "Validation Methodology and Discussion on LDE Outcomes" discusses the didactic outcomes. Conclusions are reported in the last Section.

Adopted Technological and Educational Paradigms, Strategies and Approaches

The educational effectiveness of the BYOD paradigm has been largely discussed in the recent years. On the one hand, several benefits have been clearly identified, such as: easier interaction across teachers and students, extended access to networked technologies, suitability for flipped learning and independent learning experiences (Traxler 2010; Stavert 2013). On the other hand, a series of challenges for the involved students have been also highlighted, such as: loss of attention, raise of social and technological gaps for lower income students, device misuse, security breaches in hosting schools (Gidda 2014; Bruder 2014).

Therefore, BYOD-mediated experiences would be improved if carried out by complying with specific educational strategies that foster the benefits coming from BYOD. In this sense, the IBL approach (Abd-El-Khalick et al. 2004) can be considered. In IBL, students construct their knowledge by formulating hypotheses and testing them by making observations and performing experiments (Pedaste et al. 2012). This means students are involved in self-directed, inductive-deductive learning processes where they perform simple experiments to investigate how dependent and independent variables are related, thus introducing learners to true scientific discovery processes. The effectiveness of such an instructional approach (Alfieri et al. 2011) has been investigated in several research works in correlation with the adoption of new digital technologies and devices, demonstrating that mobile devices are particularly useful during the inquiry phases, from elementary schools (Song 2014; O'Banyon and Thomas 2014) to universities (Barlow and Liaison 2015) and even remote laboratorial learning (de Jong et al. 2014).

From a pedagogical perspective, one of the key aspects in IBL is represented by the definition and activation of the inquiry cycle, so that students could be effectively stimulated to achieve practical and conceptual efficiency during their learning experiences. In this paper we refer to the Prevision-Experiment-Comparison (PEC) approach for the inquiry cycle activation (Martongelli et al. 2001; Theodorakakos et al. 2010), which has been designed and thoroughly validated by the CIRD (Inter-Department Center on Didactic Research) of the University of Udine, especially in the Physics domain.

During phase one (Prevision) of the PEC cycle, students start with phenomenological observations, which stimulate them to interpret the observed event and to provide quantitative estimations about physical phenomena (e.g., "how do you think the annoyance of a given noise source could be quantified?"). In phase two (Experiment), students are engaged into experimentation, in order to perform analyses about the phenomena under observation (e.g., "observe the real-time graphical representation of the given sound source directly on your smartphone display"). Finally, in phase three (Comparison), students validate their initial assumptions and hypotheses, by comparing them with the experimental evidences so that theoretical conclusions can be derived (e.g., "enforce your assumptions by examining quantitatively the graph from the experiment and by comparing it with your initial hypotheses"). This methodology fits very effectively with the adoption of mobile-mediated learning activities.

The fruitful combination of BYOD and IBL, moreover, paves the way for a massive scaling of the laboratorial dimension, especially when it is delivered online (through both virtual and remote labs). This is mainly determined by the specific dual nature of mobiles, which can behave at the same time both as semi-professional scientific sensing station (i.e., suitable to carry out LDEs) and as informational vectors (i.e., usable by students to access and consume didactic and learning contents). In such a scenario, the so-called MOOL (Massive Open Online Labs) (Lowe 2014) are becoming more and more spread out. The authors have already started exploring the effectiveness of the BYOD approach in STEM didactics, with promising results. Indeed, both the educational (Longo et al. 2015a) and technological (Longo et al. 2015b) aspects have been evaluated during a LDE addressing the didactics of the Electromagnetism in a first-degree academic coursework. The achieved outcomes have demonstrated a relevant improvement in students' engagement.

Consequently, in order to assess more systematically and more rigorously from an educational perspective the suitability of our proposal, we have applied a similar approach to the didactics of acoustics in this research work. A set of inquiry phases tailored to the acoustic domain has been designed in collaboration with the teachers from the involved middle and high schools in order to obtain a shared and agreed LDE. The LDE will be thoroughly described in section "The Platform".

The Platform

In order to offer students and teachers an LDE in acoustics and noise monitoring, a proper technological platform is needed. This solution has to exhibit both pedagogical and laboratorial peculiarities, since it must allow students performing lab activities and teachers improving the quality and effectiveness of their teachings on the same topics. Four platform component have been defined after the requirement elicitation phase:

1. *MCS-based sensing module*: it consists of a free mobile app for Android-based systems that allows students to monitor the acoustic environment they live within and to receive learning contents on noise monitoring and noise pollution topics. The mobile app emulates a semi-professional Sound Level Meter (SLM) since it allows gathering data according to regulation-compliant noise exposure quantifiers. Some of the mobile app functionalities are depicted in Fig. 21.1.
2. *Cloud-based data management module*: it is tasked to sensor data management and learning material organization.
3. *Visualization module*: it is represented by a Web-app allowing both students and teachers to visualize on interactive geo-referenced online maps the results of the acoustic monitoring campaigns carried out by their peers.

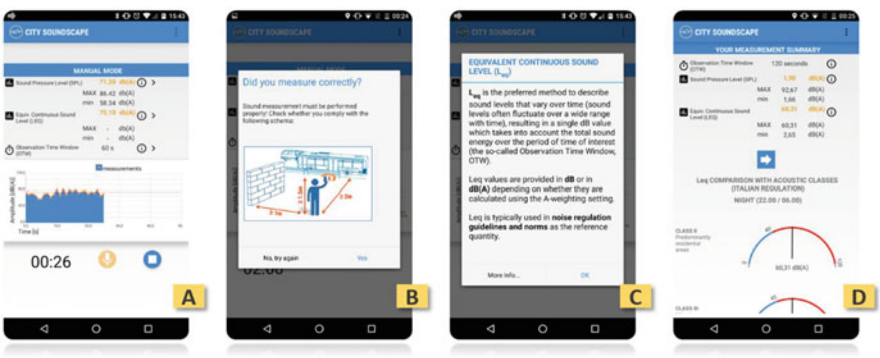

Fig. 21.1 Mobile app pages: real-time measurement (**A**); suggstions on measurement techniques (**B**); didactic material on adopted noise exposure quantifiers (**C**); measurement comparison with regulatory thresholds (**D**)

4. *Learning Management System (LMS)*: it helps managing didactic materials. It is a customized-version of the widely-adopted Moodle framework (see section "The Laboratorial Didactic Experience (LDE)")

As the technical and functional description of the proposed platform is out of scope in this context, we refer the interested readers to (Zappatore et al. 2016).

The Laboratorial Didactic Experience (LDE)

Overall Context

The LDE has involved more than 300 students and 20 teachers from 20 classes belonging to 7 different schools in Brindisi (Italy). The experimentation started at the same time in all the selected schools and it has lasted for 3 months. The experimentation has consisted of three sequential phases, according to the PEC-activated IBL approach (see section "Adopted Technological and Educational Paradigms, Strategies and Approaches"). The experimentation has consisted of three sequential phases:

1. *Preparation*: teachers from selected schools have been trained on how to introduce students to the platform and to its featuring aspects.
2. *Didactic modules*: students have been provided with learning contents from the platform. Students have also performed collaborative measurement sessions on environmental noise. The acquired knowledge has been evaluated through specific assessment questionnaires (via the LMS module) both during the modules and at their completion.
3. *Learning effectiveness analysis*: learning outcomes have been evaluated by examining the submitted questionnaires and through conclusive meetings held with the teachers.

Objectives

Primary learning objectives are geared to:

1. Engaging students in learning the core concepts in acoustics both in a descriptive and in an interpretative way.
2. Improving the laboratorial didactic experiences for students

A set of cross-disciplinary, secondary educational goals have been defined as well:

1. Improving interactions amongst teachers and students.
2. Improving interest rates in students.

3. Improving students' skills in the English language, since the majority of the accessible platform components as well as the majority of the didactic contents have been provided in English.
4. Improving students' knowledge in new technologies.
5. Fostering students' awareness in sustainable communities and environmental sustainability (since the acoustic monitoring domain is strictly related to the environmental pollution issues).

Moreover, a set of additional goals has been also defined. It enlists:

1. Disseminating a STEM-based, laboratory-oriented culture across schools.
2. Improving the overall didactic quality in STEM.
3. Fostering a positive impact on local schools (by enlarging their technological didactic offering and by motivating teachers in participating to novel IT-oriented activities).
4. Achieving tighter relationships between local schools and the local university context (since the platform has been developed by academic personnel who attended and interacted with students and teachers during the meetings).

Learning Contents

Five Learning Sections (LSs) on acoustics have been identified. For each of them, several Learning Experiences (LEs) can be proposed, each having a set of Learning Objectives (LOs) and involving a set of experiments (EXPs). The proposed LSs are: LS_1, sound sources; LS_2, sound propagation; LS_3, sound detectors; LS_4, sound pressure; LS_5, sound waves.

Let us consider, for instance, the LS addressing the topic on sound waves: its LE is "*identify how sounds propagate*", the corresponding LO is "*understand that sounds propagate as mechanical waves*" and one of the possible EXP to enforce the LO is the usage of the Kundt's tube (Sakamoto et al. 2006).

Moreover, the LDE is supported by a list of freely-available mobile apps that are presented and described in a dedicated manual, delivered in electronic format to students and teachers via the LMS module. These apps are used as didactic support during the different PDE phases, in order to allow students directly practicing the experiments for each LS on their own smartphones. The manual describes the main functionalities of each app and provides the links for its download, as well as the installation instructions. Mobile apps have been categorized into three different groups:

1. *Acoustic signal monitoring*: the apps belonging to this group allow their users monitoring sound according to several physical quantifiers and with different visualization techniques. For instance, the app developed by the authors mentioned in section "The Platform" and depicted in Fig. 21.1 allows monitoring sound w.r.t. (with respect to) two noise exposure quantifiers usually adopted in noise management regulations (i.e., instantaneous sound pressure level and time-averaged

sound level). In addition, other mobile apps from this group offer time and/or frequency analysis of the sounds acquired by the mobile embedded microphone, as they emulate sound and spectrum analysers, thus introducing students to experience the main functionalities of those equipment. The apps from this group are particularly suited for LS_1, LS_2 and LS_3.
2. *Acoustic signal generation*: these apps allow using the mobile devices for generating sound signals. They behave as frequency sound generators, therefore users can tune properly the generated signal by adjusting its waveform, volume, modulation, frequency. Teachers and students are suggested to use these apps during all the described LSs.
3. *Device sensor analysis*: these apps are not specifically related to the proposed LDE, since they allow examining the entire set of built-in sensors available in a mobile device. These apps, usually known as "*sensor boxes*", present users with a dashboard enlisting all the active sensors in their device. By selecting a given sensor, an instantaneous reading is provided, as well as a concise explanation of both the referred physical quantity and the corresponding unit of measurement. These apps are useful for introducing students to consider their own smartphone also capable of "sensing the environment", so that teachers are suggested to use the apps in the first part of the LDE.

It is important to point out that the apps are most of all suitable for a combined usage: indeed, they can be exploited during the same experiment. Let us consider an experiment belonging to the LS dedicated to the analysis of sound propagation. Students can be divided into two groups: the components of the first group use the sound generating mobile apps for creating several waveforms, whilst the students from the second group use the sound monitoring apps for observing those signals according to different perspectives (e.g., in time, in frequency, in spectrograms).

Validation Methodology and Discussion on LDE Outcomes

The LDE has involved students and teachers from 20 classes belonging to 7 different schools located in Brindisi, a city with nearly 90k inhabitants in Southern Italy. The experimentation started at the same time in all the Classes have been involved pairwise. For each couple of classes, students from the first class use the proposed platform during the LDE, while students from the second class follow a traditional teaching approach, based upon frontal lessons and without any experiential activity.

During the LDE, the following aspects have been evaluated:

1. Progressive acquisition of scientific topics on acoustic and sound,
2. Progressive acquisition of a sectorial language,
3. Progressive acquisition of usage experience for the provided app,
4. Level of motivation and personal engagement in educational activities.

Students have been surveyed and evaluated with two questionnaire types: the first one (i.e., input questionnaire) has been proposed to them before starting the LDE, in order to assess their initial background on general scientific topics and on specific topics in acoustics. The second one (i.e., output questionnaire) has been proposed after the LDE, in order to ascertain the acquired knowledge.

Therefore, at the end of the experimentation it has been possible to compare the learning outcomes from the two different approaches, since both students from the experimental and students from the traditional approach have been addressed with the same conclusive questionnaire. A specific assessment grid has been defined, based on a set of evaluation criteria assessing the following student's capabilities:

1. Observation of physical phenomena,
2. Formulation of explanatory hypotheses about the observed physical phenomena,
3. Problem formalization,
4. Application of mathematical knowledge on problem formalization,
5. Interpretation of the available datasets,
6. Explanation of the attended experiments,
7. Explanation of the adopted solving methodology.

Four overall evaluation levels (from *L1* to *L4*) have been defined, depending on whether the students show respectively *not sufficient*, *partial*, *good* or *optimal* results w.r.t. the evaluation criteria mentioned so far.

Figure 21.2 presents a chart summarizing the comparison results. The charts describe the distribution of the evaluation levels across the four examined categories of questionnaires:

1. *QIN_t*: it represents the input questionnaire performed in classes that followed the traditional didactic approach;

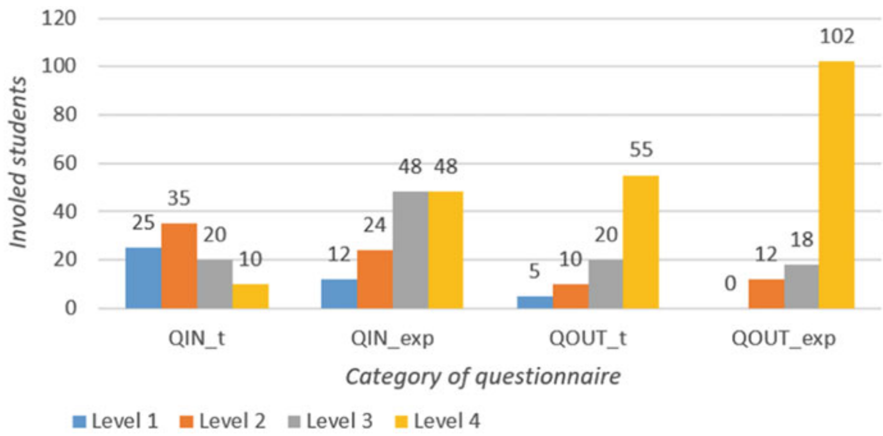

Fig. 21.2 Comparison of students' evaluation levels by questionnaire type

2. *QIN_exp*: it is the input questionnaire for classes following the experimental approach;
3. *QOUT_t*: it is the output questionnaire for the same classes from group 1;
4. *QOUT_exp*: it is the output questionnaire for the same classes belonging to group 2.

The chart reports the number of involved students in each questionnaire type. It is worth to point out that even if the validation has followed a pairwise approach, due to the inhomogeneous distribution of students across the involved classes, the participants to the LDE with the traditional didactic approach were fewer than their counterparts in the experimental approach.

As it can be easily seen, Fig. 21.2 reports a significant increase in the quality of evaluations for students, involved in experimental activities. More specifically, let us consider the proportion between negative (i.e., L1 and L2) and positive evaluations (i.e, L3 and L4) between *QIN* and *QOUT*. In the traditional approach, there are 67% of negative evaluations and 33% of positive evaluations in the *QIN* questionnaires. These percentages become 16% and 84% respectively in *QOUT*. Similarly, in the experimental approach, there are 27% of negative evaluations and 78% of positive evaluations in *QIN*. These percentages become 9% and 91% respectively in *QOUT*.

Moreover, it can be noticed that even the input questionnaire has produced better results in the classes selected for the experimentation. More specifically, the proportion between L1 and L4 in *QIN_t* is 27–11%, while the same proportion in *QIN_exp* is 9% to 36%. This is mainly determined by a better initial motivation in students from the experimental approach, who have exhibited higher interest rates from the beginning of their experience thanks to the expectation of using of mobile devices during their coursework activities.

More generally, we have detected an increased level of participation from both teachers and students in the experimental approach. Similarly, students and teachers involved in the traditional approach, as well as those who have not participated in the LDE from the remaining classes of the involved schools, have expressed the determination to participate in a similar experimentation in the forthcoming school year.

Conclusions

The recent advances in digital technologies and devices are becoming more and more suitable to be integrated into educational activities. Several methodologies and paradigms have been proposed so far in the scientific literature in order to improve both teaching effectiveness and learning outcomes in all school levels. In this paper, we refer to the Bring Your Own Device (BYOD) and the Mobile Crowd Sensing (MCS) paradigms that respectively allow students to use their own portable electronic devices during didactic activities and to use mobiles as environmental sensing stations. These two paradigms have been considered in conjunction with the Inquiry-Based Learning methodology for designing a Learning Didactic Experience (LDE) on acoustics and sound monitoring that has involved 20 classes from 7 middle and high schools in a city in Southern Italy. The LDE has been carefully planned and implemented by complying with the Prevision-Experiment-Comparison (PEC) cycle. The paper has also addressed all the relevant aspects of the LDE, in terms of learning objectives and contents, didactic strategy and validation methodology. The promising results of the validation phase has been also discussed.

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Chapter 22

Quantitative Measurements of RGB and CMYK Colours with a Homemade Spectrophotometer

Tommaso Rosi, Massimiliano Malgieri, Stefano Oss, and Pasquale Onorato

Introduction

What is a red object? Or a black, white, pink or purple one? What is the relation between an object's colour and monochromatic light? Why are there both additive and subtractive colour models and how are they related to the colours we see in everyday life?

Spectral composition of light, its transmission, absorption and diffusion are all essential concepts to grasp for a good understanding of those topics. Thus, understanding the physics underlying these topics is crucial for providing answers to the question "*What is a colour?*".

The foundations of the theory of colours have been treated in great detail in monographs (Hunt 2005) whose basic ideas are summarized in several articles (Meyn 2008; Thoms et al. 2013). Colour reproduction and subtractive mixing of artists' pigments are popular and appealing topics in physics education (Gilbert and Haeberli 2007; Meyn 2008; Rossing and Chiaverina 2000). However, it's known that these topics are very puzzling for students and a good understanding requires many different physics concepts. In fact, some conceptual steps, based on the spectral composition of light, its intensity, the partial transmission/absorption/diffusion of light by a pigment, are essential to reconcile classical school knowledge about colours (additive/subtractive mixing mechanism) and observation of daily life phenomena. Thus, recent researches in physics education have inferred that

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spectroscopy can be an essential tool for a conceptual understanding of colours (Viennot and de Hosson 2015).

In this work we present a sequence of experimental activities, based on the use of low cost spectrophotometers, aimed at making sense out of phenomena that may be observed in daily life. Students apply the spectroscopic techniques introduced in previous works (Onorato et al. 2015, 2016) to the outputs of digital devices, approaching the problem in a quantitative manner by analysing the spectrum of different colours produced by a monitor or diffused by the pigments printed by a laser printer. The sequence of activities is designed both for high school and undergraduate courses and has been proposed for preliminary testing to twenty undergraduate students.

The Experimental Setup: The Homemade Spectrophotometer

In recent times several low-cost educational setups, based on the use of consumer digital cameras (compact cameras or even smartphone cameras), were proposed for spectral measurements (Kiisk 2014; Lorenz 2014; Onorato et al. 2015; Rodrigues et al. 2016a, b; Rossing and Chiaverina 2000). In this work we use the spectroscopic techniques introduced in (Onorato et al. 2015, 2016) with few adjustments and also quite similar apparatuses. The measurements, as discussed in (Onorato et al. 2015, 2016; Rosi et al. 2016), were performed with the aid of Tracker, a free and open source video analysis software.

The apparatus iP_{1000}, used for the results reported in the following, is represented in Fig. 22.1. It is based on a 1000 lines mm^{-1} transmission grating and a smartphone (iPhone 4s) camera.

Since the 1000 lines grating requires that the incoming light from the source is not perpendicular to the grating, it can be sometimes difficult to use this kind of spectrometer for inexperienced students. Therefore students, during the activities, assembled their own spectrometer, $SP_{500,}$ by employing a 500 lines mm^{-1} transmission grating and using their smartphone to acquire the images. The main differences between the two geometries are summarized in (Onorato et al. 2016), and a scheme of both is given in Fig. 22.1.

In order to get the best results, and particularly to be able to correctly compare several images, the use of any (free) app that allows to manually control the camera's focus, ISO and exposition time is suggested and shown in Fig. 22.1.

Once the images of the spectrums were acquired students analysed the pictures with the Tracker video analysis software which provides direct measurements of RGB channels and of the brightness pixel by pixel along a line profile. To use the assembled devices as spectrophotometers a calibration procedure is needed. The procedure requires two steps: the wavelength calibration (λ-calibration) and the intensity calibration (I-calibration).

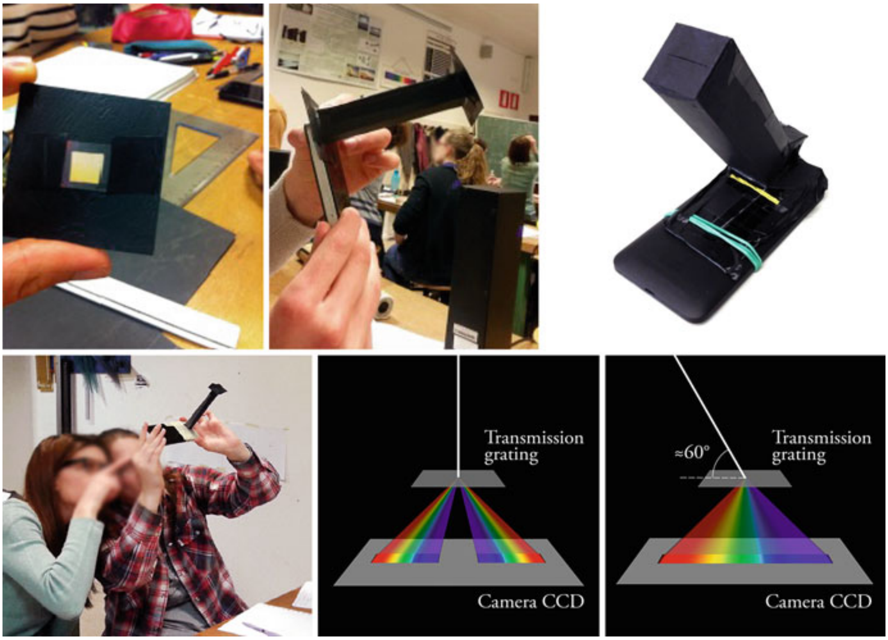

Fig. 22.1 Students assembly their own spectroscope using a black cardboard frame A narrow window is opened at the distal end of a collimating tube. The experiment's scheme: the light entering the slit is transmitted with an angle strongly dependent on the wavelength. The two different versions of the apparatus, the first one, SP_{500}, on the left, employs a 500 l/mm transmission grating; the second one, SP_{1000} on the right, a 1000 l/mm transmission grating

λ-calibration

As discussed in (Onorato et al. 2015) we use the light provided by a commercial fluorescent lamp whose spectrum has many peaks distributed over the range of wavelengths of visible light. Once acquired the pictures of the spectral lines students accurately measured the positions of their peaks by using the free video analysis software Tracker.

The uncertainty in the wavelength measurement inferred using iP_{1000} is below 2 nm while it is usually ~3–4 nm for the SP_{500}.

I-Calibration

I-Calibration is required to measure the light intensity which is calculated starting from the RGB value in colour. To obtain the measure of light intensity from RGB values for a typical gamma-corrected image generated by a photo camera, we use the formula:

$$Y_{\text{measured}} = 0.2126\ R^{\gamma} + 0.7152\ G^{\gamma} + 0\ .0722\ B^{\gamma}$$

Where Y is a measure of luminance, which is proportional to emitted light intensity per unit area, multiplied by the standard luminosity function (i.e. the CIE Photopic Luminous Efficiency Curve) (Hunt 2005), and $\gamma = 2.2$ is the factor expressing how the luminance on the screen in a JPEG image depends on the 8-bits RGB colour values (Onorato et al. 2015). The measured spectra also depend on the overall response of the apparatus (CCD camera, lenses and so on). Therefore, we prefer to experimentally evaluate the relative sensitivity (spectral response) of the apparatus by measuring the light spectrum from a known source, as described in (Onorato et al. 2015, 2016; Rosi et al. 2016).

The Experimental Activities

Students, after the construction of their own spectrophotometers, performed direct spectral measurements of colours produced by a laptop's monitor and a common printer. These two devices were chosen to be able to discuss both the RGB (Red, Green and Blue) additive colour model and the CMYK (Cyan, Magenta, Yellow and blacK) subtractive colour model. Spectroscopic results have to be understood starting from a microscopic analysis of the samples producing the colours. Thus inspecting the perceived colours coming from a monitor or printed on paper on a microscopic scale is necessary. In fact, it is on this scale that one is able to actually see the real additive and subtractive mixing of the primary colours.

A Water Droplet as a Macro Lens

With the aim of examining colours on a microscopic scale, students could use both low-cost macro lenses or microscopes. In our case we show students how it is also possible to magnify the RGB pixels of a LCD monitor or the printed colours of a laser printer by using a small drop of water (see Fig. 22.2). In fact, putting a drop of water on the lens of a digital camera effectively turns it into a macro lens. The effectiveness of this device is shown in Figs. 22.2 and 22.4 where the LED screen and the printed paper seen by the droplet are shown.

Computer Monitors and Additive Mixing of Colours

Students observed how colours of images are reproduced by modern LCD devices. In fact, displays of modern devices use the RGB additive colour mixing to create images. Each pixel is characterized by a triad of physically separated elements as shown in Fig. 22.2. A typical 8-bit monitor features $2^8 = 256$ different intensity levels for each RGB triad element, resulting in about 16.7 million different colours.

Students used the spectrophotometer to analyse the spectra of different colours displayed on a MacBook Pro (retina display, 15-in., mid 2015). In Fig. 22.3 a collage

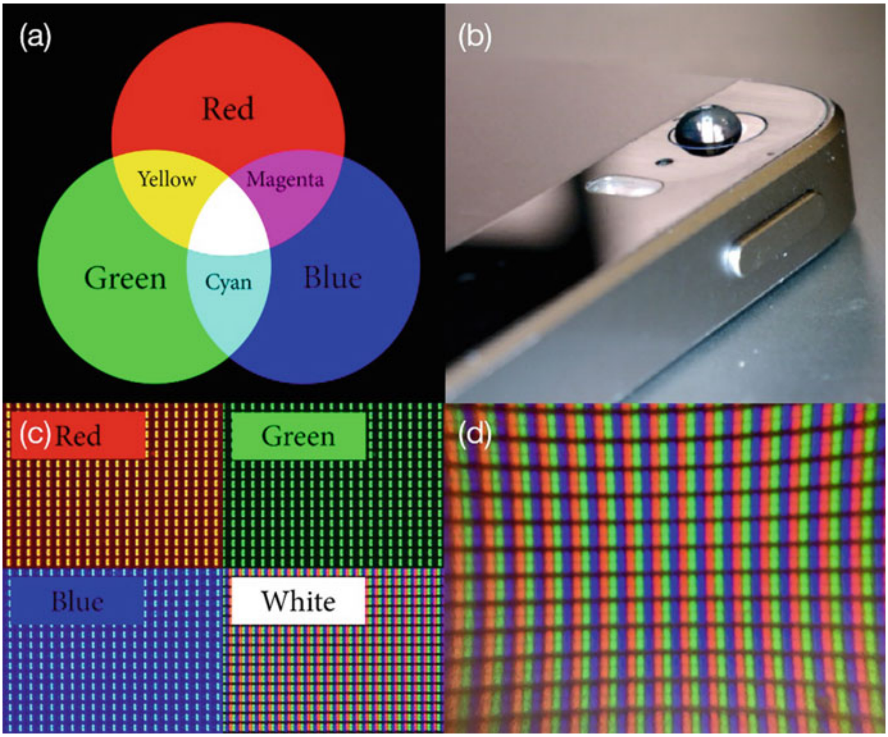

Fig. 22.2 (**a**) The RGB additive colour model. (**b**) Cheap macro lenses can be used to take photos of the monitor's pixels. (**c**, **d**) Photos of the monitor's colours: the RGB triads are well visible. Photos were taken with a macro lens (**c**) and a water droplet (**d**). The monitor used is of a MacBook Pro (Retina, 15-in., Mid 2015)

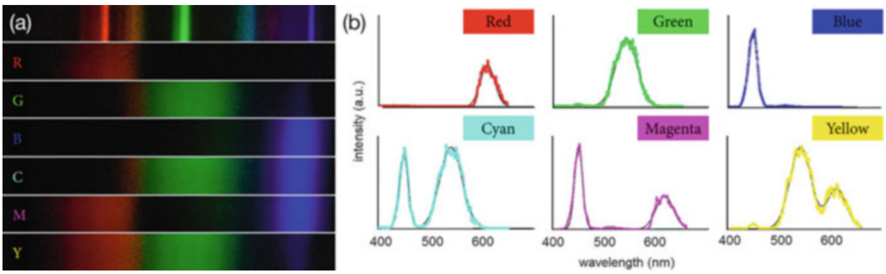

Fig. 22.3 The intensity of photoemission measured with the spectrometer for the different colours on the monitor. (**a**) Collage of the acquired photos used for the measurements. On the top, the spectrum of the fluorescent lamp used for the wavelength calibration (λ-calibration) is shown. Strips *R, G, B, C, M, Y* come from photos of the spectra when the screen produces definite colour. (**b**) Intensity in function of wavelength is reported in arbitrary units with the same scale for all the panels

of the obtained spectra and the corresponding graphs where the intensity of photoemission, $I_P(\lambda)$ for the different colours produced by the monitor are shown.

The spectrum of any colour displayed on a monitor results from a linear combination of the three RGB peaks. For example, the white spectrum is the sum of all the three peaks, as wells as the cyan, magenta and yellow spectra result from the sum of two of the three peaks.

A quantitative comparison between this kind of measurements and theoretically expected values in terms of the CIE xyz colour space may be done as described in (Rosi et al. 2016).

Printers and Subtractive Mixing of Colours

Printers work by mixing cyan, magenta and yellow pigments on paper in order to obtain darker colours: this is the basics of CMY subtractive colour mixing. Since pure black cannot be obtained using non-ideal pigments, a black pigment is also used.

Laser printers leave coloured dots of different sizes accordingly to the desired intensity of the CMY pigments. As a result, some areas will be covered with pure CMY pigments, some with a mixing of pigments, and others will be left without any (see Fig. 22.4). However, as in the previous case of displays' pixels, a uniform colour is perceived by the human eye by additive colour synthesis of these different areas.

Students analysed the transmission spectra of different printed colours by putting printed coloured strips on top of the spectrometer and using sunlight as a (white) light source. A collage of the collected spectra is shown in Fig. 22.5.

In order to measure transmittance, students needed to compare the spectra of the original and of the transmitted light recorded under identical conditions, thus they used a single photo where both the transmitted and the original spectra (after passing through white paper) are acquired.

By comparing the intensity measured when sunlight traverses the white sheet only, and the one measured when it passes through the coloured lines, students measured the transmittance at different λ values. Transmittance, $T(\lambda)$ of a sample of a material is defined as its effectiveness in transmitting radiant energy. It is the fraction,

$$T(\lambda) = \frac{I_T(\lambda)}{I_0(\lambda)},$$

of incident electromagnetic power, $I_0(\lambda)$, that is transmitted through the sample. Students identified $I_0(\lambda)$ with the measured intensity through white paper, $I_T(\lambda)$ with the measured intensity.

As it can be seen in Fig. 22.6, where the measured transmittances as a function of the wavelength are shown: cyan acts as a low-pass filter (referring to wavelengths), magenta as a band-stop filter, and yellow as a high-pass filter.

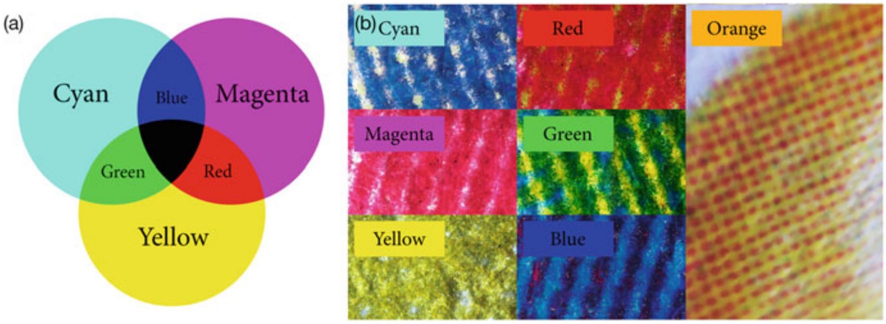

Fig. 22.4 (**a**) The CMY subtractive colour model. (**b**) Macro photos of printed colours (on the left, the pure, fully saturated CMY pigments; on the centre, the RGB colours obtained as the 'addition-subtraction' of two CMY pigments; on the right, an example of the different mixing of CMY pigments to obtain a custom colour). Typical widths of the strips are about 0.15 mm. The used laser printer is a Samsung CLX-3305FN

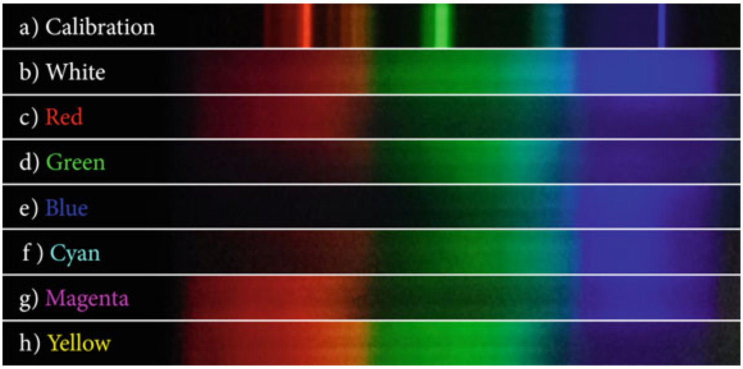

Fig. 22.5 Strip (a) shows the spectrum of the fluorescent lamp used for the wavelength calibration (λ-calibration). Strips (b), (c), (d), (e), (f), (g), (h) come from a single photo of the spectra of sunlight passing through the coloured ink lines (c)–(h) and white paper (b). Strip (b) is also used for the Intensity calibration (I-calibration) (Rosi et al. 2016)

Comparing these results to the ones corresponding to printed red, green and blue colours (Fig. 22.7) it can be intuitively seen that the subtractive colour mixing can more accurately be referred to as a multiplicative one. In fact, the red spectrum may be approximated as the product of magenta and yellow spectra, green as the product of cyan and yellow, and blue as the product of cyan and magenta. It can be highlighted how green acts as a pass-band filter, resulting from the action of both a low-pass (cyan) and a high-pass (yellow) filter.

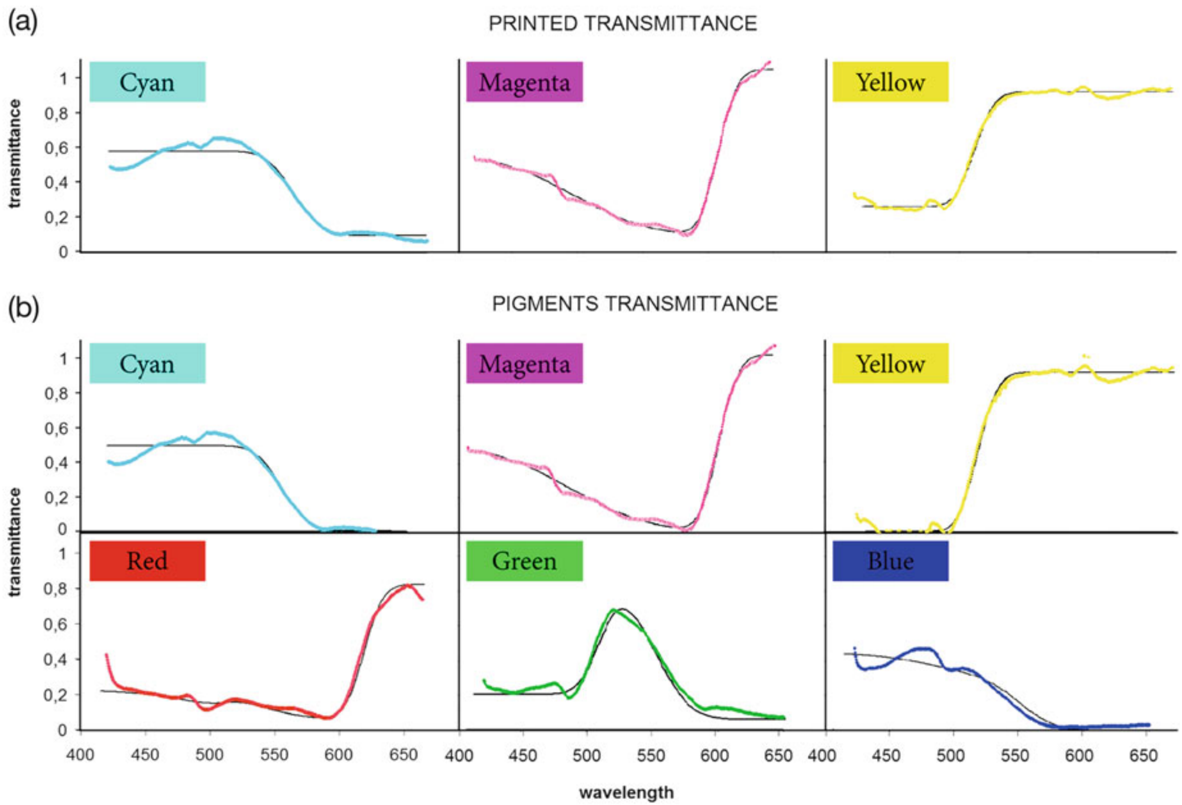

Fig. 22.6 (**a**) Transmittance T(λ) as measured with the spectrometer for the different primary CMY colour printed lines. (**b**) Extrapolated transmittance of the corresponding pigments obtained by subtracting the contribution of white unprinted regions

Testing with Students

The sequence was tested with a group of 20 undergraduate students who performed the experimental activities in groups of three and completed the sequence in one session of 3 h. Assistants worked as facilitators, giving support where necessary.

Students were attending an experimental course for future high-school teachers. Some students wrote a final report on the topic in which they also discussed which of the proposed experiments they considered essential to be taught in high school.

In their final comments, highlight the formative role played by these activities and their usefulness in teaching physics, also in the perspective of performing them with high school students. We quote some phrases which highlight how students perceived the experiments from a pedagogical point of view.

> These activities are not aimed to clarify doubts derived from the theory, but rather to invite students to reflect on the dual nature of light and colour and to question what they thought they knew. For example, often when we see two light bulbs, these seem the same, but deepening the study with the use of spectroscopes we notice differences that the naked eye does not notice.... we are surrounded by colours but we do not ask what they really are and how they are formed.

Other comments concern in general the smartphone-based spectroscopy, the image analysis and the used tools:

> The use of image analysis can be a useful tool to introduce students to physics and to get them closer to it... thanks to this experimental approach, while not knowing all the theory that explains these phenomena, students are able to see and understand, from a more quantitative point of view, both wave phenomena of light and colours, since they can measure the spectrum of a light source.

Conclusions

In this paper we investigated some aspects of colour theory, which are often overlooked in education. Students performed measurements of colours produced by a laptop's monitor and a common printer, as exempla of additive colour model and subtractive colour model respectively. A droplet of water put on a smartphone camera allowed students to inspect the apparent colours coming from a monitor or printed on paper on a microscopic scale and understand them anew. Then a homemade low-cost spectrometer let students do direct spectral measurements. By analysing the printed colours' spectrum, it becomes clear that the so called "subtractive" colour model is actually a "multiplicative" one.

This experimental approach to colours was designed for undergraduate courses or interdisciplinary courses/workshops on science and art. The activity, tested with a group of undergraduates, can lead students to discover the functioning principles of digital devices, but also to understand the physics of colours. A positive influence of the activity, both in the process of appropriation of experimental methods and in a deeper understanding of some aspects of colour theory, emerges clearly from the results of our preliminary test.

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