The PCK of Laboratory Teaching: Turning Manipulation of Equipment into Manipulation of Ideas[1]

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ABSTRACT

Exciting new technologies have entered the Physics laboratories, e.g. Micro-computer Based Laboratory (MBL), spreadsheets, simulation software such as applets, measurements on real life objects such as airplanes and sports heroes by linking video camera recordings or existing tapes/discs with MBL, high speed camera's which are now about to become affordable, and possibilities of testing hypotheses on data from large data bases available on Internet. These new technologies are highly attractive to students and can generate great enthusiasm. However, these technologies may not solve many of the pedagogical problems with regard to laboratory teaching. Over the past 30 years research has shown that the objectives for laboratory teaching –just as with other teaching methods- are often not achieved and that many laboratory sessions are highly ineffective and yet expensive in terms of student and teacher time and institutional facilities. Researchers have recommended a serious rethinking of objectives and teaching methods for the use of the laboratory in science teaching. Yet in spite of 30 years of discussion of these problems by a small group of researchers, the pedagogical problems in laboratory teaching are largely ignored.

The paper discusses objectives for laboratory teaching and summarizes evidence with respect to achievement or non-achievement of these objectives A discussion of why labs often do not meet expectations leads to practical suggestions which apply equally well in high technology and low technology laboratory environments.

Preliminary remarks

The essence of experimental science

At the frontiers of research, scientists continuously move back and forth between a world of theories, ideas, and concepts, and a world of nature (spontaneous phenomena) and laboratory experiments (contrived phenomena). *In the world of theories* scientists generate new ideas, theories, and hypotheses. *In the world of phenomena* the ideas and hypotheses are tested. Then on the way back to the world of theories, scientists try to make sense of their data using their concepts and theories and other forms of representation. Research can also start with observations in the world of phenomena rather than the world of theory, but even then the scientist is looking at the phenomena using his/her concepts and theories, even when he/she thinks to be 100% empirical. The phenomena and experiments serve as a source for *validating* ideas and theories and as a playground for *generating* new ideas and theories in a complex mix of inductive and deductive mind play.

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The essence of *learning* science in the laboratory

In student physics laboratories students carry out experiments which are often intended as *either* an exercise in doing experimental research, *or* support for understanding the theory discussed in lecture sessions, or an unclear combination of both. Both purposes require the student to make links between the world of theories and the world of phenomena and equipment. However, frequently students in laboratories only manipulate equipment and do not get to manipulating ideas (Gunstone, 1993). The conceptual or research goals of the laboratory get lost in the attention for equipment and there is no conceptual learning, nor learning of research methods or research skills. Computers can glue students minds and hands even more strongly to the world of equipment and make it next to impossible to get them to think of the goals of the experiment and concepts involved. The PCK of laboratory teaching centres around the question of how to connect the world of experiences with the world of ideas, on *how to turn manipulation of equipment into manipulation of ideas.*

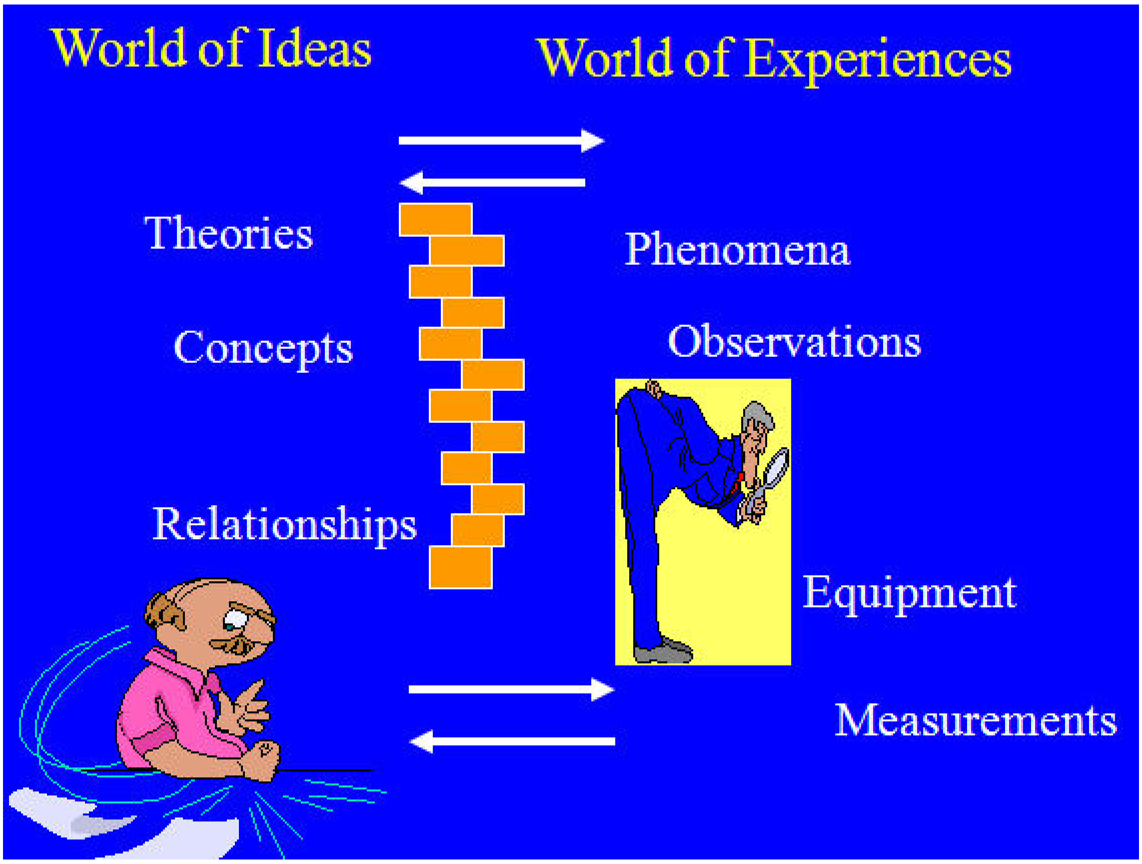

Figure 1: The Worlds of Ideas and Experiences

Goals and results of laboratory teaching

Laboratories are expensive to equip and run. They are also expensive in terms of instructor time. The student - teacher ratio is usually much lower than in lectures (½, or even ⅓ of the student-teacher ratio in lectures) and that is not even counting the time spent on preparation and checking lab reports and the cost of laboratory assistants and maintenance. Do laboratory learning results justify the extra expense?

Laboratories are usually used with one or more of the following goals in minds (Shulman & Tamir, 1973):

1. Supporting the theory (‘content’) and concepts taught in lectures. *Assumption: seeing and experiencing will lead to better understanding;*

2. Learning to do research: formulating research questions, conceptualizing ideas, designing experiments, translating variables into something which can be measured, executing experiments, interpreting data, considering possible errors, drawing conclusions. *Assumption: doing (any kind of) lab work will automatically foster these skills and develop the student's ability to do research*
3. Learning to conduct measurements and handle instruments (thermometer, multi-meter, oscilloscope, measuring with sensors and computers) and techniques (soldering, preparing solutions, etc.). *Assumption: doing will lead to mastery* and in the case of instrument handling skills, this usually works.
4. Motivating students. *Assumptions: 1) 'doing' science is motivating, and 2) this motivation will pay off in better achievement.*
5. Appreciating the experimental nature of science. Assumption: *doing lab work will automatically lead to some understanding of the nature of science.*

Please note that goal 3 can be taught primarily in the world of phenomena, experiments, and equipment, but that the other goals all require the jumping back and forth between the two worlds.

Research evidence

According to four extensive reviews of research on the outcomes of laboratory teaching (Bates, 1978; Hofstein & Lunetta, 1982, 2004; Lunetta et al, 2007; Garrett & Roberts, 1982; Hodson, 1993):

1. Labs are not better than other methods in teaching science concepts and 'content'. In other words, when we compare students who have participated in laboratory lessons with students who have not participated, the "laboratory students" do not perform better on 'content' tests. *Apparently, seeing and experiencing just by itself does not necessarily lead to better understanding.*
2. Labs probably are not better than other methods in learning to do research and acquiring research skills. *Doing lab work, does not automatically foster research skills.*
3. The lab is better than other methods (demonstrations, lectures) in teaching measurement skills and techniques. *Doing does lead to mastery in this area.*
4. Labs can lead to a better motivation but that does not necessarily result in better achievement.
5. Labs do not lead automatically to a better understanding of the experimental nature of science, unless labs are explicitly designed and taught for that purpose.

Figure 2: Statements about laboratory teaching

Bates (1978, p. 74):

Lecture, demonstration, and laboratory teaching methods appear equally effective in transmitting science content. Laboratory experiences are superior for providing students skills in working with equipment. Some kinds of inquiry-oriented laboratory activities appear better than lecture/demonstration or verification labs for teaching the process of inquiry. However, teachers need to be skilled in inquiry teaching methods.

Reif and St. John (1979, p. 950) wrote the following about undergraduate physics laboratory lessons at a major university (probably Berkeley):

We found that most students cannot meaningfully summarize the important aspects of an experiment they have just completed. Usually they recall some of their manipulations in the laboratory, but are unable to articulate the central goal of the experiment, its underlying theory, or its basic methods. Thus, despite several hours spent working with the laboratory apparatus, many students seem to learn from this experience little of lasting value.

With relatively simple modifications in the design of the laboratory teaching methods Reif and St. John were able to get much better learning results in the laboratory.

Reviews of recent literature (Hofstein & Lunetta, 2004; Lunetta et al , 2007) arrived at similar conclusions.

These findings contradict the convictions of many science teachers, lecturers and science educators and they have ignored these results for 25 years now. Even many specialists in science education continue to have a holy belief in “activities” and laboratory and do not know about the major research reviews quoted above. Although it is possible to criticize many of the studies evaluating outcomes of laboratory teaching, their collective results are consistent and force us to either lose faith in the laboratory teaching method, or fundamentally rethink the way laboratories should be used. We should be aware that these conclusions concern “average” results, averaged over many classes and many instructors. There are teachers whose labs are very successful, but in “average” situations the results of many laboratory lessons are disappointing. Should we invest our valuable resources (time and money) in laboratories, or should we invest them in other approaches to improve teaching, or should we take a good look at proper PCK for laboratory teaching? We will do the latter.

What is wrong?

The number one conclusion from the research is that the laboratory is not a place where students will automatically learn science. Just like in lectures and other teaching methods, labs have to be thought out carefully using teacher questions like the following: *What do I want students to learn? Is the laboratory the most effective and efficient means for learning that? (it might not be!) Which experiment(s) should students perform? How should the lab be presented to the students to achieve these objectives? What should the students do in the lab, what is the role of the teacher? How should student performance be evaluated?* These are typical PCK questions and they may seem trivial, but research (Berg & Giddings, 1992) shows that many labs fail and continue to fail on these questions. For extensive discussions of what goes wrong in laboratory teaching the reader be referred to Berg and Giddings (1992), Hodson (1990, 1993), and Woolnough (1991).

What are the weaknesses in the ways laboratories are commonly used? Before attempting to answer that question, we first present a classification of lab goals, which will prove to be quite helpful later on.

CLASSIFICATION OF LABS BY GOALS

Most science laboratory experiments have a variety of goals including concept learning (the lab as support for theory/lectures), process learning, and learning to handle certain instruments. These goals are usually not clearly distinguished and not explicitly formulated and taught. In this article we will first distinguish between three different types of labs and later discuss the integration of conceptual, process, and equipment aspects:

a. *concept* labs with emphasis on teaching concepts and overcoming misconceptions;
b. *inquiry* or *research* labs with emphasis on learning how to do research: exercising intellectual skills needed in generating and validating knowledge;
c. *instrument* labs with emphasis on learning a manipulative skills such as using microscopes, making solutions, measuring with oscilloscopes

Each of these kinds of labs requires a different approach to teaching, learning, and assessment.

A *concept* lab should consist of a carefully designed sequence of activities, which systematically builds up the concept and/or *exposes/reconstructs* misconceptions. The control required in such activities justifies a rather structured approach –such as guided discovery-, which should still leave ample opportunity for free communication between students and between students and the teacher so that conceptual problems of students will not remain hidden. Concept labs should also be memorable (White, 1979) which can be often be achieved using predict-observe-explain experiments in demo or lab form (White & Gunstone, 1992). Using rather complicated equipment or placing high demands on experimental design and inference or other process skills, could distract from the main goal of concept attainment. The final goal of a scientist's training, of course, is that the scientist is capable of developing and refining concepts through inquiry: an integration of methods of seeking and validating knowledge (inquiry) and concept development. However, at introductory levels in secondary school and college and when it concerns notorious concepts, it may be too ambitious to demand such integration except for some special occasions such as end-of-term projects.

In *inquiry* or *research* labs it might be better to give priority to the higher process skills and use relatively simple subject matter in order not to confound the objectives. Furthermore, there are so many aspects to research and so many intellectual skills (Table 1) that one could not expect each aspect/skill to be exercised in every lab. Sometimes one might want to emphasize the conception and planning of experiments (formulating research questions and hypotheses, controlling variables, defining variables operationally). Other times one might want to emphasize data analysis (clear presentation of data, computations, experimental error, graphing), and again at other times one might focus on interpretation and validity of conclusions. Lower level skills such as basic manipulating of equipment, measuring, and recording data are exercised in almost any kind of lab. Please note that process skills are not independent of content. It is impossible to generate reasonable hypotheses or to formulate operational definitions without conceptual knowledge, just as it is impossible to formulate anything without language. However, for exercising higher-level process skills the teacher can avoid concepts which are complicated and would result in less effective process learning. The leading concepts in research labs are **validity** (of experimental designs, of operational definitions of variables, of interpretations and conclusions) and **reliability** (measurement error and replicability of results). Please note that non-lab activities such as critical discussions of designs, or results, or research papers can also contribute to understanding of validity and reliability and process skills involved in design and interpretation of experiments.

Quite a few teachers and researchers (Woolnough, 1991) have proposed a more holistic approach to teaching “how to do research” through investigations. In their approach students just start a research project and the skills are learnt when needed, not unlike the “just-in-time” approach for supplying raw materials in a manufacturing process. However, even in this approach, one will have to recognize the underlying skills and somehow plan their “just-in-time” or “when needed” delivery.

Another type of lab -instrument labs- might concentrate on manipulative skills like the use of the microscope or other specific techniques (reading meters, soldering, dissecting, titrating, arranging electric circuits from a diagram). Many of these skills and techniques are useful both outside the science classroom and as prerequisite skills for science labs. Too often it is assumed that students master basic prerequisite lab skills. Various studies reported in Bryce and Robertson (1985, p. 4) have shown that simple prerequisite skills like reading meters and graphs are not mastered by students (at both high school and college level) and interfere with their lab performance, while teachers and lab instructors were unaware of this. Therefore it is important to pay special attention to the teaching of prerequisite skills. Skill labs often do not take up a complete lab lesson. Many skills may be efficiently exercised in short 10 minute pre-lab sessions. Yet it is helpful to distinguish the skill lab as a separate category as it requires a rather different teaching approach compared to concept labs and research labs. Skill labs should be straightforward and highly structured as there usually are clear-cut instructions how things should be done (accurately and safely) to obtain optimal results. Most likely the teacher will know best how to perform the skills. For example, how to measure resistance, how to use a microscope, or how to measure pH accurately and reliably. The main function of teacher-student discussion in the skill lab is to clarify procedures and to stimulate student thinking about how best to perform the skill. However, such discussion is followed by the teacher explaining and demonstrating the best and safest way to perform the skill. Therefore the skill lab is most efficient when it is highly structured. On the other hand, exercise of process or inquiry skills requires greater emphasis on student decision-making and a much more open and less didactic type of teaching. Concept labs require an open atmosphere for students to express their conceptions, yet these labs also require sufficient structure and teacher control to generate cognitive conflict. So each of the three types of labs mentioned, requires a different teaching approach.

Table 1: List of Process Skills (Fuhrman, 1978)

1.0 CONCEPTION, PLANNING AND DESIGN OF EXPERIMENT
The student:
1.1 Formulates question or problem to be investigated.
1.2 Formulates hypothesis.
1.3 Designs experiment (independent, dependent variables).
1.4 Designs observation and measurement procedures (including design of experiment and operational definitions).
1.5 Predicts results.

2.0 EXECUTION OF EXPERIMENT
The student:
2.1 Observes, measures.
2.2 Manipulates.
2.3 Records results.
2.4 Calculates.
2.5 Explains or makes decisions about experimental techniques.
2.6 Works according to own design.

3.0 ANALYSIS AND INTERPRETATION
The student:
3.1 Transforms results into standard form (tables).
3.2 Determines relationships (could include graphs).
3.3 Discusses accuracy of data.
3.4 Discusses limitations/assumptions of experiment.
3.5 Formulates generalizations.
3.6 Explains relationships.
3.7 Formulates new questions/problems.

4.0 APPLICATIONS
The student:
4.1 Predicts based on results of investigation.
4.2 Formulates hypotheses for follow-up.
4.3 Applies experimental technique to new problem or variable.

At lower levels of science teaching or at the start of lab courses one might divide labs into concept labs, research labs (emphasizing inquiry skills), and instrument skill labs. At higher levels these labs could be more integrated, however, always with specific priorities in objectives rather than trying to achieve everything at once. With a clear choice of objectives and priorities lab instructions should become clearer and both the teacher and students would know better what performance is expected (and how it will be assessed). Some elementary science programs do have these clear priorities between concept goals and selected process skills (Science: A Process Approach). Most secondary and tertiary level lab courses tend not to differentiate between these priorities, except perhaps at the very start of a course for one or two labs sessions.

Please note that it is impossible to have a concept lab which does not require processes and skills. Similarly it is impossible to design research labs without concepts. What we propose is that concept labs should make use mainly of processes and skills which are already familiar to students so that the concept(s) remains the primary focus. Similarly a process lab should avoid complicated new (subject matter) concepts and skills which have not been exercised yet in order to not distract attention from the process focus.

Suggestions:

1. Decide about the main objective of a particular lab session (a concept, investigation skills, or instrument skills) and choose an appropriate teaching method.
2. Once a particular experiment or set of experiment has been chosen, identify the main a) concepts, b) investigation skills, c) instrument skills involved. Try to keep down the number of new concepts, investigation skills, and instrument skills.
3. If some new instrument skills are needed, then practice these in a short pre-lab exercise.
4. If one prefers to teach through open-ended projects where the three kinds of labs are integrated, then in pre-lab and post-lab discussions clearly separate conceptual, methodological (research), and equipment aspects and identify a small number of objectives/priorities for each.

Some criticisms of common laboratory lessons and PCK to fix the problems

Weaknesses of science teaching in the laboratory can be summarized as follows:

1) the lack of distinction between priorities and objectives (e.g. between concepts, research, and skill labs),
2) the choice of experiments commonly used,
3) the mismatch between lab goals and written lab instructions,
4) the mismatch between lab goals and teaching strategies,
5) the mismatch between lab goals and assessment practices.

1. Lack of distinction between concept, process, and skill aspects of laboratory

Previously we argued for the need to distinguish between concept, process and skill labs as each of these requires a rather distinct teaching approach. Concept labs require a carefully designed interaction between students and experiments (hopefully) resulting in correction and refinement of student concepts (and misconceptions) with the lab as educational tool. Research labs require rather open lab experiments with ample room for students to make their own decisions regarding various steps in the experimentation process (goals, design, set-up, analysis, etc.), the lab is research setting. Skill labs will be highly structured with the lab as exercise setting.

2. Choice of experiments commonly used

Many experiments have been canonized in laboratory manuals with little serious evaluation of their educational value and method of presentation. For example, what would students learn from an experiment on thermal expansion? Students easily believe that matter expands when heating. A 5-minute demonstration with a sagging wire heated by electric current would be enough, no need for a 2 or 3-hour lab. Conceptually expansion does not present too many difficulties, if any, the conceptual problems would be with the microscopic visualization of expansion and a microscopic applet might help more there than a traditional expansion experiment. Gaining experimental skill with the equipment might be a good reason, but which skills? Skills that are relevant in today's physics and engineering? Or could a thermal expansion experiment be made into a research project by having students take all kinds of different materials and develop ways to measure thermal expansion of them in such a way that measurements are comparable?

Films like *Minds of our own* (Annenberg, 1997) show laboratory work of students on circuits and on photosynthesis which clearly lack some of the crucial outcomes intended by the teachers. Somehow the technical nature of the labs and the postlab discussions were not effective.

Verification of Newton's second law is part of most laboratory courses. Yet student are very willing to believe in the validity of $\Sigma \mathbf{F} = m\mathbf{a}$ Their conceptual problems are in the distinction between acceleration and velocity and in the nature of force, not in the second law itself. So why confuse students in a verification of a law they would very willingly accept, a verification always plagued by friction, thus making the law *less* plausible through verification rather than more plausible!

Many lab experiments on electric circuits continue to ignore the findings of misconception studies even though the basic misconceptions with regard to electric circuits were already known in the early 1980s (e.g. Osborne & Freyberg, 1985; Cohen et al., 1983; Duit et al., 1984, Millar & King, 1993). For example, popular misconceptions concern a) the consumption of electric current rather than conservation, b) a voltage source as a source of constant power or current regardless of the circuit connected, c) mixing of conceptions of current, energy, power and voltage. Knowing these popular misconceptions, one would do different lab experiments in order to start where students are in their thinking and then try to bring them to more scientific conceptions of electric circuits (McDermott & Shaffer, 1992; Berg & Grosheide, 1997). Similar comments can be made for other topics in physics such as mechanics, optics, and heat. The PCK is there in many studies of remediation of alternative conceptions, however, the PCK is not applied!

Often, even the nature of the equipment used, limits the educational value of experiments by forcing students in a kind of hardware straight-jacket which leaves no options for experimental design. Some of the commercially available laboratory equipment hides in a "black box" rather than reveals its science. In other instances, the equipment does not allow for alternative ways of executing an experiment thus encouraging a cook-book approach, particularly in modern physics school experiments. The use of simple equipment often helps to link laboratory science to every-day-life phenomena, while sophisticated equipment may obscure that link.

Similar comments can be made regarding the investigation lab and the skill lab. For example, there are few references dealing with the application of what is known how to teach and learn lab techniques and instrument skills (Beasley, 1979, 1983).

Suggestions (for concept labs):

1. Make an inventory of conceptual problems in the topic concerned.
2. Plan a teaching strategy and consider whether demo's and labs could be helpful and cost effective.
3. Choose whether demo or lab would be more effective (particularly when focusing on conceptual goals).
4. Choose experiments with simple and "transparent" equipment as opposed to black box equipment, and with clear results.

For learning concepts one may want to consider doing a few real experiments and then expand student experience using simulations/applets as these are more time efficient when the purpose is to learn concepts. From experiments and simulations one could then jump back and forth to the world of concepts and theories by considering representations, math, etc. These jumps could be more focused and more effective when using simulations as one can eliminate the "noise" of poor measurements due to equipment problems and lack of experimental skill. In a recent (2007) module on electric circuits for Dutch secondary schools we decided to teach/learn basic knowledge first through simulations and then introduce labs.

3. Mismatch of lab goals and written lab instructions provided to students

We have noted earlier that knowledge about cognitive psychology and student misconceptions tends not to be used in the design of concept labs. Consequently, instructions for concept labs usually ignore knowledge about common misconceptions of students. The student is assumed to be learning a new concept from scratch and no conscious effort is made to adjust the teaching to what is already in the student's mind (preconceptions).

With regard to the process lab, Fuhrman et al. (1978) developed a checklist to evaluate written laboratory instructions. They checked whether students were provided with opportunities to exercise skills related to process goals. For example, do the laboratory instructions for an experiment require a student to formulate hypotheses, interpret results, or design an experiment? If not, it would be unlikely that such an experiment would result in significant learning of these process skills. An analysis of laboratory instructions in some major American science programs such as PSSC (physics), CHEM Study (chemistry), and BSCS (biology) showed that most laboratory instructions do not force students to use higher level inquiry skills (Tamir & Lunetta, 1981), in spite of the fact that all these programs emphasized the importance of process skills in their goals. In the words of the authors (Tamir and Lunetta, 1981, p. 482):

Seldom, if ever, are students asked to:

a. formulate a question to be investigated;
b. formulate an hypothesis to be tested;
c. predict experimental results;
d. work according to their own design;
e. formulate new questions based on the investigation; and
f. apply an experimental technique based on the investigation just performed."

Experiments in many widely used texts have answers which are known by students before they start the lab or which can easily be found by students looking in the text. So students work through a cook-book recipe to obtain the expected results and sometimes they fiddle their data to "get it right". Sometimes students also have access to lab reports of past course graduates.

Of course these conclusions apply to each of the curricula mentioned to a different degree. Simple checklists like those of Fuhrman (1978) and Hellingman (1982) can be very helpful in assessing whether lab instructions are consistent with the process goals of the authors or the teachers.

The research of Fuhrman, Lunetta, and Tamir was done around 1978 and was published in research journals and in teacher journals in the early 1980s. A recent analysis of US Biology laboratory manuals (Germann et al.,1996), Chemistry laboratory instructions (Domin, 1999), and elementary and junior secondary science (Chinn & Malhotra, 2002) confirmed the findings of Lunetta and Tamir. Apparently textbook writers had learned nothing of the widely published research findings of Lunetta and Tamir.

Much work on investigations has been done in UK over the past 25 years starting with the APU (Assessment of Performance Unit, based at King’s College and the University of Leeds) which assessed many aspects of experimenting in thousands of students of different age groups. Various strands of educational development work resulted. Adey and others (Adey, 2003) have developed the CASE materials: Cognitive Acceleration through Science Education. Their focus is on pushing the development of formal operations through science education such as experiments which require students to recognize relevant variables, operate simultaneously on these different variables, for example in controlling them. There is very extensive documentation both on how to accomplish this and on results in the classroom. Others have focused on investigations for investigations sake such as Gott and Duggan (1995). Rens et al (2004) used the Concepts of Evidence ideas of Gott and Duggan and embedded investigative labs in a mix of literature study, classroom discussion, lab work, reporting, communicating results to peers at other schools through a website and e-mail, reacting to results from others, just like among scientists but carefully structured en focused on learning objectives. The PCK of the authors had been translated into a sophisticated structured set-up which helped teachers and students to achieve acceptable research reports at the end.

Suggestions (especially for investigation labs)

1. Choose the investigation skills/aspects which will be the main target of the lab.
2. Is laboratory necessary, or are there more efficient ways to exercise the skills involved?
3. Check the lab instructions or worksheet to see whether the intended skills have really been incorporated.
4. If you let students design their own experiment or set-up, contrast the validity of designs in a plenary interactive classroom discussion. Link validity of outcomes to design.

4. Mismatch between lab goals and teaching strategies

Another weakness in laboratory teaching concerns the role of the instructor. In an interesting series of studies, Kyle et. al. (1980) observed teacher and student behavior in university undergraduate laboratories. They found that the instructors inhibited rather than stimulated the kinds of learning related to goals 2, 3, 4, and 5. No wonder students only seem to learn manipulative skills in handling equipment and do not show any improvement in their understanding of scientific thinking, process skills, and science concepts. University level lab instructors in the study tended to act as technical assistants providing equipment service and related advice. In many labs, part of the time was spent lecturing (which would be more cost effective in bigger lecture groups rather than small lab groups).

In UK Galton and Eggleston (1979) observed the behavior of experienced teachers and found that students were rarely asked to make predictions or give explanations. My own experience in both industrial and developing countries matches the results of Kyle et al. and Galton and Eggleston. Most interaction between teacher and students concerns execution of the experiment and equipment (the hardware level) rather than design and interpretation (level of concepts and investigation skills). The main task of the teacher in the lab is to get students to keep going back and forth between the world of experiences and the world of concepts/theories and connect the two worlds.

Studies on student assignments/tasks and how they are implemented (Doyle, 1985; Sanford, 1987) suggest that teachers often tend to reduce the difficulty level of tasks by giving hints or even providing answers. Students are clever in teasing out answers either from the teacher or from good classmates. The result is that even when lab instructions require higher level thinking, teacher behavior and common classroom management practices make it possible for students to complete their tasks way below the intended level of thinking.

In labs students often work in groups. Quite often groups do not function properly. Sometimes only one student performs the experiment while others are passive or become secretaries. In groups consisting of boys and girls, girls often become secretaries while boys handle the equipment and take the measurements and none of them knows what they are doing. To the teacher (busily going from group to group) the class makes an active impression, but many students are not learning. Students need training and guidance to work effectively in groups. Cooperative learning techniques might help if seriously implemented rather than being paid lip service only.

Suggestions

1. In most lab sessions it is imperative to organize a pre- and a post-lab discussion. The pre-lab could be done in the lesson preceding the lab session, possibly in connection with home work (think of an experiment to find out whether ……). The post-lab discussion should be right after the lab. It is often better to interrupt the lab work in order to get to the post-lab discussion than to

have students finish and postpone the post-lab discussion for several days.
2. For each lab session the teacher should write down some questions which are directly linked to the main objectives of the lab and which force students to think and go back and forth between the world of ideas and the world of equipment/experiments. Go around the room with those questions. If one does not prepare such questions, teaching will probably be limited to assisting with equipment only and students will not rise above the world of equipment.
3. Group processes need to be monitored and can be influenced positively by assigning roles to students and shifting roles regularly (cooperative learning).

5. Mismatch between lab goals and assessment practices

Much lab assessment is based on science content rather than process and skill tests. If process skills are assessed, then it is often through lab reports only, or at most through paper-and-pencil tests, rarely by actual hands-on laboratory tests. If mastery of manipulative skills and techniques (psycho-motor skills) is assessed, then it is usually only indirectly by looking at the quality of experimental data obtained. As such data may have been "edited" by bright students, such indirect assessment does not excel in validity. That content oriented paper-and-pencil tests have a limited validity in assessing typical laboratory process and psychomotor skills is also shown in low correlations between content tests and genuine laboratory test (Ben-Zvi et al., 1977). Content achievement and laboratory achievement are clearly different dimensions with a limited common variance. It is not surprising that the lab is not making a difference in achievement, typical lab outcomes such as process and psychomotor skills are not being measured properly. Moreover, the common practice of evaluating lab outcomes by content tests and lab reports also fails to communicate the proper lab goals to students. One can imagine the influence of typical paper-and-pencil tests on average and below average students who could potentially do quite well in experimental problem solving and manipulative skills (Ben-Zvi et al., 1977). In many instances in which results are (or can be) known in advance and students are being graded on how close they get to these results, there is no excitement in the lab and consequently, motivation and interest will not increase. For an extensive review of common practical assessment in science and new alternatives we refer to Bryce and Robertson (1985).

Hands-on assessment is time consuming and assessment of process skills and typical laboratory psychomotor skills is difficult. Concept labs can be partially assessed in written form. Some aspects of process lab performance may be. However, many aspects of research labs and skill labs definitely cannot be assessed with paper-and-pencil tests or lab reports only. Alternative methods are needed such as those used in national high school biology exams in Israel (Tamir, 1974) and those described in Bryce and Robertson (1985) and developed in UK as part of the various projects on promoting student investigations (Black, 1995). That genuine yet realistic laboratory assessment is possible on a national scale is described by Bennett and Kennedy (2001).

Suggestions:
1. What are the main objectives, how can these be assessed?
2. How can the objectives be made clear to the students to guide them in their learning?
3. Frequently there are time saving alternatives for lab reports.
4. Whatever the method of assessment, focus should be on questions like: What is the question being investigated? What did I do? What did I see? What can I claim? What is my evidence? What did others say? How have my ideas changed? (Keys et al, 1999).

6. Laboratory teaching and information technology

Information technology has greatly expanded the possibilities for student experimentation by automating part of the data collection and analysis and adding possibilities for data presentation, modeling and simulation and collection of data through the Internet. Instead of spending lots of time on measuring data points one by one, tabulating and graphing data, students potentially have much more time for analysis and interpretation. Using modeling one can do real world physics where friction is taken into account as well either tacitly as part of a given model, or explicitly. However, also here there is great inertia for staying in the world of phenomena, or staying in a "computer world", rather than move back and forth between the world of phenomena and the world of concepts and theories. The computer wizard in the group might try out all kinds of variations of the experiment without any link to concepts, or *(s)h*e might waste lots of time on maximizing pretty representation of data (decoration effort) rather than doing science. For other group members the trivial details in handling MBL software may long remain a smoke screen for hiding science. In short, most of the suggestions given above still very much apply in MBL and simulation environments. Nevertheless, MBL offers exciting possibilities. For example, the Dutch Coach Platform (Coach, 2008) can handle data acquisition by many different sensors, data representation, modeling, video measurement, and control. It even allows for measurement with high speed cameras and one can take the cursor along model and data graphs and simultaneously see the corresponding video frames, one could say the worlds of theory (model) and experiments (video) side by side on the screen.

In Dutch secondary schools there have been exciting student projects which used iterations of experiments and modeling such as video *measurements* on water rockets and *modeling*, measurements on a table size model of a bungee jumper and modeling, an analysis of the movement of a walker (Heck & Dongen, 2008). Iteration of modeling and experiment is another example of putting the worlds of theory and experiment side by side on the screen. The bungee jumping model and video measurements led to lively debate in the journal of the Dutch Physics Association about whether acceleration of the jumper can be greater than 9,8 m/s^2 as measured and modeled. Eventually theoretical physicists backed up the high school students.

In short, ICT can be a powerful tool to bridge the theory – experiment divide, but use of sophisticated technology has to follow some of the same pedagogical rules outlined earlier.

Conclusions

In short, there are still many questions around the effectiveness of laboratories. The reasons for the low effectiveness of laboratory compared to other methods are: not clearly defining objectives and setting priorities, mixing goals which are *initially* incompatible (conceptual, research, instruments), inconsistency between objectives and their operationalization in worksheets and lab manuals, and methods of evaluation. If this "sermon" had to be summarized into some main suggestions then these are the main lessons regarding the PCK of effective laboratory teaching:

1. Decide about the main objective(s) of the lab session.
2. If the emphasis is on concepts or investigation, are there prerequisite skills, which need to be practiced in a pre-lab?
3. For a research lab: choose main investigation skills from the table 1 and focus on them. Make sure that in the course of a lab series most skills are exercised.
4. For a research lab: some skills can be practiced without labs, for example graphing, interpretation of graphs, (sometimes) interpretation of data, or critical reading of lab reports and research papers.
5. For concept labs: choose experiments which are meaningful to students and not just to the teachers (the traditional experiments), experiments which are meaningful considering the preconceptions of students.
6. For each lab formulate some questions to:

   a. start the lab (without giving away the results);
   b. for guidance during the lab activity, to keep student attention for the overall goals and methods;
   c. for the post-lab discussion: what was our purpose, what have we achieved, what do we know now that we did not know before, what surprised us? These questions relate to the content and concepts of the lab. A separate discussion needs to be conducted about the methods and procedures: How do we know? What is the evidence? How can validity and reliability of the experiment be improved? It is best to separate these discussions.
7. For research labs is often best to give some questions for homework preceding the lab session.
8. Look for appropriate ways to evaluate student performance. For concept labs this could be a paper-and-pencil test, for a research lab it could be interviews during the lab with a student team about their methodology, or it could be a description of a proposed experiment, or a research report, or continuous assessment and portfolio, for an instrument lab it could be an evaluation of the accuracy of results obtained and/or observation during the lab session.

And all of this should result in: **Turning manipulation of equipment into manipulation of ideas.**

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