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The Physics Laboratory – A Historical Overview and Future Perspectives

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Abstract. In the framework of teaching the natural sciences, "laboratory" is a general name for activities based on observations, tests, and experiments done by students. It is hard to imagine learning to do science, or learning about science, without doing laboratory or fieldwork. In this paper, a historical overview of the place, purposes, and goals of the laboratory in physics teaching is presented, together with perspectives for its future related to the most recent results of research in physics education, mainly those concerning the constructivist and social constructivist learning approaches. Based on these approaches we try to validate the belief that microcomputer-based laboratories (MBLs) are one of the most promising perspectives in physics laboratory teaching, based on both theoretical and empirical grounds.

Key words: Goals and purposes, historical overview, microcomputer-based laboratories, students' engagement, the physics laboratory, traditional versus constructivist approaches

1. Introduction

About ten years ago, Arons (1993) wrote:

> The usefulness and effectiveness of the introductory laboratory have been bones of contention in physics teaching as far as one cares to go back in the literature. Laboratory instruction is costly, and, since its effectiveness has been difficult to substantiate compellingly, some responsible administrators have viewed it is a luxury we cannot afford. Yet most physicists have a deeply rooted, intuitive feeling that laboratory experience is essential to learning and understanding our subject, and they fight hard for maintaining such instruction in the face of frequently expressed doubts and occasionally formidable opposition (p. 278).

Nevertheless virtually all science teachers recognize that empirical enquiry is the hallmark of the natural sciences. It is hard to imagine learning to do science, or learning about science, without doing laboratory or fieldwork. Experimentation substantiates all scientific knowledge and understanding. Laboratories are wonderful venues for teaching and learning science. They offer students opportunities to think about, discuss, and solve real problems. In this paper, a historical overview of the place of the laboratory in physics teaching is presented, together with

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perspectives for its future related to the most recent results of research in physics education.

2. Goals and Purposes of the Physics Laboratory Work: A Brief Historical Overview

In the framework of teaching the natural sciences, “laboratory” is a general name for activities based on observations, tests and experiments done by students. Student laboratories have been an essential element of the physics curriculum for more than a century. Unfortunately, there is still no agreement as to the educational goals or the best way to assess those goals for physics laboratories.

We can find in the literature (Wilson 1962; Novak 1963; Hurd & Row 1966; Sund & Trowbridge 1967; Romey 1968; Novak 1970) a long list representing the purposes of supporters of laboratory work up to the 1970s. We can summarize them according to four different categories: (a) skills (accurate use and manipulation of instruments, inquiry skills, order and communication, critical thinking, and problem solving), (b) concepts (concrete representation of concepts, application of learned concepts to higher levels, and discovery of new concepts), (c) the nature of science (understanding the nature of science and its development, and knowing how scientists work), and (d) attitudes (curiosity, openness, reality, objectivity, accuracy, and cooperation in teamwork).

When we compare this list of purposes with the general goals of science teaching at that time (see, e.g., Bingam 1969; Pella 1961), we see that they are very similar. So we cannot be surprised that laboratory work was generally valued as the primary means of teaching science.

According to Hurd (1969), the purposes of the laboratory were

> . . . to involve the learner in the use of logical procedures and strategies, to demonstrate the implications of scientific theories and laws, to provide experience in asking good questions of nature, to provide practice in recognizing regularities, symmetries, diversities, and commonalities among observations. In general, the purpose of the laboratory is to aid the student to impose intellectual order on data; the skills he needs are more intellectual than manipulatory. (pp. 111–112)

Schwab (1962), one of the most prominent adherents of “self discovery” or “self inquiry” laboratory work, claimed that a considerable part of this work was made to lead rather than follow the classroom phase of science teaching:

> the enquiring laboratory . . . displays the phenomena which give rise to problems, the circumstances surrounding the acquisition of data for solving these problems, and the difficulties of working with and among these circumstances. And it does so in conjunction with classroom work which moves from the problem situation so displayed to exposition of the means by which the problem is formulated and solved. It is in the service of this function that the laboratory should lead, rather than follow, the course of classroom instruction. (p. 54)

According to Schwab (1962), the second function of the inquiry laboratory was to provide opportunities for the running of small but exemplary programs of inquiry. The manual for such a laboratory ceases to be a volume telling the student what to do and what to expect. Such instructions had to be replaced with loose and open materials that point to areas in which problems can be found, to problems themselves, to viable but alternative procedures, and so on. Three different levels of openness and permissiveness are available for such calls to laboratory inquiry. At the simplest level, the manual can present problems and describe ways and methods by which the student can find out relations he does not already know from his books. At the second level, the manual poses problems but means as well as answers are left open. At the third level, the problem, as well as the answer and method, are left open: the student is confronted with the raw phenomenon.

In contrast, Ausubel (1968) claimed:

> This led . . . to the exaggerated emphasis that progressivists placed on direct, immediate, and concrete experience as a prerequisite for meaningful understanding, on problem solving and inquiry, and on incidental learning and learning in natural, uncontrived situations. From this type of emphasis grew activity programs and project methods, and the credo of 'learning for and by problem solving" as the principal objective and method, respectively, of the educational enterprise. Two final by products of this point of view were deification of the act of discovery associated with the inductive and incidental learning methods of teaching, and extrapolation to the secondary school and university student of the elementary school child's dependence on recent concrete-empirical props in the comprehension and manipulation of ideas. . . . An all-or-none position regarding use of the discovery method is warranted by neither logic nor evidence. The method itself is very useful for certain pedagogic purposes and in certain educational circumstances. (p. 468)

Ausubel was not totally opposed to approaches for inducing discovery; he only argued against the interpretation that the organizing and integrative effects of learning by discovery are attributable to the act of discovery rather than to the structure and arrangement that the developers impose on such curricula as the Physical Science Study Committee courses in secondary-school physics. He approved of highly prearranged discovery methods, which guide the learner to a desired generalization through the use of cautiously ordered problem examples. He argued:

> . . . Providing guidance to the learner in the form of verbal explanation of the underlying principles almost invariably facilitates learning and retention and sometimes transfer as well. Self-discovery methods or the furnishing of completely explicit rules, on the other hand, are relatively less effective. . . . The most efficacious type of guidance (guided discovery) is actually a variant of expository teaching that is very similar to Socratic questioning. It demands the learner's active participation and requires him to formulate his own generalizations and integrate his knowledge in response to carefully programmed leading questions; and it is obviously much more highly structured than most discovery methods. (p. 504)

In this sense, we may see Ausubel as one of the forerunners of the present constructivist teaching approach. Following Ausubel's line of "guided discovery", Klopfer (1990) emphasized that science teachers have the responsibility of helping students to understand the nature of scientific inquiry. He claimed:

> To some extent, students will come to understand the nature of scientific enquiry by engaging in enquiries. However, for most students and particularly younger students, teachers need to make some specially directed effort to help them attain the goal of understanding scientific enquiry. (p. 97)

Accordingly, he defined five intended laboratory-based purposes relevant to scientific inquiry processes, each with several component behaviors. The first two purposes, which underline the "hands-on" features of scientific inquiry and the kind of skills that develop by engaging in laboratory activities and the handling of data, are the following: (a) the skills to gather scientific information through laboratory work, and (b) the ability to organize, communicate, and interpret the data and observations obtained by experimentation. Contrasting with these are the other three purposes, which place more emphasis on the reflective aspects of scientific inquiry: (c) the ability to ask appropriate scientific questions and to recognize what is involved in answering questions via laboratory experiments, (d) the ability to draw conclusions or make inferences from data, observations, and experimentation, and (e) the ability to recognize the role of laboratory experiments and observations in the development of scientific theories.

If we compare these purposes with those summarized at the beginning of this section and dating from the 1960s and 1970s, we see substantial agreement regarding skills and abilities students were supposed to acquire by working in an inquiry laboratory, but we find no reference to issues like the learning of scientific concepts, the understanding of the nature of science, and the development of positive attitudes to science. Hodson (1993) claims that empirical substantiation regarding the effectiveness of laboratory work as a way of learning scientific concepts is hard to interpret and somewhat uncertain. On the whole, it cannot be argued that laboratory work is superior to other approaches (Hofstein & Lunetta 1982; Tobin 1990a). Likewise, research findings on the impact of laboratory work on students' understanding the nature of science are also unsatisfactory (Millar 1989; Klopfer 1990). Finally, attitudes to science are influenced by many variables. One variable, laboratory instruction, seems to have an ambiguous effect on students' attitudes to science.

Some research studies, reviews, and summaries of research in science education since the 1970s report that hands-on, activity-based laboratory instruction improves students' attitudes to science (Keys 1987; Lawson et al. 1989), but there is a considerable minority who express an aversion to laboratory work (Head 1982; Delamont et al. 1988).

A major change in the goals and purposes of the laboratory work took place when an alternative approach to science learning, constructivism, began to gain acceptance. Constructivists hold that learning is an interpretive development, as new information is given sense in terms of the student's prior knowledge. From a constructivist point of view, each learner actively constructs and reconstructs his or her understanding rather than receiving it passively from a more authoritative source.

Moreover, using a viewpoint known as social constructivism, Vygotsky (1978) explained the significance of the relationship between language and action as students learn in social settings. With respect to learning science, Vygotsky's theory suggests that social interaction is crucial as learners internalize new or difficult understandings, problems, and processes. The laboratory is a place for social exchange and exploration (and expansion) of ideas; it is indeed a place for personal maturation and cognitive growth.

Redish (1997), a salient supporter of a constructivist approach in physics teaching, said:

> As a physics teacher I am not satisfied to have my students memorize a few equations and algorithms and be able to apply them in limited examples. I would like them to understand what physics is about, how it works, and why we believe it. I would like them to understand the basic concepts and the different representations used by physicists and to understand how these relate to the real world. I want them to see links between the different ideas in physics and to build a strong, accurate, and useful intuition for physical phenomena.

According to these constructivist principles the AAPT (1997) published a new set of goals for the physics laboratory:

Goal 1. The art of experimentation: The introductory laboratory should engage each student in significant experiences with experimental processes, including some experience designing investigations.
Goal 2. Experimental and analytical skills: The laboratory should help the students develop a broad array of basic skills and tools of experimental physics and data analysis.
Goal 3. Conceptual learning: The laboratory should help students master basic physics concepts.
Goal 4. Understanding the basis of knowledge in physics: The laboratory should help students understand the role of direct observation in physics and to distinguish between inferences based on theory and the outcomes of experiments.
Goal 5. Developing collaborative learning skills: The laboratory should help students develop collaborative learning skills that are vital to success in many lifelong endeavors.

3. The Constructivist Model of Learning

Thornton (1987), on the basis of many previous studies, claimed that traditional science instruction has been shown to be ineffective in altering student misconceptions and simplistic understandings. Even at the university level, students continue to hold fundamental misunderstandings of the world around them: any science learning remains within the classroom context and has no effect on their thinking about the larger physical world. As Halloun & Hestenes (1985) stated, the ineffectiveness of these traditional courses is independent of the apparent skill of the teacher, and student performance in such courses does not depend on whether students have taken physics courses in secondary school. The worst courses consist of the presentation of collections of unrelated science facts and vocabulary, with no attempt to develop critical thinking or problem-solving skills. Not only do students not have an opportunity to form their own ideas, they rarely get a chance to work in any substantial way at applying the ideas of others to the world around them.

Traditional science courses do not make strong connections with the everyday experiences of the students and the “understandings” that serve them well within united domains do not help them to comprehend the general principles underlying deeper scientific knowledge.

This traditional teaching approach tended to suppose that most students have no scientific knowledge before starting a new topic, but if they did have prior knowledge they would have little difficulty in replacing their (deficient) understanding by another (better) understanding. Neither assumption seems to be right. Children do have scientific ideas about many of the topics they study in school, though they are often at variance with scientists’ ideas, and children are often reluctant to give them up (Gilbert et al. 1982; Osborne et al. 1983). If this is the case, we need to take a different view of teaching science, a view based on exploring, developing, and modifying children’s ideas rather than attempting to displace or replace them.

Given the above problems, it should be fruitful to alter the way most science courses are taught: to begin with what students know, continue with what they can learn by arranging their interaction with the physical world around them, and connect this learning to the underlying principles of scientific knowledge. An instructional practice that has emerged over the last two decades began with what is commonly termed the personal constructivist model of learning, or simply personal constructivism. A personal constructivist model of learning assumes the existence of learners’ conceptual schemata and the active application of these in responding to and making sense of new situations.

Maor and Taylor (1995) suggest that constructivism has emerged as an alternative to the transmissionist epistemology of conventional science teaching, which holds that knowledge can simply be transferred from the teacher to the learner (Tobin et al. 1990). From the latter perspective, students’ knowledge “can be accumulated bit by bit, subject by subject” (Pope & Gilbert 1983, p. 194). The transmissionist epistemology gives rise to a pedagogy that regards the student as a passive receiver of knowledge rather than an active participant in the construction of his or her own knowledge.

By contrast, a personal constructivist perspective conceives of personal knowledge as being constructed by learners who interpret new experiences in terms of their prior knowledge and previous experiences. This perspective stresses a cognitively active approach to learning in which students construct knowledge as it is feasible for them, and integrate it within their views of the world (Pope & Gilbert 1983).

Watts and Bentley (1987) claimed that personal constructivist theories of learning understand processes of conceptual change in school science as being motivated by dissatisfaction with students’ existing ideas in the face of empirical evidence, images, analogies, or instruction. The change is seen to occur when students are encouraged to make explicit their own ideas lest ensuing explorations find them wanting (Strike & Posner 1985).

Hewson and Hewson (1984) stated that for a conceptual change to take place, instruction should reduce the plausibility of the existing conceptions by illustrating how those conceptions are not satisfactory and then encouraging the acceptability of the new conception. The motivation for change arises when the student recognizes that the new conception is more fruitful than the old ones.

Use of teaching strategies that influence conceptual change could positively affect student performance. A personal constructivist approach is based on a view of learners as active and purposive in the learning process and involved in bringing their prior knowledge to construct meanings in new situations (Driver 1987). Such teaching requires a thorough understanding of subject-matter knowledge, including knowledge of students' likely preconceptions and representations of subject matter that students can grasp. Teachers must be able to identify students' misconceptions and know how to challenge them (Neale et al. 1990). The key aspects of personal constructivism that should influence the materials for developing students' understanding can be expressed as the need for teachers

1. to have knowledge of students' existing understanding in the targeted conceptual areas and to use this as a starting point for the design of appropriate teaching materials;
2. to provide experiences that will help students confront discrepancies between their own incorrect or limited views and accepted scientific views;
3. to verify that students do in fact adhere to correct scientific views.

Consequently, general teaching strategies must incorporate both instructional methodology and content and induce students to make changes in their beliefs of how the world works (Dykstra et al. 1992). Although these strategies require students to experience phenomena that run counter to their existing beliefs, they rely upon the development of a supportive classroom climate.

Redish (1997) has recently summarized a number of principles that may get students both to hear what we are trying to say and to change their deeply held ideas. These principles have been developed as a result of research in physics education:

1. Go from the concrete to the abstract.
2. Put whatever is new into a known and understood context.
3. Make students articulate what they have seen, done, and understood in their own words.
4. To change people's ideas, you must first get them to understand the situation, then make a prediction, and finally, to see the conflict between their prediction and their observation.
5. Explaining a concept to someone often has little effect on developing his or her thinking or understanding of that concept. Learning includes doing, but "hands-on" activity does not suffice. It must be "brains-on" – that is, a cognitive activity that leads to the reconstruction of currently held concepts or the emergence of new ones.

6. “Constructive” activities in which students feel they are in control are much more effective than activities in which the students are being shown results, no matter how eloquently or lucidly the results are presented.

Accordingly, constructivism implies that learners must be given

> ... opportunities to experience what they are to learn in a direct way and the time to think and make sense of what they are learning. Laboratory appeal as a way of allowing students to learn with understanding and, at the same time, engage in the process of constructing knowledge by doing science. (Tobin 1990a, p. 405)

Hodson (1993, p. 109) summed up a series of teaching steps that are intended to bring about conceptual development and modification in students and that are particularly appropriate for laboratory work:

i. Making children’s own ideas explicit through writing and through discussion with other children and with the teacher.
ii. Exploring the implications of those ideas.
iii. Matching and testing ideas against experience and the experience of others.
iv. Criticizing the ideas of others. Subjecting one’s own ideas to criticism.
    (a) At this point the teacher should challenge children to find evidence and support for their ideas. Critical interpretation of evidence is the basis for maintaining a particular theoretical view in science.
v. Using theoretical ideas to explain observations, phenomena, and events.
vi. Applying theoretical ideas to new situations.
vii. Modifying and refining ideas to ensure a better match with “reality”.
viii. Making predictions. Subjecting theories and predictions to critical tests in the search for support, refutation, and refinement.
    * At this point the teacher should begin activities designed to effect a shift in understanding.
ix. Introduction of experiences to challenge and contradict children’s existing views.
x. Encouraging the generation of alternative conceptual frameworks and explanations by means of “brainstorming” activities.
xi. Introduction of the “official” explanatory framework as one of the alternatives – if necessary.
xii. Exploration and testing of all alternatives (repeating steps i–viii)
xiii. Comparison, judgement, and selection of the alternative that proves most acceptable to the learning group (including the teacher), i.e., reaching consensus – a key step in the practice of science.

Environments where students work with others on common, truly problem-oriented tasks are vital to the learning settings proposed (Roth 1994). By working together on problems, new knowledge is first constructed collaboratively in the shared problem space, whence the learner consequently appropriates it, that is, individually constructs his own representations (Newman et al. 1989; Rogoff 1990). Learning is situated in a particular context but is a function not only of the physical context but also of the social framework.

Constructivist-oriented science educators (Driver 1988; Tobin 1990b; Solomon 1991; Cobern 1993) realized that personal constructivism does not recognize the importance of the social facets of learning, and added an emphasis on teachers' and students' social construction of scientific knowledge.

From a social constructivist viewpoint, learning is considered a social activity in which learners are engaged in constructing meaning through negotiations and talks among peers, students, and teachers (Edwards & Mercer 1987). At the same time, students' individual constructions of meaning take place when their ideas are evaluated, explored, and supported in a social setting, such as that provided by the laboratory, with each student having the opportunity to restructure his or her ideas through talking and listening (Driver 1988; Solomon 1991). Through social interactions students become aware of others' ideas, look for reconfirmation of their own thoughts, and reinforce or reject their personal constructions.

In the social constructivist perspective, referred to in Vygotsky's work (1978), thinking processes and knowledge development are seen as the consequence of personal interactions in social contexts and of appropriation of socially constructed knowledge. Recently, the cognitive potential of collaborative work in the laboratory, namely the opportunity to endorse and encourage higher-level thinking and reasoning processes by social cognitive interaction, has been recognized.

In a Vygotskian frame of reference, the basic assumption is that reasoning in children is generally exhibited in the externalized mode of reasoning and arguing with someone else. In this regard, the collaborative work that can take place in laboratory group discussions on specific knowledge objects, aimed at motivating inquiry and transforming the results into knowledge, has been emphasized (e.g., Pontecorvo 1993; Mason 1996).

Vygotsky (1987) took interest in the conversion of social relations into mental functions, as mediation and internalization are traits of higher-order thinking. The laboratory part of a science course could be the best occasion for students not only to achieve this goal but also to put their learning to the test.

In any case, knowledge acquisition and conceptual change take place through a process of formulation, reformulation, and reinterpretation of knowledge, in which the learner is continuously evaluating their significance, comparing different points of view, and testing their validity. The learner is an active constructor of his/her own knowledge, and the process of knowledge acquisition is greatly assisted by interactions with peers and in particular with a teacher acting at the zone of proximal development (Vygotsky 1978).

However, as stressed by Gil-Perez et al. (2002), we have to keep in mind that "what we call constructivism in science education has little to do with philosophical constructivism" (p. 559). Furthermore, we are talking about constructivism as a theory of learning, with its old ancestry going back to Socrates, and not as a theory of scientific knowledge (Matthews 1997, 2002). We should not confuse the constructing in which students engage in learning science with the constructing scientists may engage in while actively doing science (Nola 1997). As Samarapungavan (1992) suggests, for scientists, theories are successful because they offer a range of explanations, consistency with empirical evidence, and logical reliability which gives them explanatory force.

Gil-Perez et al. (2002) define what they see as a proper consideration of students's role in science learning:

> . . . it is difficult to oppose the view that pupils *by themselves* cannot construct *all* scientific knowledge. . . . A metaphor that contemplates pupils as *novice researchers* gives a better appraisal of the learning situations. Effectively, every researcher knows that when someone joins a research team, he or she can catch up quite easily with the standard level of the team. And that does not happen by verbal transmission, but through the treatment of problems in fields where his or her more experienced colleagues are experts. (p. 560)

Although, students' understandings of natural phenomena are to be valued and treated with respect, and in many cases they can be used as a starting point for their experimental work in the laboratory (Jenkins 2000), the role of the teacher has two important components. The first is to introduce new ideas where necessary and to provide support and guidance for students to make sense of these for themselves, by asking students "How do you know?" "How would you justify that view?" or "Why do you believe you are right?" We must recognize that there is a role for telling, showing, demonstrating, and seeing as methods that allow the construction of new knowledge. As stated by Matthews (1990), the emphasis is on students' engagement in problem identification, hypothesis development, testing, and argument.

4. Traditional Versus Constructivist Approaches to Learning Physics in the Laboratory

As previously stated, access to laboratories and experiences of inquiry have long been recognized as important aspects of school science. Most of the curricula developed in the 1960s and 1970s were designed to make laboratory experiences the core of the science learning process (Shulman & Tamir 1973). Science in the laboratory was intended to provide experience in the handling of instruments and materials, which was also thought to help students in their conceptual development.

It is difficult to think of learning to do science, or leaning about science, without doing laboratory or fieldwork. Experimentation underlies all scientific knowledge and understanding. Laboratories are superb settings for teaching and learning science. They provide students with opportunities to think about, discuss, and solve real problems.

Still, Thornton (1987) claimed that laboratories are often excluded from, or de-emphasized in courses because many laboratory instruments are hard to use, delicate, unreliable, and costly. In addition, the teaching laboratory is not thought to be a place where students can learn physics but a place for developing laboratory skills, which are of restricted academic value. As Woolnough & Allsop (1985, p. 8) say, "For more able students the pedestrian pace enforced by preprogrammed practical work in order to deduce what is blindingly obvious can be very frustrating". Laboratory activities are unsuccessfully associated with physics concepts, calculations are time-consuming and the results that come out after a huge amount of effort are what one would expect in any case. Laboratories of this type are better omitted from courses because they discourage students, offer no new information about nature, and even present a wrong view of the process of science. Yet science laboratories are not a frill that can be removed without any consequence. The lack of the direct experience provided by the well planned laboratory can make science less attractive and less comprehensible to students.

Direct experience with physical phenomena is particularly critical to the naïve science learner of any age, and although the teaching laboratory can allow the novice to take part actively in a scientific investigation, the problems with teaching laboratories described above are compounded when they are for students who have little or no experience with science. Because such students have not developed advanced laboratory techniques, investigative abilities, or familiarity with analytical skills, it is hard to construct laboratory experiences in which they can successfully ask and answer questions that engage their attention. The effort to ensure that students with minimal laboratory skills get the "right" answer has led to the so-called "cookbook" instructions for exercises that verify known answers to unexciting questions: students follow recipes for gathering and recording data without a clear sense of the purposes and procedures, and their interconnections. Typically, students work their way through a list of step-by-step instructions, trying to reproduce expected results and wondering how to get the right answer. As Redish (1994, p. 796) described it: "Many of us who have taught introductory physics for many years recall with dismay a number of salient experiences: a reasonably successful student who can produce a graph but can't say what it means". So, despite the significance of experimentation in science, laboratories often fail to transmit the thrill of discovery to the greater part of our students (Laboratories 1997). When laboratory manuals dictate to students "*what to think*, *how to think*, and *when to think*, lab activities essentially lose impact for learning" (Pushkin 1997, p. 240).

Hodson (1993) suggested that for students, the difficulties are severe:

> Frequently, they are put into the position where they have to understand the nature of the problem and the experimental procedure (neither of which they have been consulted about), assemble the relevant theoretical perspective (with only minimum assistance from the teacher), read, comprehend and follow the experimental directions, handle the apparatus, collect the data, recognize the difference between results obtained and results that "should have been obtained", interpret those results, write an account of the experiment (often in a curiously obscure and impersonal language), and all the time ensure that they get along reasonably well with their partners. (p. 100)

In short, laboratory work, as currently put into practice, has too many avoidable obstacles to learning (too much noise) (Johnstone 1984; Newman 1985). It could be claimed that it is the very concreteness of laboratory experiences that creates the noise and serves to distract the learner from the central conceptual issues, thereby obstructing rather than encouraging concept acquisition and development.

These problems are, to a great extent, the enduring inheritance of the discovery learning methods introduced with such enthusiasm by the science courses in the 1960s. Unfortunately, these science courses complicated their problematic assumptions by combining progressive student-centred ideas underlining direct experience and learning by inquiry and discovery with obsolete inductivist views about the nature of scientific inquiry (Hodson 1993). Although it may be easy to see how the curriculum developers of the 1960s, without the benefit of current views in the philosophy and sociology of science or recent research findings about students' learning in science, tended towards inductively-oriented discovery learning, it is much more difficult to explain the continued use of this methodology (Harty et al. 1989; Meichtry 1992).

Hodson (1993) sees a number of contributing factors:

1. Its apparent simplicity. The inductivist view of science summed up in discovery learning is more "straightforward" than other styles of science and "easier" for students to follow.
2. The pedagogical respectability of student-centred models, which, because of common linguistic characteristics (inquiry, investigation, observation, discovery, etc.) appear to support an inductivist model of science.
3. Teachers' own inadequate views about the nature of science, which are a consequence of their own learning experiences in school and university science courses and are highlighted by the tradition of science textbooks and materials.
4. The comfort derived from trust in an idiosyncratic scientific method, or even a well-defined algorithm, for performing scientific inquiries.

It is this last reason that in part sustains the so-called *process approach* to the teaching and learning of science, giving rise to programs such as *Warwick Process Science* (Screen 1988), *Science in Process* (ILEA 1987), and *Active Sciences* (Coles 1988). Wellington (1989) provides some historical background to the development of the process-oriented curricula in Britain and the USA, referring to a number of contributing factors, including disappointment with the subject-matter-oriented curricula, the growth of the "Science for All" movement, the "information explosion", the advance of information technology, and the influence of assessment, particularly the interest in practical work assessment (Buchan & Jenkins 1992). Overarching all of these is a commitment to the view that the skills and processes of science are generic (i.e., content-free and generalizable) and can be transmitted to other environments, a view that has been strongly condemned by Wellington (1988), Jenkins (1989), and Millar (1991).

Recent developments in cognitive science and education corroborate the importance of empirical, heavily phenomenological experiences in learning science skills and concepts (e.g., McDermott et al. 1983). One of the ways Arons (1983) suggests to increase student learning is to provide the means for students to form concepts from concrete experience. A well-designed science laboratory can provide the sorts of experiences necessary to correct misconceptions and to develop useful physical insight. It is one of the few places where students can actually involve themselves in the processes of science: students gain first-hand understanding of physical phenomena, construct for themselves the theories needed to comprehend the physical world and express their own questions, further engaging them in the learning process.

Over the last few years, some interesting projects have been developed, following some of Arons' (1993) guiding instructions for learning in the physics laboratory. He proposed some modes of inquiry and thinking that seem to promise greater effectiveness and firmer justification for maintaining the laboratory as a critical part of physics teaching:

1. Observing phenomena qualitatively and interpreting observations.
2. Forming concepts as a result of observations.
3. Building and testing abstract models in light of observation and concept formation.
4. Figuring out how a piece of equipment works and how it might be used.
5. Deciding what to do with a piece of equipment, how many measurements to make and how to handle data.
6. Asking or pursuing "How do we know . . . ? Why do we believe . . . ? What is the evidence for . . . ?", questions inherently associated with a given experiment.
7. Explicitly discriminating between observation and inference in interpreting the results of experiments and observations.
8. Doing general hypothetical-deductive reasoning in connection with the laboratory situations.

Arons agreed with the view that rigidly controlled and directed laboratory experiments are boring and upsetting for the students, and create little in the way of concept development or physical understanding. On the other hand, he thought that the other extreme of entirely free situations, in which students are supposed to carry out their own observations, inquiry, and final syntheses, are also useless.

Improving laboratory instruction has become a priority in many institutions, driven, in part, by exciting programs being developed at various colleges and high schools.

This approach is very similar to what we formerly described as a constructivist model of teaching. From a constructivist point of view, each learner actively constructs and reconstructs his or her understanding in a social context, rather than receiving it from a more authoritative source, such as a teacher, a textbook, or a laboratory manual. In consequence, constructivism implies that learners must be given opportunities to experience what they are to learn in a direct way and the time to think and make sense of what they are learning. The role of the teacher is to mediate scientific knowledge for learners and to help them to make personal sense of the ways in which knowledge claims are generated and validated (Driver et al. 1994).

Some laboratories, guided by Arons' (1993) methods, encourage critical and quantitative thinking, some emphasize demonstration of principles or development of laboratory techniques, and some help students deepen their understanding of fundamental concepts. As prominent examples we may cite the Physics by Inquiry program at the University of Washington (McDermott 1996), the Socratic Dialog Inducing laboratories in high school and college (Hake 1992, 1998) and the Workshop Physics project at Dickinson College (Laws 1991, 1997).

The common attribute of these successful physics laboratory activities, as reported by Redish (1997), is that they are learner-centered. They induce students to become active participants in a scientific process in which they explore the physical world, analyze the data, draw conclusions, and generalize their newly gained scientific understanding to phenomena that are a part of their everyday world.

5. Microcomputer-Based Laboratories

Sabelli (1995) claims:

> We teach as we were taught. But what and how we learn have always depended on the tools available to students and teachers and should change with significant changes in the tools available. As the affordability of powerful microcomputers increases, educators become responsible for exploring the profound pedagogical implications of the changes brought about by technology on the practice of science. (p. 7)

A variety of computer applications have been developed and used in teaching physics, such as spreadsheets (Dory 1988; Krieger & Stith 1990), modeling (Silva 1994; Guisasola et al. 1999, Jimoyiannis & Komis, 2001, Godsen 2002), multimedia (Wilson & Redish 1992; Watkins et al. 1997; Calverley et al. 1998; Kumpulainen & Mutanen 1998), simulations (Eylon et al. 1996; Andaloro et al. 1997; Peña & Alessi 1999, Ronen & Eliahu 1999, 2000), tutorials (Crosby & Iding 1997; Schulze et al. 2000), Internet (Veen et al. 1998; Enloe et al. 1999; Shen et al. 1999, Gonzalez-Castaño et al. 2001) and microcomputer-based laboratories.

Most of the researches listed above report positive results in improving students' understanding of different physical concepts, but they reached the conclusion that they cannot replace lectures or actual laboratory work. Calverley et al. (1998) state that the multimedia package they presented called SToMP (Software Teaching of Modular Physics), which was intended to replace most of the lectures of a course, "has not ultimately replaced the main lecture component, but instead complemented it and caused it to be used in a different way" (p. 167). Gonzalez-Castaño et al. (2001), who presented a distributed virtual educational environment for remote access to real equipment through the Internet, providing the whole functionality of the real laboratory with several important advantages like geographical and temporal independence, a cooperative learning environment, and non-intrusive student monitoring, concluded that the "virtual laboratory is an excellent complement for the conventional one" (p. 166). Finally, Ronen & Eliahu (2000), who have developed a very successful simulation dealing with electrical circuits, claim:

> Many teachers tend to regard simulations as a potential replacement for real experiments, a common expression being "simulating experiments". Simulations should, by no means, replace any activity aimed at experiencing and investigating the real phenomena. Nevertheless, it seems that simulations

> can provide unique advantages for enhancing students' understanding of the theoretical principles and for bridging the gap between the theoretical idealised models, their formal representations and reality. (p. 25)

Some years ago, a brief discussion was held in the Physics Learning Research List that arose from a question asked by one of the participants, Marcelo Robles Castillo (1998):

> I think computers [in the laboratory] are not as useful there as many people may think. Perhaps if the experience is carefully designed ... But students don't understand what is going on; they only see numbers or graphs, usually teachers don't operate correctly the PC and sensors, and at depth, what are now the objectives of the activity of laboratory in Physics? (Anyway, what are the classical objectives of lab in Physics?).

Some of the participants in this physics education research list provided their colleague with several important references, both published or online manuscripts, but the most interesting response came from Dr. Pratibha Jolly (1998), who claimed that despite the technical difficulties related to the use of computers and interfaces in laboratory (both in India and in Chile), it was worth making the effort.

As we can see from this short discussion, teaching physics in the laboratory, and more specifically the use of computers in the physics laboratory, is a question of worldwide concern. In this last section we shall try to validate Dr. Jolly's assertion and our belief that the microcomputer-based laboratories (MBLs) are one of the most promising perspectives in physics laboratory teaching according to the constructivist principles defined in the previous sections, based on both theoretical and empirical grounds.

Thornton (1987) claims that in order to generate laboratories engaging and efficient for developing worthwhile scientific insight, students need strong, easy-to-use scientific tools with which to gather physical data and to present them in a way that can be operated, thought about, and remembered. To allow students to focus on the scientific ideas that are the purpose of their inquiries, such tools should get rid of the drudgery linked to data collection and display, and should be planned to encourage an investigative approach to science. He argues that well designed microcomputer-based laboratory instruments are especially suitable for the revival of science laboratories for students at all levels because they place understanding of physical phenomena more within reach of the naive science learner and because they expand the investigations that more advanced students can take on. Thornton (1987, pp. 235–237) summarizes the pedagogical advantages of MBL tools as follows. They:

1. Enhance learning by extending the range of student investigations.
2. Are usable by the novice.
3. Can encourage critical thinking skills by reducing the drudgery of data collection and manipulation.
4. Can encourage learning from peers.
5. May be an effective means of teaching graphing.
6. May make the "abstract" concrete through immediate feedback.

7. Can be an aid to those with science anxiety.
8. Seem especially effective for the underprepared student.

Microcomputer-based laboratories might help constructivist applications, in which the computer is used to facilitate the students' personal and team explorations by giving them tools and guidance to work things through by themselves. The computer in a microcomputer-based laboratory can capture and display data from the real world quickly and accurately. This helps students make the link between concrete elements in the real world and the abstract representations of physics.

In traditional laboratories analysis of results, drawing conclusions, and making inferences are often done quite some time after the experiment is performed. There is usually no opportunity for a student to change an original hypothesis, and alter the procedure to test the new hypothesis. Using the computer to collect and display data, there is the immediate link between the process of doing the lab and the analysis of results. Using these methods can produce practitioners of science rather than observers of science.

Researchers claim that MBL activities are effective in improving students' understanding of graphs of physical events (Mokros 1986; Thornton 1987), in producing better learning of concepts than traditional methods (Redish 1997), and in helping them to get a proper view of scientific experimentation. This has been supported by many research studies carried out on middle and high school students, teachers in pre-service training, and university students (Grayson et al. 1987; Nachmias & Linn 1987; Wiser et al. 1989; Zuman & Kim 1989; Adams & Shrum 1990; Beichner 1990; Friedler et al. 1990; Solomon et al. 1991; Layman & Krajcick 1992; Laws 1997; Redish et al. 1997; Sokoloff & Thornton 1997; Thornton & Sokoloff 1998; Trumper 1997; Trumper & Gelbman 2002). A detailed review of many of these studies was given by Nakhleh (1994) and by Redish (1997).

In typical MBL applications, the computer is interfaced with probes to measure physical phenomena, such as motion, light, temperature, force, pressure, sound, and other physical variables. The student is provided with a software tool that makes the measurement function easily accessible, "giving the computer the same role in the laboratory as electronic instrumentation, except that it is extremely flexible" (Mokros & Tinker 1987, p. 369). Using the same software with different sensors allows students to have a consistent, friendly interface for gathering data so that they can focus their attention on the underlying physics principles.

Data are displayed in digital and graphic form on the computer monitor as the measurements are taken. Students can transform and analyze the data, print graphs or tables, or save data to disks for later analysis. This facility also allows the results of one experiment to be used in association with those of a later one, for calibration or comparative purposes. Thornton and Sokoloff (1990) claim:

> The tools dictate neither the phenomena to be investigated, the steps of the investigation, nor the level or sophistication of the curriculum. Thus a wide range of students from elementary school to university level are able to use this same set of tools to investigate the physical world. (p. 859)

For example, after using these tools within a guided-discovery curriculum in mechanics, up to 90% of introductory students answered simple conceptual questions in the Newtonian way, whereas in traditional instruction the average is close to 20% (Sipson & Thornton 1995). Several studies (Linn et al. 1987; Thornton & Sokoloff 1990; Svec 1995) indicated that MBLs successfully improved students' conceptual understanding of motion. Specifically, they improved students' ability to differentiate between velocity and acceleration.

Graphs are the main way of communication with students in the developing of the MBL materials. Data are reported to the students in the form of graphs that evolve as the experiment progresses. The student can predict results in terms of graphs, and if there is a discrepancy between the graphs of the observations and the predictions, students must be aware of this and make the required adjustments in either the experiment or the prediction on the basis of this graphic information. The use of graphs as a central means of communications raises some important cognitive and educational questions. There is plentiful evidence that students even at the college level can have the ability to produce graphs from ordered pairs, while being very deficient in their ability to interpret graphs. Yet, observers have noted that students as young as 10 years old accurately use graphs in an MBL setting.

Mokros and Tinker (1987) suggest:

> It is useful to think of graphs as a symbol system similar in some respects to language, with its own grammar, syntax, and cultural connotations. It is a symbol system particularly well adapted to conveying information about experimental measurements. Certainly graphs represent the preferred communication medium for scientists, mathematicians, and engineers. Graphing constitutes a key symbol system in science because it summarizes the covariance of two or three variables over a large number of measurements. It also allows us to use our powerful visual pattern recognition facilities to see trends and spot subtle differences in shape.

Gardner (1983) states that understanding the use and interpretation of symbol systems, such as graphs, is a vital developmental task for all children. McKenzie & Padilla (1984) assert that graphs are an important tool for enabling students to predict relationships between variables and to corroborate the nature of these relationships. They have even shown that inadequate mastery of graphing skills is a major barrier to understanding scientific concepts (Shaw et al. 1983). According to Gardner (1983), "mastering of symbolic systems might even be regarded as the principal mission of modern educational systems" (p. 302).

Why does MBL appear to be such a powerful vehicle for teaching graphing skills? Mokros and Tinker (1987) propose four possible reasons: MBL uses multiple modalities; it pairs, in real time, events with their symbolic representations; it provides genuine scientific experiences; and it eliminates the drudgery of graph production.

Researchers (Mokros 1986; Thornton 1987) suggest that this linking in time of a physical event with a simultaneous graphic representation may make possible a corresponding linking in memory. Real time graphing allows learners to process information about the event and the graph simultaneously rather than sequentially.

Short-term or working memory is limited in capacity, in holding time, and it is restricted in the pace at which it can transfer information to long-term memory. Brasell (1987) assumes that the initial entry and processing of information in the brain takes place in short-term memory, and claims that "real-time graphing may allow rapid cognitive linking within short-term memory ... and thus increase the likelihood of the linked information being transferred to long-term memory as a single unit" (p. 386). She performed a study in which the usual MBL activities were compared to an activity that included a modified version of the MBL software. In the latter version, the graphs were produced with a 20–30 second delay. Brasell (1987) found that the group that had used the unmodified MBL software performed significantly better than both the delayed MBL group and the control groups.

The Computer as Lab Partner (CLP) junior high school project has been carrying out a continuous effort to devise and implement an MBL curriculum to support scientific experimentation (Linn & Songer 1988). This group found that students use three types of knowledge in constructing their scientific understanding. These knowledge types formed a continuum: action knowledge to intuitive conceptions to scientific principles. They defined action knowledge as contextually tied understanding that arises from students' previous experiences. They claimed that intuitive conceptions emerge when students combine their action knowledge with their observations to make predictions. Finally, instructions interact with these other types of knowledge to move the students toward scientific principles. This brings to mind Lawson's (2000) suggestion that both students' and scientists' knowledge acquisition pattern involves the generation and test of ideas and takes the form of several *If/and/Therefore* arguments. Linn & Songer (1988) found that this progress along the continuum took place most successfully when MBL was combined with suitable tutoring.

Thornton and Sokoloff (1990) also came to the conclusion that although the use of the MBL tools to do traditional physics experiments may foster the students' interest, such activities do not automatically improve student understanding of fundamental physics concepts. These gains in learning physics concepts seem to be produced by the combination of the tools and the proper curricular resources. They believe that the following five characteristics of the MBL learning environment – made possible by the tools, the curriculum, and the social and physical setting – are primarily responsible for the learning achievements:

1. Students focus on the physical world.
2. Immediate feedback is available.
3. Collaboration is encouraged.
4. Powerful tools reduce unnecessary drudgery.
5. Students understand the specific and familiar before moving to the more general and abstract.

To this list Redish et al. (1997) added a sixth conjecture: 6. Students are actively engaged in exploring and constructing their own understanding. These arguments are consistent with constructivist theories of learning (see references in Redish

(1994)). These assumptions appear to be confirmed by the different studies quoted above, many of them having indicated that MBL also promotes student-student interactions and peer group discussions. Most of the computers in schools are used by groups of children rather than by a single child (Crook 1994; Wegerif & Scrimshaw 1997). Because of this, some authors argue that the students using computers take part in activities that are more similar to the collaborative and inquiry-driven practice of real scientists. This is only one of many arguments for computer-supported collaborative learning, though. Many studies indicate that learning processes involving students working in pairs or in small groups in front of a computer differ in a positive way from those of students working alone with a computer. Light and Littleton (1998) write: "In a wide range of situations involving working with computers, pairs or small groups of children not only appear to perform tasks better than individuals, but also learn more from doing so" (p. 2).

Teasley and Roschelle (1993) characterize the collaborative process as "a coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem" (p. 235). This description is partially built on Clark's (1996) concept of a common ground, a satisfying agreement that two or more persons shape together and maintain through their communication. The discursive process of creating meaning in collaborative laboratory groups is an important part of learning science. MBL protocols differ from typical laboratory experiences in that students can quickly acquire and analyze data. This allows time for deliberation. Cycles of data acquisition, analysis, discussion, and reframing of the research question can be created. Furthermore, data acquired in real time can be viewed in multiple representations (events, graphs, tables, and equations) and manipulated to answer students' questions. Thus, the MBL context may foster student learning by allowing students to operationalize and test their initial conceptions, generate and reconcile problematic data, recognize anomalies to common sense conceptions, and put their ideas to deliberative tests. The MBL setting is thus methodologically interesting because the computer offers representations that must be interpreted by the students. As Kelly and Crawford (1996) stated: "students need to talk curves and squiggles into concepts and ideas".

As any scientist knows, the interpretation of experimental data and graphic information is just as important as the act of obtaining the data. Today, all MBL softwares include (or are easily linked to) easy-to-use spreadsheets that can make data acquired in the laboratory come alive to the student. A computation/graphing package which allows rapid graphic and mathematical analysis can buy time for a student to explore many possible mathematical relationships in his or her data. This gives the students more time to actually think about their data, rather than doing excessive number crunching and hand-plotting of graphs.

Thornton and Sokoloff (1990) provided a vivid testimony from visiting an MBL laboratory:

> A visit to an MBL laboratory illustrates the contrast with a traditional class. Students are actively involved in their learning. They are sketching predictions and discussing them in groups of two or

> three. They are appealing to features of the graphs they have just plotted to argue their points of view with their peers. They are asking questions and, in many cases, either answering them themselves or finding the answers with the help of fellow students. There is a level of student involvement, success, and understanding that is rare in a physics laboratory. (p. 862)

Common ground among constructivists of different persuasions is commitment to the idea that the development of understanding requires active engagement on the part of the learner. Knowledge cannot be "given" or handed over and received passively (Jenkins 2000). Furthermore, laboratory teaching methods may vary widely, but there is no substitute for an instructor moving among the students, answering and asking questions, drawing attention to subtle details or workable applications, and generally guiding students' learning. Some instructors rely on a lab handout, not to give cookbook instructions, but to set a thoroughly constructed progression of questions that help students design experiments that illustrate important concepts, and that are structured to encourage an inquiring approach to science. The main advantage of the well-designed handout is that the designer controls what students do in the laboratory more carefully.

In conclusion, changing the way that students learn involves rethinking the way we teach in the laboratory, writing new laboratory handouts, setting up a training program for teaching assistants and instructors, and perhaps designing some new experiments for a wide range of students from elementary school to university level. The microcomputer-based laboratory can help to realize the previously defined constructivist principles of teaching and thus comply with the laboratory goals as defined by the AAPT (1997). It can make physics more understandable and appealing to the increasingly large numbers of students and future citizens. Universal access to this computing methodology can considerably increase the number of students who learn physics by doing physics and not just by hearing about physics.

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