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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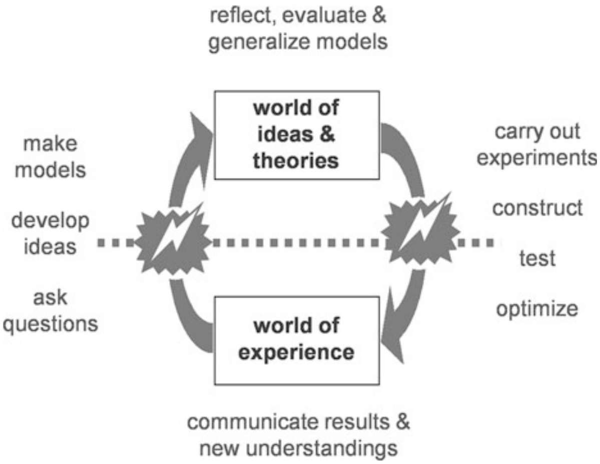
Fig. 1.1 Cyclic model of inquiry and design



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

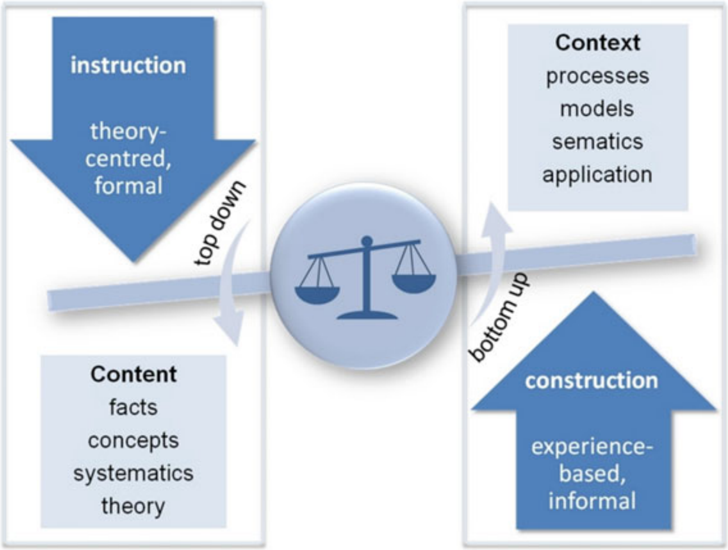


Fig. 1.2 Balance between instruction and construction in teaching

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

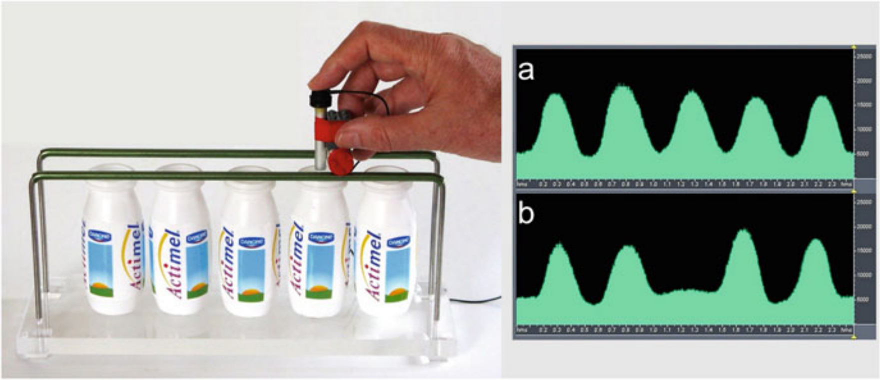


Fig. 1.3 One-dimensional acoustic scanning of resonating yogurt bottles

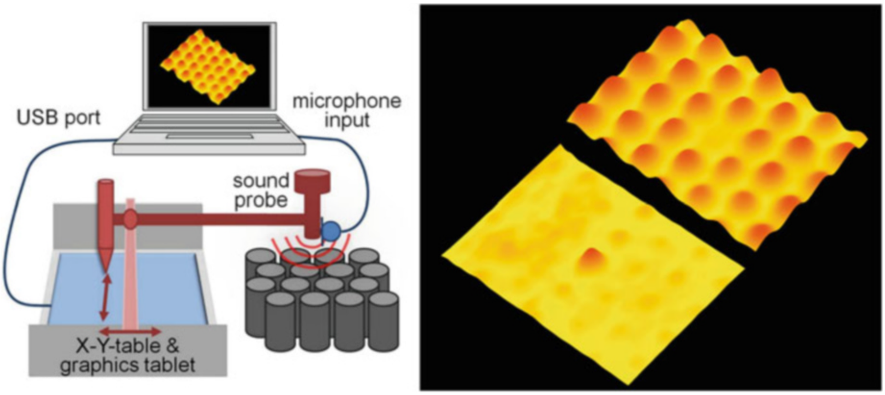


Fig. 1.4 Principle of the acoustic imaging setup and scans of the bottle array with different frequencies. An impurity atom is simulated by changing the resonance frequency of one bottle

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 ≈ 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

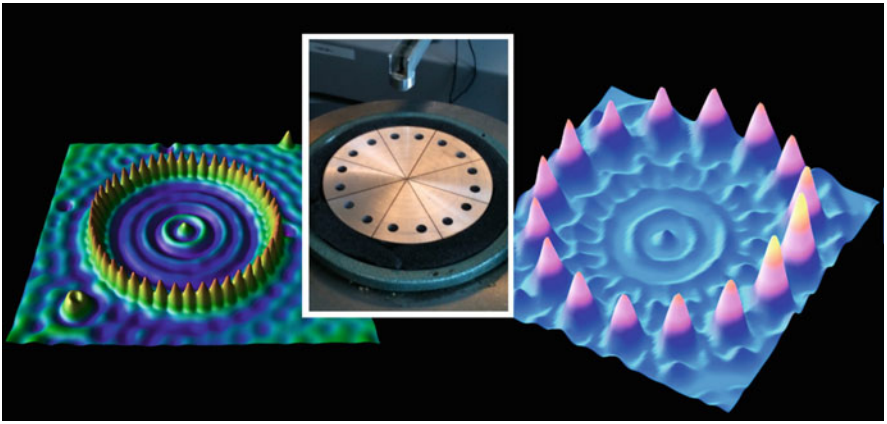


Fig. 1.5 An icon of nanoscience in classical reconstruction; the quantum corral (left) and its acoustic model (right). The middle image shows the acoustic setup with the ultrasound source above the perforated plate. The microphone is located in the center of the circular disk below

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

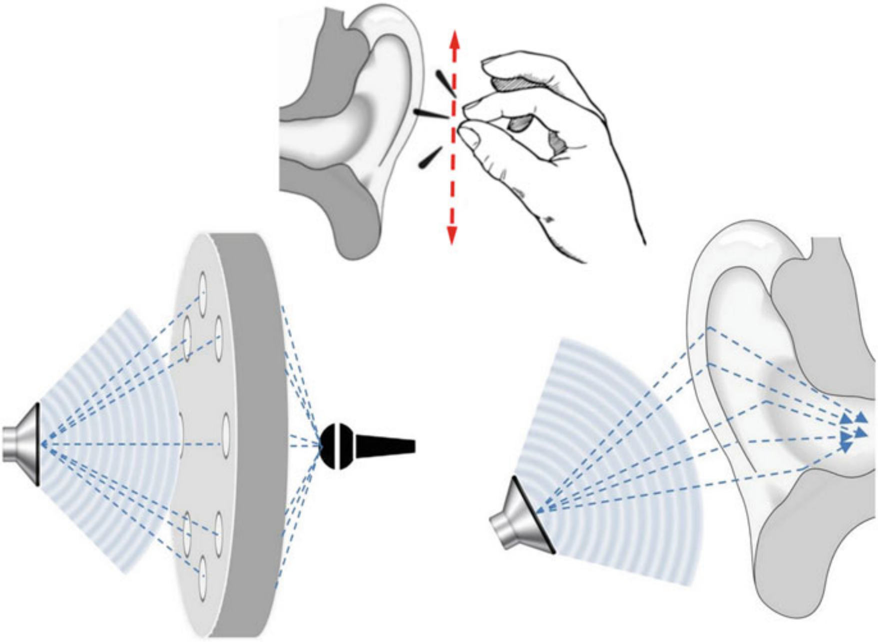


Fig. 1.6 Experiments in near field imaging. The monaural localization of sound sources uses multiple scattering of sound at the outer ear. The principle is similar to imaging the corral structure

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.

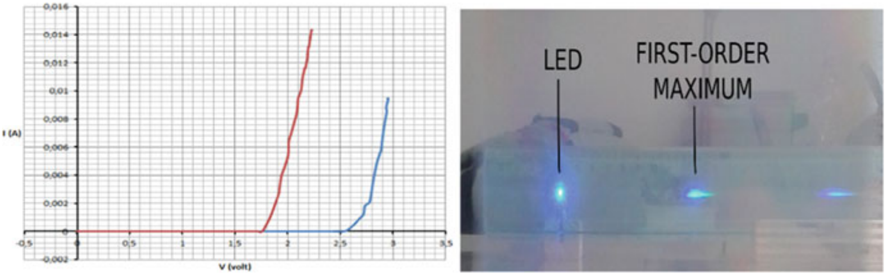

Fig. 2.1 Current-tension (I-V) characteristics curves for a red and a blue LED (left) and spectrum of a blue LED visible along a ruler (right)

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).