Maurício Pietrocola *Editor*

Upgrading Physics Education to Meet the Needs of Society

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Foreword

This book is an initiative, recently promoted by GIREP by means of an agreement with Springer to contribute in physics education research and praxis with a series of publications. It contains selected contributions on the topic “Contemporary Science Education and Challenges in the Present Society: Perspectives in Physics Teaching and Learning.” By a peer review process involving 854 reviews carried out by 149 referees, we selected the papers published in this volume among 307 contributions we had already selected for the presentations in the Second World Conference on Physics Education (2nd WCPE). We have to thank Maurício Pietrocola for editing the book and leading the peer review process after the organization of the 2nd WCPE and Claudia Haagen Schuetzenhoefer for managing the editorial process for GIREP.

GIREP is an international membership organization founded in 1966, open to academics, teachers, curriculum developers, and all other stakeholders with the concern to improve physics teaching and learning by means of physics education research (PER), innovative experimentation in physics teaching/learning, innovative materials and methods, suggestions for stakeholders, international cooperation in conferences, seminars, and selected paper books. In the past 50 years, 1400 physics education researchers, teachers, and other specialists of 72 countries shared their common problems, studies, results, and experience in GIREP. Out of researchers and teachers scattered in faraway schools and colleges and universities, GIREP created a community. From 1967 to 2016, GIREP organized 32 international conferences in cooperation with EPS, ICPE, MPTL, and UNESCO.

GIREP’s main focus is to connect research and teaching from primary to university level. This is motivated by the following reflections. The quality of teaching is determined by cross-fertilization of research and praxis. Teacher education and teacher professional development need a connection with physics education research, and we experiment that this is not extensively done in the different countries. Continuity in vertical and in transversal perspective is very important. A large society engagement is needed to promote scientific learning, policies for teacher education, and quality in teaching and learning. We mainly focus on content research, because learning is content specific; subject matter and pedagogy are not enough for teacher professional development: there is a wide need on didactics on subject matter. Our goals are to improve practice by means of research (PER), to promote content structure research, and to explore teaching/learning processes for new topics conceptual learning and lab work, methods, strategies, and tools' role in learning. Active research lines in GIREP represented in this volume are different: content-oriented theory, students' conceptions/reasoning, students' learning pathway and processes, developing content-specific tests, role of approaches, concepts, contexts, motivation for learning on specific topics, individuate conceptual profiles and parallel conceptions, variation theory, design-based research, curricular research, conceptual profile, learning progression, and teacher education.

In the last 5 years, GIREP formalized the cooperation with the following international bodies, signing agreements: American Association for Physics Teaching (AAPT), American Physical Society (APS), Education Division of European Physical Society (EPS-ED), European Science Education Research Association (ESERA), Inter-American Conference on Physics Education (IACPE), International Commission on Physics Education (ICPE), interAsian Scientific Education Research (iSER), Latin American Physics Education Network (LAPEN), Multimedia Physics Teaching Learning (MPTL), International Association of Physics Students (IAPS), and Japanese Physics Education Society (PESJ). In this framework, the exchange of research results and experience gain an open high scientific value for each GIREP conference and find a common working area initiative in the WCPE 4-year conferences.

The world of physics education research does not have a wide range of journals in which to publish and compare the results of their work. Making available in a book the best research contributions in physics education and significant teaching interventions presented at the 4-year World Conference on Physics Education, it seemed to us the best way to serve the research community and the stakeholder in the field of physics education. We hope this contribution will be useful to this community and to teachers in general. Comments and suggestions will always be welcome in order to better realize the mentioned GIREP objectives.

GIREP Committee, Physics and Math
Section of DCFA University of Udine
Udine, Italy

Marisa Michelini

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Part IV Diversity and Difference in Teaching Physics

Chapter 1
How Should We Teach Physics Today?

Maurício Pietrocola

Abstract This question is being asked by physicists around the world in the face of the global societal changes that have taken place over the last 50 years. Those same five decades have seen the publication of the original version of the current best-selling book in the world for teaching physics at the university level, as well as many updated editions. First released in 1960, Halliday and Resnick's *Physics for Students of Science and Engineering*—now in its 10th edition and known as *Fundamentals of Physics*—has shaped the teaching of basic physics at the university level and strongly influenced physics in secondary education. The authors' initial intentions clearly involved creating a community of science and engineering researchers capable of developing and incorporating basic and technological knowledge for the benefit of postwar industrial society.

This question is being asked by physicists around the world in the face of the global societal changes that have taken place over the last 50 years. Those same five decades have seen the publication of the original version of the current best-selling book in the world for teaching physics at the university level, as well as many updated editions. First released in 1960, Halliday and Resnick's *Physics for Students of Science and Engineering*—now in its 10th edition and known as *Fundamentals of Physics*—has shaped the teaching of basic physics at the university level and strongly influenced physics in secondary education. The authors' initial intentions clearly involved creating a community of science and engineering researchers capable of developing and incorporating basic and technological knowledge for the benefit of postwar industrial society.

Although the Halliday and Resnick collection continues to be the main reference for physics teachers around the world today, the early twenty-first century is very different from the late 1950s. Today's society presents individuals with difficult dilemmas. As science and technology progress, we find ourselves on the frontiers of knowledge and capabilities so complex and extraordinary that absolutely no one is

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able to fully understand their contours. At the same time, this unprecedented context generates a diversity of possible futures about which we need to be informed in order to develop opinions and make crucial decisions.

In general, two fundamental transformations are affecting the lives of people today. Both are connected with the growing influence of science and technology, though not completely determined thereby: the end of nature and the end of tradition.

The world of nature that humankind has learned to deal with and to know since the very beginning of our existence no longer exists. Over the past 75 years, humanity began to be less concerned with what nature could do to us and to worry more about what we had done to nature. The awareness that the environment in which we live had begun to degrade is something that dates back at least to the 1980s. It has become increasingly clear that human settlements are not surrounded by nature; on the contrary, nature has been surrounded by humanity. This has occurred to such an extent that our wild resources—nature preserves, forests, wetlands, rivers, springs, oceans, and so on—have become objects of action for groups defending nature. This transition is fundamental to our entry into what Beck (1988) defined as a risk society. We are now a post-nature society, reflecting and experiencing how science and technology have transformed nature into techno-nature.

In this modified society, the earlier societal mode of danger-security pair, in which tradition took center stage, has been replaced by risk-confidence. This new status may seem to imply a zone of semantic overlap between danger and risk, but these notions belong to very different worldviews. The idea of risk is connected with aspirations toward control and in particular with the idea of controlling the future—a relatively recent concern in human history which probably stems from the end of the Modern Age. Social risk emerges as a factor in societies when they start to worry about the future and to seek to guarantee its success and safety. European explorers in the fifteenth century, who sought to minimize risk on overseas trips by means of techniques and knowledge, were some of the first to implement this style of risk management. From this novel perspective, risk entails both negative and positive connotations. On the one hand, it is associated with the idea of avoiding an unwanted result. But its positive side resides in the ability to take initiative in the face of a problematic future. Thus, risk-confidence societies must develop their citizens' abilities vis-à-vis managing risk.

And what are the risks today? Paradoxically, the current need for the continual production of knowledge and technology brings risks of various kinds: environmental degradation, increasing poverty, widening inequalities, exclusion of minorities, etc.

It is important to highlight certain important developments in the science-society context as constitutively related to these risks:

- Over the last two centuries, science and technology developed in such a way that science became the cornerstone of the Western tradition.

- Scientific knowledge was once seen by most (and is still seen by some) as capable of overcoming previous traditions but has become a given, an authority certain, and secure in its own right.
- Because as science and technology became more complex, they became more and more distant from people's lives; people began to respect them as a means of generating security.
- In the absence of access to learning and information that would allow them to form their own opinions—and to calculate and manage their own risks—laypeople sought the opinions of the experts (scientists and engineers).
- We thus now need ways to inculcate a much more dialogic and engaged relationship with science and technology in students—and in citizens in general.

Within this context of questioning which types of scientific knowledge should be taught, the contents that emerge as key are those aimed at analyzing the role and importance of such knowledge to the basic formation of a social conscience in the individual. The field of physics—influencing as it does students' perceptions of the natural world—has much to offer in this process

The report to the European Commission of the expert group on science education (2015) affirms:

> We need science to inform policy, objectively. We need science to inform citizens and politicians in a trustworthy and accessible way. We need to make decisions together—rather than from polarised positions—and to take responsibility for those decisions, based on sound scientific evidence. (p. 5)

These kinds of needs cannot be met if we think of how physics has been taught and learned. In this sense:

> Science education research, innovation and practices must become more responsive to the needs and ambitions of society and reflect its values. (p. 6)

For this we must turn to three basic questions: Why do we teach? What do we teach? How do we teach?

The present book is part of the movement to respond to these questions from the physics teaching research point of view.

The chapters of part 1 of the work take the influence of science and technology in the means of teaching physics. Computers, technology for teaching, and contemporary content worked in school are the focus of the chapters.

Ian Lawrence states that computers can be usefully thought of as representation tools. Many demonstrated difficulties in learning physics depend on re-representing the world to yourself: imagining it as other than it appears and then reasoning with that new representation, to develop new expectations about the lived-in world. To keep physics live in classrooms during this process requires the most responsive and adaptable tool we can lay our hands on, to encourage teachers to do physics with children. Rather careful thinking about matching the desirable affordances and resistances present in the practices enabled by any tool to the existing physics curriculum suggests casting the net more widely than numerical integration of differential equations. This paper draws on a number of years of working with computational modelling tools with teachers and with pupils (8–18), as well as significant work in constructing teaching sequences and supporting representations in the Supporting Physics Teaching initiative and Advancing Physics (both supported by the Institute of Physics). The foci are on exploiting flexible diagrammatic representations without being able to draw and on evolving responsive representations to support developing ideas during teaching sequences while seeking also to exploit the new enthusiasm for coding in a culturally valuable way and on keeping the implementation straightforward enough that teachers might be persuaded to use it.

Tom Ellermeijer e Trinh-Ba Tran willing to answer the questions “How to make physics education more challenging, relevant, and attractive for our high school students? How to stimulate the development of creative thinking, problem-solving, and other higher cognitive skills?” In many countries governments like to stimulate science and technology in schools but in this direction, STEM (or STEAM), IBSE, and MINT (Germany) are the more recent alphabet soup acronyms. Can technology applied in physics education bring us closer to the desired goals? Clearly it has been demonstrated that technology can help make physics education more relevant, more linked to real life, and more authentic and can increase the opportunities for own investigations by the students. So it really has an added value and not just provides another way of teaching the same. This is known for decades but still applied at a relatively small scale. They will present several examples of the use of measurements with sensors, video measurements, and modelling demonstrating these benefits.

Marcia Begalli and Uta Bilow present issues from activities where research institutes and universities around the world invite students and their teachers for a daylong program to experience life at the forefront of basic research. These International Masterclasses (www.physicsmasterclasses.org) give students the opportunity to be particle physicists for a day by analyzing real data from CERN’s Large Hadron Collider (LHC). The project attracts each year more than 13,000 high school students from 46 countries. In the International Masterclasses, high school students work with real data collected by the experiments at the LHC. The program bridges the gap between science education at school and modern scientific research. Participants can explore the fundamental forces and building blocks of nature and are informed about the new age of exciting discoveries in particle physics, e.g., the *Discovery of the Higgs Boson*. Moreover, they can actively take part in cutting-edge research and improve their understanding in science and the scientific research process. The program offers authentic experience and adds valuable experiences to physics education at school, thus stimulating the students’ interest in science.

In part 2, the privileged topics are evaluations about established methods of teaching physics, which are the peer instruction method and the simple experiments.

Hideo Nitta develops a few mathematical models of learning that were developed previously. Then he presents his mathematical model that describes dynamics of the response of students in peer instruction (PI). In this model, for evaluating the effectiveness of each question for PI, the “peer instruction efficiency (PIE)” is introduced in analogy with the Hake gain. It is shown that, in the simplest approximation, PIE becomes proportional to the relative number of students answering correctly before discussion. The mathematical model is applied to introductory physics courses at a university and physics classes at a high school. It is found that overall practical data of PIE moderately agrees with theory. Application of PIE to data analysis is also discussed.

Leos Dvorak develops considerations about simple experiments, being cheap, requiring just a short time, and often providing interesting results; simple experiments have been used in physics classes for a long time. However, how is it nowadays? Can they compete with what ICT, modern technologies, and ubiquitous sophisticated gadgets provide for us and our students in more and more attractive forms and formerly unimaginable range and quality? Are not simple experiments with a few straws, skewers, and threads obsolete and even ridiculous in the age of the Internet offering tons of applets, virtual labs, and latest achievements of physics at multimillion-dollar international facilities with one click? The purpose of the talk is to show that simple experiments "are not dead" and can be much more that qualitative toy experiments and their potential are greater than just to generate "small wow" reaction in students. Of course, this statement is something most physics teachers and educators would probably agree with; we like such experiments and the fact that they are useful belongs to internal beliefs of most of us. However, it should not be just a blind belief. Therefore, the aim of the lecture will be to support this claim by concrete examples (some of them hopefully at least partially new for the audience). So, we will try to "add ammunition" to our conviction that simple experiments can really have their firm place and good perspectives even in physics education in times to come.

In recent years, the subject of innovation has been a recurring theme in the international literature on science education research. Perhaps because of the large amount of update/renovation projects for school curricula in the last few years, this focus has been adopted by many researchers in the field, making it a point of study. These works are normally related to projects aimed at introducing and evaluating the impact of curricular innovation (Pinto 2002, 2005; Ogborn 2005; Mansour 2010).

In part 3 of the work, the focus becomes the results of research-based alternatives to traditional physics.

Jenaro Guisasola provides an overview of trends with regard to different methodologies of instruction and analysis of students' learning. The chapter aims to describe and discuss teaching approaches and students' achievement on specific topics of the curriculum at university level. At university level, scientific-technological education should support a diverse student population where actually using knowledge, not just memorizing it, is becoming more important. He discusses and compares teaching approach frameworks and their features across different characteristics, such as transformation of the content, explicit monitoring of students' learning, and evaluation. He draws different lines of teaching approaches.

Cristiano Mattos trabalja na perspectiva de prospectar alternativas ao ensino tradicional. Your main purpose is to localize alternative teaching proposals in the education's activity chain, since higher education activity is part of a larger educational system that connects basic school to productive working life.

In the same direction, Limiñana, R., Menargues, A., and Rosa, S. will present the development of a teaching/learning sequence based on a structure of problem-solving that generates a tentative environment, where students and teachers have to plan a possible strategy to advance/solve the problem, carry out this plan, and analyze results. He will analyze the specific topic of latitude and longitude.

Marisa Michelini and *Alberto Stefanel* present "Innovation in Physics Teaching/Learning for the formative success in introductory physics for Bio-Area degrees: the case of fluids." Research-based intervention modules are studied in the last 2 years, for degrees in the University of Udine. The main aspects to be faced are:

(A) To redesign the way in which physics is offered so that its role can be recognized in the specific subject matter characterizing the degree: turning the ways in which physics is approached, changing the role of each topical areas, and individuating specific applications of physics in the professional field of the degree
(B) To offer instruments and methods building a physics competence in different fields
(C) To individuate strategies able to produce an active role of students in learning physics and to give them the opportunity for an appropriation of the applied physics methodologies
(D) To support students learning in multitasking ways by means of ICT tools, of lab activities, and of problem-solving and step-by-step evaluation of learning outcomes

Genaro Zavala presents "the design of problems based on cognitive scaffolding to teach physics." He has been working on the design of problems based on cognitive scaffolding to teach physics. These problems are designed to be used in almost any setting since no equipment is needed. Students work in collaborative groups of three or four students each. The design consists on transforming a traditional problem to a tutorial-format problem which takes the student through scientific reasoning steps to build concepts, that is, cognitive scaffolding. In this contribution some examples will be presented, and results of reasoning of students will be analyzed.

Mila Kryjevskaia will deal with "Examining the Relationships Among Intuition, Reasoning, and Conceptual Understanding in Physics." In an ongoing project focusing on student reasoning in physics, she has been developing and applying various methodologies that allow her to disentangle reasoning, intuition, and conceptual understanding in physics. The dual process theory is used to account for the observed patterns in student responses. Data from introductory physics courses will be presented, and implications for instruction will be discussed.

We suggest that there has been progress but that more work is needed toward identifying the effectiveness of the approaches in different countries with similar contexts and curriculum. The products of the innovation must be reproducible, as is not often the case, to constitute a reasonable foundation of accepted didactical material.

In her chapter Laurence Viennot states that critical thinking is unanimously presented as of central importance to science teaching. But the present focus on competencies observed in many countries correlates to the reduced conceptual structuring of resources that are commonly used in teaching. A crucial question then arises: is it fruitful to envision conceptual and critical developments separately? In operational terms, can critical thinking be fostered in students without conceptual structuring? Based on an epistemological framework stressing the pivotal role of a search for coherence in science, the content to be taught will be referred to a dialogue between a thorough content analysis and what we know of students' prescientific ideas, also keeping in mind the striking persistence of teaching rituals. The type of critical attitude considered here consists in questioning explanations that would be inconsistent or very incomplete, in the search for intellectual satisfaction. This chapter presents a brief synthesis of some recent investigations bearing on the co-development of conceptual understanding and critical attitude in university students. In characterizing students' responses when confronted to various explanations of a physical phenomenon, these studies bring to bear conceptual markers as well as meta-cognitive, affective, and critical indicators. Some profiles of co-development will be characterized, including "delayed critique" and "expert anesthesia of judgment." The results strongly suggest that to disregard the objective of conceptual structuring is counterproductive for the development of students' critical attitude. Through these exploratory studies, it appears that the conditions in which students can begin to search for coherence—whether in pursuit of conceptual understanding or to activate their critical potential—constitute a crucial objective for further research.

In part 4, the book turns to an emergent subject in all educational contexts, i.e., the necessity to encompass the teaching for and from diversity and difference among persons, nations, and knowledges.

Antonia Candela and Johanna Rey provide ethnographic descriptions and analyses of interviews with indigenous and Afro-Colombian teachers and of some discursive interactions with their students in primary-school classrooms in underserved communities. At those contexts they mobilize their local community knowledge for science lessons. We analyzed the teachers' purpose in incorporating indigenous and Afro knowledge in teaching science and how these different knowledge systems work in the interaction. These teachers' and students' co-constructions modify and enhance the official science curriculum with forms of resistance to the scientific myth of only one universal truth about physical phenomena. This resistance is based on the strength of their collective identity constructs as well as their connection with and respect toward nature. These kinds of studies are relevant references for a culturally sensitive science curriculum development.

The goal of *Katemari Rosa* chapter is to discuss academic climate for underrepresented groups in Brazilian physics departments. The conversation stems from looking at hate crimes happening worldwide and asking whether this hateful environment of society at large affects academic institutions. Would sexism, LGBTphobia, and racism be present in physics classrooms? Could hate speech or behavior, somehow, affect physics teaching and learning? Grounded on feminist perspectives, theories of identity, and critical race theory, the paper looks into diversity and physics education by examining the situation of race, gender, and sexual minorities in physics. Specifically, it takes on hashtag activism to analyze the experiences of students from underrepresented groups in science. The site of research is social media and the narratives produced by #MyTeacherSaid in Brazil, which was a hashtag used to reveal aggressive comments professors make to students. Results show that analyzing activism through social media can be helpful for unveiling oppressive environments in academia. Specifically, this study shows there is an oppressive climate for gender, racial, and sexual minorities of Brazilian students in STEM. The comments range from subtle but harmful comments loaded with gender and race stereotypes to open threats to students. Finally, the paper urges for a change within physics education research community to include intersectional approaches that take into account race, gender, and sexuality so that we can better understand the teaching and learning of physics, in addition to providing resources to help making more inclusive STEM environments.

Tanja Tajmel's chapter deals with "diversity in physics education" from a theoretical and discourse-analytical point of view. The discourse on "diversity" is being examined from different perspectives. Due to different motives in promoting diversity—utilitarian as well as emancipatory ones—a critical awareness of physics teachers and education researchers regarding diversity becomes increasingly relevant. The common conceptual delineation of diversity, especially through categorizing individuals by certain characteristics, bears the risk of "othering" and discrimination. In this contribution, the human rights perspective is highlighted as an approach toward a critical understanding of diversity in physics education.

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Part I

Science and Technology in the Means of Teaching Physics

Chapter 2
Dialogic Development of Children's Ideas Using Computation in the Classroom: Keeping it Simple

Ian Lawrence

Abstract Computers can be usefully thought of as representation tools. Many demonstrated difficulties in learning physics depend on re-representing the world to yourself: imagining it as other than it appears and then reasoning with that new representation, to develop new expectations about the lived-in world. To keep physics live in classrooms during this process requires the most responsive and adaptable tool we can lay our hands on, to encourage teachers to do physics with children. Rather careful thinking about matching the desirable affordances and resistances present in the practices enabled by any tool to the existing physics curriculum suggests casting the net more widely than numerical integration of differential equations. This paper draws on a number of years of working with computational modelling tools with teachers and with pupils (8–18), as well as significant work in constructing teaching sequences and supporting representations in the Supporting Physics Teaching initiative and Advancing Physics (both supported by the Institute of Physics). The foci are on exploiting flexible diagrammatic representations without being able to draw and on evolving responsive representations to support developing ideas during teaching sequences whilst seeking also to exploit the new enthusiasm for coding in a culturally valuable way and on keeping the implementation straightforward enough that teachers might be persuaded to use it.

2.1 A Place for Diagrams in Learning Physics

Discussions between teachers and students have been studied and extensively theorised over the past few decades in ways that have had impact on practice and on reflections about practice. Some work has also been done on developing drawn representations and some work on what it would take to make computational modelling possible with younger children. I think it would be fair to say that these

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have not challenged the hegemony of speech, either in research output or as what is seem on classroom walls, at least in the UK, as 'topic words'. In spite of those who have theorised about communication in science classrooms, writing about the nature of explanation in the classroom, research, examining and classroom practice has tended to emphasise words as the primary medium for expressing ideas in physics.

The use of all three media—words, diagrams and computational models—in teaching and learning physics is concerned with developing and using representations to reason about situations or processes, whether exploring existing representations or shaping your own. Reasoning is possible with either exploratory or expressive use of representations.

Delineating this division between exploratory and expressive use of a (modelling) medium was a significant outcome of the London Mental Models group that did so much to establish the possibilities of computational modelling with younger children.

In classrooms, the different communicative modes described in studies of dialogic conversations point to a similar difference between exchanges used to elucidate expressions from students and other exchanges used to explore the ideas of teachers.

Diagrams are a third kind of medium for reasoning but appear as less plastic than words, being more difficult to construct and more difficult to adapt. The skill of a hand-constructed diagram is not something that seems to be as well practised as the skill of a well-constructed sentence. And many diagrams in physics are highly compressed representations, adopting any inventions that encapsulate many kinds of knowledge, both tacit and declarative.

Perhaps because we expect language to be more flexibly interpreted, we are better at filling in the gaps with language than with diagrams, especially highly encoded or compressive diagrams, that use many conventions. The lack of plasticity affects the interpretation, as the communicative act is more constrained than in the case of language: usually in the direction of requiring more commitment on the part of the person creating the attempted communicative act. An example may help. There is more precision associated with this diagram than with the statement 'there is a force exerted on the mass'. In part this is because of the conventions associated with the diagrams, but it is also the case that constructing the diagram requires more decisions to be made by the constructor.

But there is a pedagogic danger in the propensity and ability to interpret what is 'missing' in linguistic acts: the filling-in carried out by teacher and children often leaves them at cross-purposes, both 'hearing' what they want to. Both parties adapt the inputs to fit their own ideas of the purposes of the transaction and of the ideas communicated by the transaction. This is an amalgam of constructivism and the asymmetric relationships of classroom behaviours. The plasticity of words impedes the clear communication of the ideas in physics.

More exploratory and expressive use of diagrams in classrooms, thus, seems likely to reduce this mismatch, given the greater rigidity of the diagram as a communicative tool. There are trade-offs, implicit in the encoding and decoding of diagrams, that any pedagogy that advocates their use will have to work on, but it seems that the gains from such an approach make it worth exploring.

The use of computational models in classrooms can make the rendering of the ideas being expressed or explored even more rigid, forcing a more explicit commitment of what the author intends. However this use is currently a minority interest, in spite of decades of encouragement and exploratory studies. Again the potential for gain seems substantial, but so far access to this potential has not been widely or evenly distributed, as the practice seems to happen in only a few classrooms.

2.2 Perspectives on Research and Practice

Words: A Common Probe

Formative assessment is a part of successful classrooms, and often this relies on expository writing as a probe. Children write, and teachers try to work out from their writing what they are thinking and how that can be worked on so that they can think in about physics more helpfully. All too often this writing is to satisfy external goals: it is not about the child representing and reasoning in order to figure out what is going on. So there is often an element of trying to guess what the teacher wants in the exercise. This, together with the plasticity of interpretation and the often extensive inferences about the stability of ideas revealed by these words, suggests that at the least this kind of probing might usefully be supplemented. If the idea is put to work, then we might find out more about how robust it is and how widely applied. But still there are limits to the medium, partly driven by the plasticity of the mode of expression, and partly by the nature of physics, which has adopted the quantitative route to rigour. Words are rarely sufficient—hence the unsuitability of 'What do you mean by?' as a probe.

Ideas, not words, are the real target, and we do not really know what an idea means until I see what I can do with it: ideas do not function in splendid isolation: you need to connect them up, and in particular connect them up to the lived-in world, to see what they really mean. This is a form of triangulation, of assembling different multiple perspectives on an idea by using different illuminating probes. Many research papers focus on streams of words, and this focus on language has perhaps supported teacher dialogue which so often, perhaps particularly with the harder ideas such as 'energy', seeks to settle on the correct form of words as the arbiter for what is correct and to be effectively transmitted. Words are useful, but they are not everything. For physics, which has essential connections to the lived-in world and is therefore intrinsically multimodal, the quote misattributed to E.M. Forster ('How do I know what I think until I see what I write?') is necessary, but not sufficient.

However the most common formative assessment pattern is a series of questions and answers—usually teacher's questions and children's answers. If anything this is even more subject to flexible reinterpretation than written words. Whereas the underdetermination of meaning by syllables uttered is an advantage in supporting everyday speech, this plasticity is often unhelpful in exploring understanding and misunderstanding, because there is simply too much flexibility in interpretation available to both participants in the communicative act. This warping of meaning can still be seen in action even if there are serious attempts probing the meanings—itself a hard job in busy classrooms. And the difficulties in communication persist across both expressive transactions, teacher and children working together finding out what children think, and exploratory transactions, teacher and children working together finding out what the a canonical view is.

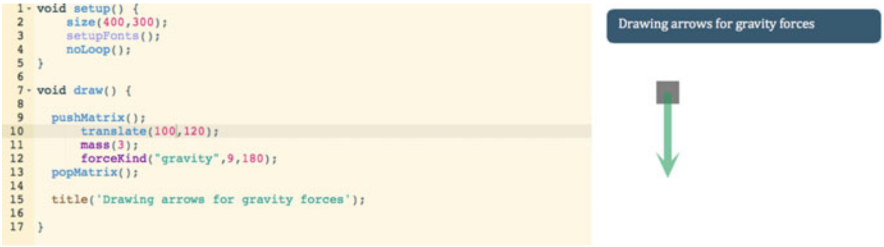
There is also the difficulty of knowing whether the thinking is final or provisional or more likely some superposition of the two. To engage in dialogue is partly to work out what you think. There is more than a kernel of truth in the aphorism: ‘How can I tell what I think till I see what I say?’

In the light of this, I think there is a case to be made for more exploratory and expressive use of diagrams, whether dynamic or static, to increase the range and variety of evidence on which we base our understanding of the ideas the children are deploying and developing. Whereas there is some work on developing representations towards the canonical (Tytler et al. 2013), there seems to be a dearth of tools that allow children and teachers to codevelop diagrams. The tools should provide some assistance and some prosthetic building blocks so that we do not need to start from just a pencil and a blank canvas. Just as words are deployed to package up collections of conventions and understandings, however particularly, so elements of diagrams carry centuries of refinement in thinking about depicting situations of processes. Consider the simple (obvious?) act of representing the force of gravity acting on an object. A diagram is rather unambiguous, and perhaps straightforward to read, after some practice (Fig. 2.1).

However saying the precisely the same thing in words takes a lot of them and requires significant explicit commitment to precision that is implicit in the diagram, being encapsulated in elements of the diagram. This kind of assisted disambiguation has, I think, considerable potential to encourage commitment and clarity in communicative acts.

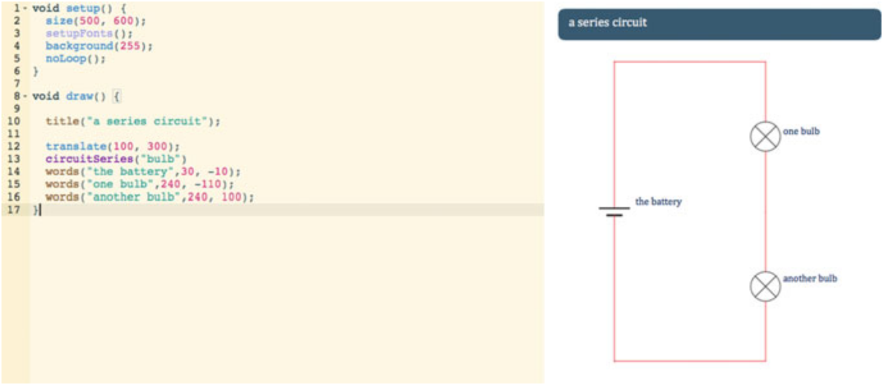
2.3 Developing Sketching and Drawing

Words are commonly used and reused as an understanding develops in classrooms, adapted in both meaning and context as they are used by teachers and children. They’re relatively easy to mix and match into new sentences, in which meaning and understanding evolve, whether spoken or written. There are not only many different tools for creating and rearranging written words, from pencil, paper and eraser to the



```
void setup() {
    size(400,300);
    setupFonts();
    noLoop();
}

void draw() {

  pushMatrix();
      translate(100,120);
      mass(3);
      forceKind("gravity",9,180);
  popMatrix();

  title('Drawing arrows for gravity forces');

}
```

Fig. 2.1 A gravity arrow



```
void setup() {
  size(500, 600);
  setupFonts();
  background(255);
  noLoop();
}

void draw() {

  title("a series circuit");

  translate(100, 300);
  circuitSeries("bulb")
  words("the battery",30, -10);
  words("one bulb",240, -110);
  words("another bulb",240, 100);
}
```

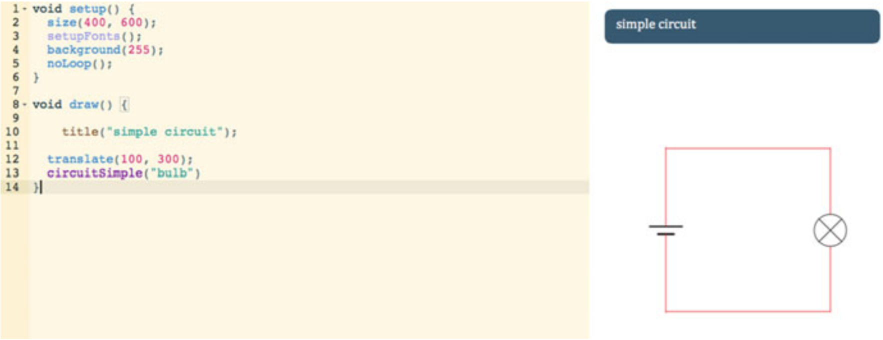
Fig. 2.2 A circuit with series connections, simply drawn

many varieties of text editor on a smartphone, but it is also the case that cultural expectations and norms firmly encourage people to acquire a competence with such tools. The inability to write grammatically is widely considered an impairment. By contrast, the inability to express yourself well using diagrams is less valued (Fig. 2.2).

Diagrammatic representations are not so often developed in classrooms: contrasting this with the affordances available for such developments in words reveals several possible reasons. Firstly elements of diagrams are less easily used and reused in such ways, when compared with the simplicity in mixing and matching words. There is, for a start, no equivalent to the enforced linear structure of the sentence (or the parallel linear interpretative framework as a result of an utterance in time, if the communication is oral). This structural freedom in diagrams adds an extra burden in both authoring and interpreting diagrams. But it may also be partly because the tools to rearrange elements of existing diagrams are somewhat more complex than text processors and partly because communicating with well-formed diagrams is less widely valued than communicating with well-formed sentences. There seems to be less of a cultural or educational imperative to develop this competence.

Yet reasoning with diagrams is a rich resource in physics: one only needs to look at the space-time diagram in relativity, the Feynman diagram in quantum mechanics and the free-body diagram in Newtonian mechanics. All three encapsulate knowledge about the domain, and manipulating the representations guides methods of reasoning about that domain.

In the educational sphere, several approaches have been made. One interesting example is to explore a set of particular geometrical interpretations in the relationships between electrical measures in resistive circuits: the AVOW diagrams. However successful, this has not been exploitable in other domains, and so there is a real question about the feedback on investment. There is a reasonable case that learning



```
void setup() {
  size(400, 600);
  setupFonts();
  background(255);
  noLoop();
}

void draw() {

    title("simple circuit");

  translate(100, 300);
  circuitSimple("bulb")
}
```

Fig. 2.3 A simple circuit

to work with these diagrams enables children to reason successfully about a restricted class of resistive circuits. There is a question about the generalisability of the approach, as it relies on simple geometrical interpretation of relationships: it is difficult to see how this would work even in the case of the simplest non-linear relationships. This may explain why the work has not spread to other domains.

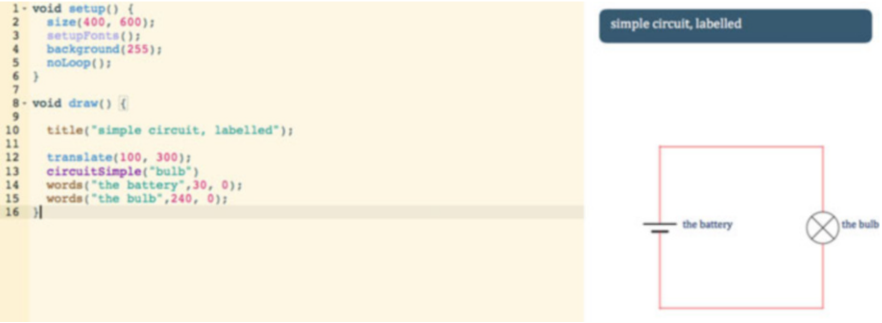
Another recent approach has explored children reworking their own representations, getting a better understanding of the value of the canonical representations. However this starts at a very low level, with the equivalent of a pencil and paper, but no words. Everything has to be built from the simplest possible operations, and there seem to be no building blocks, which to adapt and remix to construct their own diagrams.

Here I am after a meso-level, incorporating some culturally valued attributes into the elements of the diagram but allowing these to be assembled in ways that enable a degree of shaping of the communication by the teachers and children in a classroom (Figs. 2.3, 2.4, and 2.5).

Sharing an adaptable diagram is as easy as sharing the few lines of code, and changing the diagram is simple, after making the investment of time to find out how. There are inevitably questions about investment of time and trade-off between what is gained and lost: probably only pervasive use of such diagrams will tip the balance in favour of use. And diagrams are no more ‘self-documenting’ or self-evident than words.

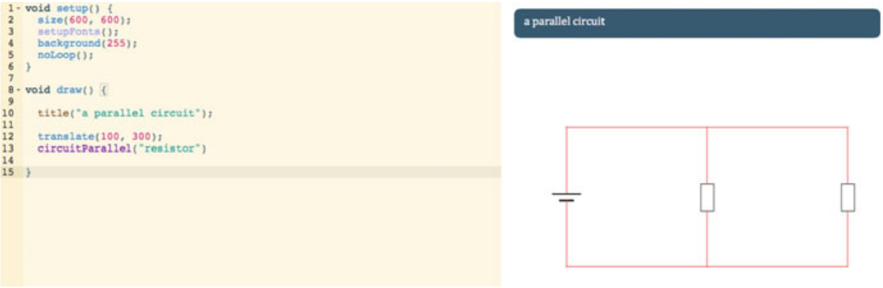
On Making Adaptable Diagrams a Part of Classroom Discourse

The idea is that a kind of structured drawing can enter the classroom conversations, as a partner. Here is a connected series of diagrams, complete with the code that generates the diagram. It should not be imagined that these are all to be deployed in a single lesson, or even in adjacent lessons, but rather that they illustrate the way in



```
void setup() {
  size(400, 600);
  setupFonts();
  background(255);
  noLoop();
}

void draw() {

  title("simple circuit, labelled");

  translate(100, 300);
  circuitSimple("bulb")
  words("the battery",30, 0);
  words("the bulb",240, 0);
}
```

Fig. 2.4 A simple circuit, labelled



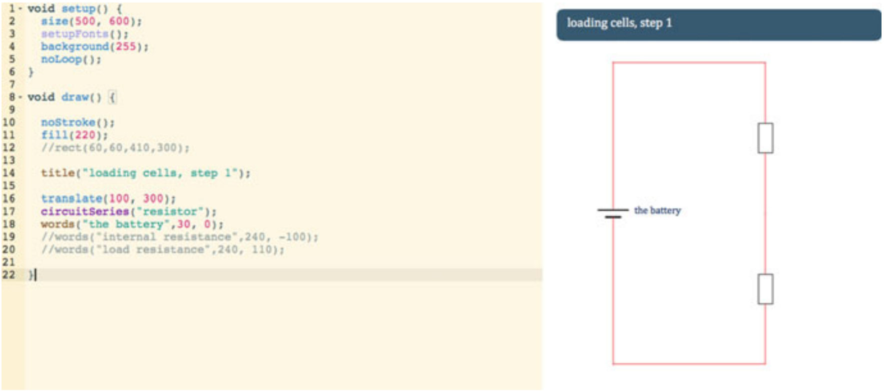
```
void setup() {
  size(600, 600);
  setupFonts();
  background(255);
  noLoop();
}

void draw() {

  title("a parallel circuit");

  translate(100, 300);
  circuitParallel("resistor")

}
```

Fig. 2.5 A circuit with parallel connections, from a simple change in the code

which such a technology can encourage the expressive and exploratory use of diagrams (Figs. 2.6, 2.7, and 2.8).

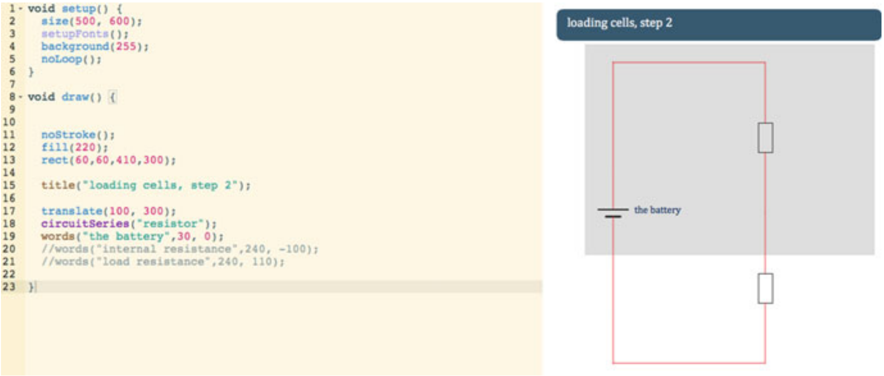
A particular concern is to exploit the idea in the processing language of a 'sketch': the code remains adaptable, and one should expect to iterate the diagram, exploring your expressions and using both canonical and personal representations to hope meaning. The diagrams should be purposeful, rather than independent artefacts, open to interpretation and open to reinterpretation. Users are able to inhabit the purposes of the diagram, in the same way that readers can be drawn into inhabiting a novel, seeing how the narrative plays out as the characters evolve: because diagrams, and elements of diagrams have connotations, just as words and paragraphs have associations through which they tell a story (Figs. 2.9 and 2.10).

Here the different representations will have different implicit and explicit connotations: as the conversation evolves, we can draw on these, hiding what we do not want. again the computer is functioning as a representation machine, encapsulating operations and encapsulating meanings. Elements of diagrams have a compressive function, just as technical words do (Sutton 1992), and these need constructing, and sometimes unpacking, to remind both teachers and children of the judgements that enable, and perhaps even constitute, that depiction.



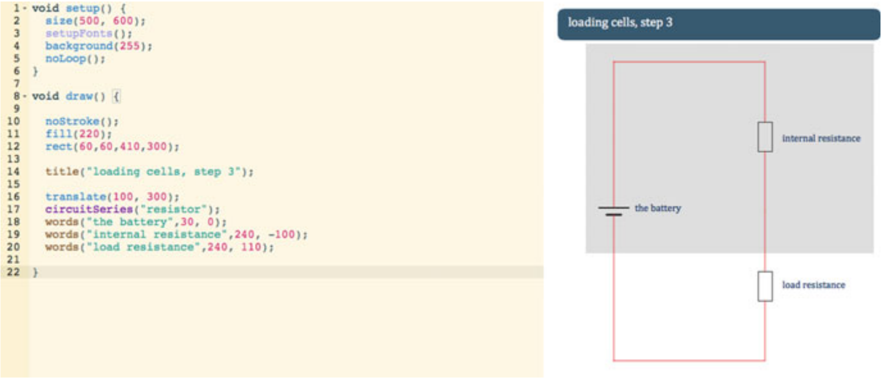
```
void setup() {
  size(500, 600);
  setupFonts();
  background(255);
  noLoop();
}

void draw() {

  noStroke();
  fill(220);
  //rect(60,60,410,300);

  title("loading cells, step 1");

  translate(100, 300);
  circuitSeries("resistor");
  words("the battery",30, 0);
  //words("internal resistance",240, -100);
  //words("load resistance",240, 110);

}
```

Fig. 2.6 A circuit with series connections, with the code prepared, but commented out, ready for a dialogic sequence



```
void setup() {
  size(500, 600);
  setupFonts();
  background(255);
  noLoop();
}

void draw() {


  noStroke();
  fill(220);
  rect(60,60,410,300);

  title("loading cells, step 2");

  translate(100, 300);
  circuitSeries("resistor");
  words("the battery",30, 0);
  //words("internal resistance",240, -100);
  //words("load resistance",240, 110);

}
```

Fig. 2.7 The same circuit but now with a part of the circuit marked off as being ‘internal’ to be battery



```
void setup() {
  size(500, 600);
  setupFonts();
  background(255);
  noLoop();
}

void draw() {

  noStroke();
  fill(220);
  rect(60,60,410,300);

  title("loading cells, step 3");

  translate(100, 300);
  circuitSeries("resistor");
  words("the battery",30, 0);
  words("internal resistance",240, -100);
  words("load resistance",240, 110);

}
```

Fig. 2.8 The circuit labelled, preparatory to the next step of measuring or modelling. All of the commenting out of the code is now removed