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Didaktická znalost obsahu v laboratorní výuce: Od práce s přístroji k práci s myšlenkami

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Abstrakt

Před 35 lety se objevil první přehled výzkumů o efektivitě laboratorní výuky (Bates, 2008). Dospěl k závěru, že neexistují důkazy o tom, že by studenti *se zkušeností* s prací v laboratoři dosahovali lepších konceptuálních nebo procesních dovedností v porovnání se studenty *bez* těchto zkušeností. Následovala řada přehledů s podobnými výsledky (Hofstein, Lunetta, 1982, 2004; Lunetta et al, 2007; Hodson, 1993; Dillon, 2008), ty ale byly dosud většinou ignorovány. Výzkum ukázal, že laboratorní výuka – podobně jako je tomu u jiných výukových metod – často nedosahuje proklamovaných cílů a mnohá laboratorní cvičení a praktika nejsou efektivní, i když jsou náročná jak na čas učitelů a studentů, tak na potřebné vybavení. Článek analyzuje důvody neuspokojivých výsledků laboratorní výuky a podává náměty, jak ji zefektivnit. Mnohé návrhy jsou vlastně triviální, ale přesto nejsou většinou učitelů využívány. Již dlouho přitom někteří autoři referují i o úspěšných aktivitách v laboratorní výuce (např. Reif, St. John, 1979; Etkina et al, 2010), v praxi však zatím stále převažují tradiční a méně úspěšné přístupy.

Klíčová slova: laboratorní aktivity, laboratorní výuka, učení se v laboratoři, bádání, zkoumání, dovednosti, efektivita.

The PCK of Laboratory Teaching: Turning Manipulation of Equipment into Manipulation of Ideas

Abstract

Thirty-five years ago the first review of research on effectiveness of teaching in the laboratory appeared (Bates, 1978) and concluded that there was no evidence for better conceptual or process skill achievement for students *with* as compared to *without* laboratory experience. Other reviews with similar results followed (Hofstein, Lunetta, 1982, 2004; Lunetta et al, 2007; Hodson, 1993; Dillon, 2008) but were largely ignored until recently. 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 ineffective and yet expensive in terms of student and teacher time and facilities. This paper analyzes reasons for disappointing results of laboratory teaching and provides suggestions for making laboratory teaching more effective. Many suggestions are trivial, yet not currently used by most teachers. All along there have also been reports of successful laboratory activities (e.g. Reif, St. John, 1979; Etkina et al, 2010), however, traditional and less successful approaches still predominate.

Key words: laboratory activities, laboratory teaching, laboratory learning, inquiry, investigation skills, effectiveness.

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 objects (spontaneous phenomena) and laboratory experiments (contrived phenomena). *In the world of ideas* scientists generate new ideas, theories, and hypotheses. *In the world of objects* the ideas and hypotheses are tested. Then on the way back to the world of ideas, scientists try to make sense of their data using their concepts and theories and other forms of representation (Figure 1). Research can also start with observations in the world of objects rather than the world of ideas, 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.

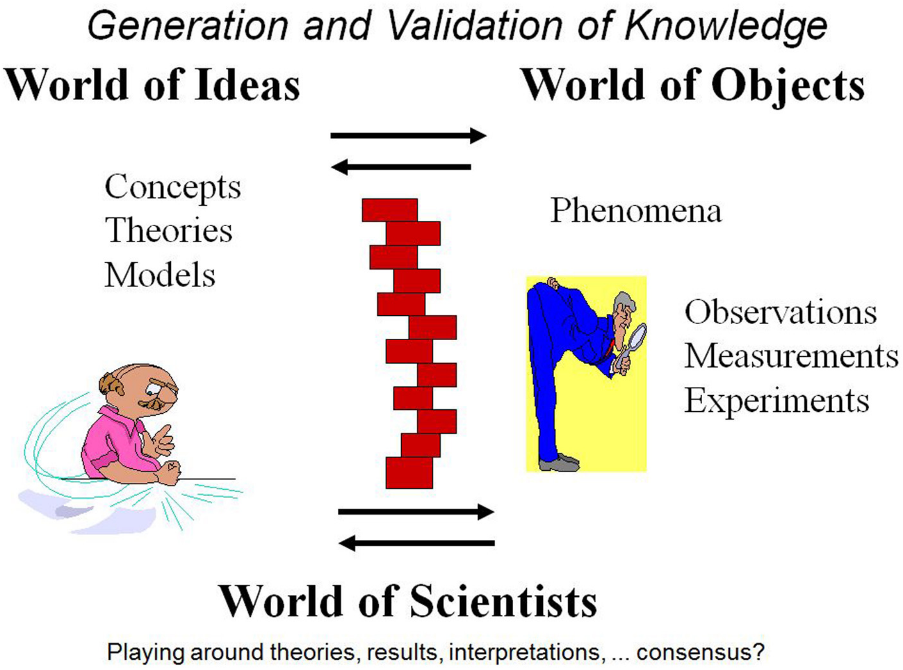

Fig. 1: The worlds of ideas, objects, and scientists

THE ESSENCE OF learning SCIENCE IN THE LABORATORY

In student science 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 ideas and the world of objects. However, frequently students 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 investigation skills. The PCK of laboratory teaching centres around the question of how to connect the world of objects with the world of ideas, on *how to turn manipulation of equipment into manipulation of ideas.*

GOALS AND RESULTS OF LABORATORY TEACHING

Laboratories are expensive to equip and run. They are also expensive in terms of instructor time preparation, equipment and technical support. Do results of laboratory learning 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, designing experiments, translating variables into something which can be measured, executing experiments, interpreting data, considering systematic and random error, 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, microscope, sensors and computers) and techniques (soldering, preparing solutions, etc.). *Assumption: doing will lead to mastery.*
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 objects, but that the other goals require the thinking back and forth between the two worlds.

RESEARCH EVIDENCE

According to extensive reviews of research on the outcomes of laboratory teaching (Bates, 1978; Hofstein, Lunetta, 1982, 2004; Lunetta et al, 2007; Garrett, Roberts, 1982; Berg, Giddings, 1992; Hodson, 1993; Abrahams, Millar, 2008; Dillon, 2008):

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** lead to better understanding.*
2. Labs probably are not better than other methods in learning to do research and acquiring investigation skills. *Doing lab work, does **not** automatically foster investigation 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 (Lederman, 1992).

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 modifications in the design of laboratory sessions Reif and St. John were able to get much better learning results in the laboratory.

Recently Abrahams and Reiss (2012, p. 1 050) concluded after observing practical activities in 10 primary and 20 secondary schools:
Indeed, what emerged from the comments made by both the primary and secondary students was that there was little evidence of any enduring conceptual understanding that could be clearly attributed to a specific practical task.

Fig. 2: Statements about laboratory teaching

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 laboratory teaching, 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 (I will discuss some later on), but in “average” situations the results of many laboratory lessons are disappointing. Should we invest our valuable resources in laboratories, or should we invest them in other approaches to improve teaching, or should we take a good look at proper PCK (Pedagogic Content Knowledge) for laboratory teaching? We will do the latter.

Reviews of recent literature (Hofstein, Lunetta, 2004; Singer et al, 2005, p. 100; Lunetta et al, 2007; Abrahams, Reiss, 2012) arrived at similar conclusions. An example: Pine et al (2006) tested 1000 grade 5 children from 41 schools with a knowledge test and a performance assessment (a mini-investigation). Half of them had been exposed to hands-on (inquiry intended) science, half of them had done textbook science. There were no differences between the two groups, neither on the knowledge test nor on the performance assessment (a mini-investigation) where children with experience in inquiry should have been superior. The authors wondered whether the reported inquiry had been real inquiry. On the other hand, Furtak et al (2012) conducted a meta-analysis in which they applied very stringent conditions to select studies qualifying as inquiry. The result came out in favor of inquiry (effect size 0.50), showing that if some requirements are fulfilled, positive effects are possible.

The research findings contradict the convictions of many science teachers, lecturers and science educators and they have ignored these results for 35 years now. Even many specialists in science education continue to have a holy belief in "activities" and laboratory and ignore the major research reviews quoted above. The *Getting Practical* project organized by the Association for Science Education (ASE) in UK with copies in some other countries like the Netherlands might succeed in triggering a turnaround in thinking about laboratory teaching.

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!) How to integrate the lab experience with other learning activities? Which experiment(s) should students perform? How should the lab be presented to the students to achieve the objectives? What should the students do in the lab, what is the role of the teacher? How should student performance be monitored and evaluated?* These are typical PCK questions and they may seem trivial, but research shows that many lab activities fail and continue to fail on these questions.

What are the weaknesses in the ways laboratories are commonly used? Before answering that question, we first take another look at lab goals.

Teaching concepts, inquiry skills, and lab techniques

Most science laboratory experiments have a variety of goals including concept learning (the lab as support for theory/lectures), learning investigation skills, and learning to handle certain instruments. These goals are usually not clearly distinguished and not explicitly formulated and taught:

a) *learning concepts*, developing students' understanding of concepts/theory;

b) *learning to do research* (*inquiry*) which is learning and exercising intellectual skills needed in generating and validating knowledge through experiments;

c) *learning laboratory techniques* such as using microscopes, preparing solutions, arranging electric circuits, measuring with various instruments, etc.

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

To learn *concepts* a lab should consist of a carefully designed and scaffolded sequence of activities (Goldberg et al, 2010), which systematically builds up the concept and/or *exposes/reconstructs* misconceptions. Students should see what we intend them to see (Millar, 2010). The control required in such activities justifies a rather structured approach — such as guided discovery —, which should still leave ample opportunity for free student-student and student-teacher communication so that conceptual problems of students will not remain hidden. Concept activities should also be memorable (White, 1979) which can often be achieved using predict-explain-observe-explain experiments in teacher demo or student activity form (White, Gunstone, 1992). Using rather complicated equipment or placing high

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.

Fig. 3: List of Investigation Skills (Fuhrman, 1978)

demands on experimental design and data analysis skills, could generate ‘noise’ that distracts 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. Having said that, I must admit that over the last few years I have worked in elementary schools with concept cartoons (Naylor, Keogh, 2013) where students design experiments (inquiry) to find out more about the phenomena in the cartoon (concepts). Mixing inquiry and conceptual aspects can work well if the teacher focusses clearly on two questions: 1) what do we learn from the activity about science concepts? and 2) what is the evidence? The latter question concerns methodology thus investigation skills. Perhaps my advice about the carefully designed sequence of activities is for the beginning teacher or when time is very restricted.

To learn *investigation skills* (Figure 3) students need freedom to make choices in the design of experiments and debate about pro’s and con’s of a design and try it out. That is different from the guided discovery advocated for concept learning.

Furthermore, there are so many aspects to research and so many inquiry skills that one could not expect each aspect/skill to be exercised in every lab activity. 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, computing experimental uncertainty, 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 lab activity. Please note that investigation 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 investigation skills the teacher sometimes may have to avoid concepts which are complicated and could result in less effective process learning. The leading concepts (Gott, Duggan, 1995) in investigation activities are **validity** (of experimental designs, of operational definitions of variables, of interpretations and conclusions) and **reliability** (measurement uncertainty and replicability of results). Please note that non-lab activities such as critical discussions of designs, or results can also contribute to understanding of validity and reliability and investigation skills involved in design and interpretation of experiments. One particularly interesting approach is to have students replicate or test designs and experiments and results of other students.

Many teachers and researchers now prefer a more holistic approach to teaching “how to do research” through investigations. In this approach students start a research project and the skills and concepts are learnt when needed, a “just-in-time” approach. Projects can be very motivating, much more than “exercises” in particular skills. However, even in this approach, one will have to recognize the underlying skills and somehow plan their “just-in-time” or “when needed” delivery. This can work well when the teacher per session determines which skills to pay extra attention to and uses an observation checklist and plans for learning progressions in all skills across the year. Klentschy’s (2008) student notebook approach could be a helpful tool to have students document their own progress in reasoning and inquiry. There are other self-assessment tools around as well (Etkina et al, 2010).

Learning laboratory skills/techniques: 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. Often lab techniques can be efficiently exercised in short 10 minute pre-lab sessions. Teaching lab techniques 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 (Beasley, 1979, 1983). Most likely the teacher will know best how to perform the skills. 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 skill teaching is most efficient when it is highly structured. On the other hand, exercise of investigation skills requires greater emphasis on student decision-making and a much more open and less prescriptive type of teaching. Learning concepts requires an open atmosphere for students to express their conceptions, yet these concept activities also require sufficient structure and teacher control to generate cognitive conflict. So each of the three types of educational goals, requires a different teaching approach. The easy and effective option for teaching lab techniques is a 10–15 minute pre-lab exercise. Another option — more difficult for the teacher and more interesting for the students — is to integrate the pre-requisite skills in an investigation and make sure to check mastery.

A beginning teacher might want to separate lab activities clearly into concept focused, inquiry focused, or lab technique focused and separate the clearly different teaching approaches. More experienced teachers will have a spectrum of teaching approaches available but will have to differentiate very well which ones to use. Then it helps to prioritize a small number of concepts and skills per lab activity to pay attention to. 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 can be assessed).

Suggestions:

1. Carefully decide about one or two main objectives of a particular lab session (concept, investigation skills, or instrument skills) and choose an appropriate teaching method.
2. After choosing a particular experiment or set of experiments, identify the main a) concepts, b) investigation skills, c) instrument skills involved.
3. If new lab techniques or instruments are used, then organize the guided practice needed (for example: a short pre-lab exercise) and assess mastery before proceeding.
4. When teaching through open-ended projects, then in pre-lab and post-lab discussions and guidance clearly separate conceptual, methodological (research), and equipment aspects and identify a small number of objectives/priorities for each.

Criticisms of common laboratory lessons and PCK to fix the problems

The problems in many laboratory activities can be summarized as follows:

1. the lack of distinction between learning concepts, investigation skills, and laboratory techniques,
2. the choice of standard experiments which do not connect with typical learning problems,
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 learning of concepts, investigation skills, and laboratory techniques and lack of integration with other (non-lab) teaching learning activities

We already explained the need to distinguish between learning concepts, investigation skills, and lab techniques as each of these requires a rather distinct teaching approach. Learning concepts requires a carefully designed interaction between students and experiments (hopefully) resulting in correction and refinement of student conceptions with the lab as *educational tool.* Learning inquiry skills requires rather open lab experiments with ample room for students to make their own decisions regarding various steps in the experimentation process (research question, design, set-up, analysis, etc.), the lab is *research setting.* Learning lab techniques requires a structured approach with the lab as *exercise setting.* Furthermore, the lab is often quite separate from other teaching-learning activities while particularly activities to support concept development require careful integration (Singer et al, 2005, p. 97).

2. Choice of experiments

Many experiments have been canonized in laboratory manuals with little serious evaluation of their educational value and method of presentation. For example, 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 with the distinction between acceleration and velocity, and force and momentum, **not** with the "truth" of the formula. 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). 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 the concepts current, energy, power and voltage. Knowing this, one would do different lab experiments in order to start where students are in their thinking and then try to bring them closer to scientific conceptions of electric circuits (McDermott, Shaffer, 1992; Berg, Grosheide, 1997). Similar comments can be made for most other topics in physics. The alternative conceptions should be considered the starting capital and there are numerous examples in the literature how a mix of teaching strategies including laboratory and demonstration can bring students closer to the scientific explanations of phenomena. The Pedagogical Content Knowledge (PCK) exists but is not widely applied!

Sometimes the nature of the equipment used, limits the educational value of experiments by forcing students in a 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 doing an experiment thus forcing 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.

Suggestions for teaching concepts through lab activities:

1. Make an inventory of conceptual problems in the topic concerned.
2. Plan a teaching strategy and consider whether demo's and lab activities could be helpful and cost effective, and if so, integrate them properly.
3. Make a deliberate choice between lab activities or demonstration. The latter could greatly reduce "noise" which might confuse the learning process.

4. Be critical of standard experiments and how they are used in a lab activity.
5. Choose experiments with simple and "transparent" equipment and clear results as opposed to black box equipment.

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 (such as PhET electric circuit applets). In the simulations one can more easily jump back-and-forth between the worlds of ideas and objects (here simulations) as "noise" due to poor measurements and experimental skills can be avoided.

3. Mismatch of lab goals and written lab instructions

With regard to learning to investigate, Fuhrman et al. (1978) developed a checklist (an extension of Figure 3) to evaluate written laboratory instructions. For each lab activity they checked whether students were provided with opportunities to exercise skills related to process goals. For example, is the student required 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 investigation skills. An analysis of laboratory instructions in 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 inquiry in their goals. In the words of Tamir and Lunetta (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 or which can easily be found by students on the next page. So students work through a cook-book recipe to obtain the expected results and sometimes they fiddle their data to "get it right" or copy lab reports from others.

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. More recent analyses 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 30 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 was on stimulating 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 extensive documentation both on how to accomplish this and on results in the classroom. The UK National Curriculum (1999) puts much emphasis on inquiry objectives, yet actual classroom implementation of an inquiry focus is disappointing as shown in the studies of Abrahams (next section).

In the Netherlands Rens et al (2010) used the Concepts of Evidence ideas of Gott and Duggan (1995) and embedded investigative labs (senior secondary) in a mix of literature study, classroom discussion, lab work, reporting, communicating and discussing results with peers at other schools through internet, just like among scientists but carefully scaffolded and focused on objectives. The authors transformed their PCK knowledge about *learning to investigate* into a sophisticated structured and scaffolded set-up which helped teachers and students to achieve good research reports.

Suggestions when emphasis is on inquiry:

1. Choose the investigation skills/aspects which will be the main target of the activity.
2. Is laboratory necessary, or are there more efficient ways to teach the skills involved?
3. Check the lab instructions or worksheet to see whether the intended skills will really be used to complete the task.
4. Let students design their own experiments when possible and have a plenary discussion with a focus *on reasoning with evidence* and the *validity* and *reliability* of experiments.

4. Mismatch between lab goals and teaching strategies

In an interesting series of studies, Kyle et. al. (1980) observed teacher and student behavior in university undergraduate laboratories taught by student assistants. They found that the instructors inhibited rather than stimulated the conceptual and inquiry learning. 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. The 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 objects and the world of ideas (Figure 1) and connect the two worlds**. Abrahams and Millar (2008) observed 25 secondary laboratory lessons and Abrahams and Reiss (2012) observed 10 primary and 20 secondary lessons and concluded: *Indeed, what emerged from the comments made by both the primary and secondary students was that there was little evidence of any enduring conceptual understanding that could be clearly attributed to a specific practical task.* Furthermore, teachers were focused on subject matter and getting the expected results through recipe-like instructions. They did not pay attention to inquiry aspects in spite of the beautifully formulated inquiry objectives in the National Curriculum for England and Wales since 1999.

Studies on student assignments/tasks and how they are implemented (Doyle, 1985; Sanford, 1987) suggest that teachers 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 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 write while boys handle the equipment and take the measurements and none of them know 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 help if seriously implemented rather than being paid lip service only.

Suggestions:

1. Make sure there is a pre- and a post-lab discussion. The pre-lab could be done in the lesson preceding the lab session, possibly in connection with homework (design 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 to the next lesson.
2. For each lab session the teacher should write down main points to watch for and questions to ask which are directly linked to the lab objectives and which force students to think back and forth between the world of ideas and the world of objects. The teacher goes around the room observing and questioning. Without this, teaching will be limited to assisting with equipment only and students will not rise above the world of objects.
3. Group processes need to be monitored and can be influenced positively by assigning roles to students and shifting roles regularly (cooperative learning) and separating girls and boys.

5. Mismatch between lab goals and assessment practices

Much lab assessment is based on science content rather than research and skill tests. If investigation skills (Figure 3) 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 assessment usually is indirect by looking at resulting measurements. As 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 abilities 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.

Hands-on assessment is time consuming and assessment of investigation skills and typical laboratory psychomotor skills is difficult. Concept learning can be assessed in written form. Some aspects of investigation skills may be. However, many aspects of investigation skills and laboratory techniques cannot be assessed with paper-and-pencil tests or lab reports only. Alternative methods are needed such as those once used in national high school biology exams in Israel (Tamir, 1974), those described in Bryce and Robertson (1985), and *performance assessments* developed in UK (Black, 1995). These are mini investigations which are assessed by direct observation and worksheets. Worked out examples can be found in Pine et al (2006) and the associated website. That genuine yet realistic laboratory assessment is possible on a national scale (Ireland) is described by Bennett and Kennedy (2001). The pilots on Assessment of Pupils Progress (APP) in elementary and junior secondary education in UK have shown the feasibility of assessing higher order investigation skills through continuing assessment without having to maintain extensive portfolios (Ardron, Monahan, 2010).

Klentschy (2008) experimented for 14 years with science notebooks from Kindergarten to 12th grade to improve the quality of science and language education in one of the weakest California school districts. The notebooks focused on: *what do I expect to happen (prior knowledge), what happened/what did I see, and what do I think now* (knowledge after the experiment). In notebooks students document the emergence of their own thinking and support this with evidence from experiments. The many examples in Klentschy's book show that students can learn to document their own thinking and this could be input for both formative and summative evaluation.

Suggestions:

1. Formulate clear objectives and assessment strategies.
2. Find ways to make objectives clear to students to guide their learning.
3. Think of time-saving alternatives to 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).
5. Students themselves could document their learning (Klentschy's notebooks).

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 sensors or Internet. Instead of spending lots of time on measuring data points one by one, tabulating and graphing, students have more time for analysis and interpretation *once they master the software*. Modeling *is* thinking back-and-forth between ideas and phenomena But students do have to learn many prerequisite skills in handling software. If they do not master these skills, the lab activity can easily drown.

In short, most of the earlier suggestions in this paper also apply to MBL and simulation environments. Nevertheless, MBL does offer exciting possibilities and I myself interviewed 5th and 6th grade children who could reason very well between sensor-recorded graphs and phenomena after only two MBL activities (Berg et al, 2010). For example, the Dutch Coach Platform (Coach, 2013) 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 see the worlds of theory (model) and experiments (video) side by side on the screen. Similar facilities are offered by systems of Vernier and PASCO.

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. A bungee jumping model and video measurements led to lively debate in the journal of the Netherlands 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.

7. SUCCESSFUL USES OF LABORATORY ACTIVITIES

This paper was about “typical” use of laboratory activities in many schools and not about successful use in pilot projects. However, there have **always** been successful uses of laboratory activities but less widespread than “typical” laboratory teaching. After concluding that their Physics lab activities did not produce the expected educational results Reif and St. John (1979) modified their system of lab teaching to include better focused objectives, teaching methods, and assessment and the educational outcomes improved greatly.

Elementary science programs of the 1960s and 1970s such as Elementary Science Study (ESS), Science A Process Approach (SAPA) and the Science Curriculum Improvement Study (SCIS) in the USA and Science 5–13 in UK in the 1960/70s, did offer children opportunities to design their own investigations and some teachers were able to realize these opportunities. Updated versions such as INSIGHTS, Science Technology & Children (STC), and Full Option Science System (FOSS) offer lots of opportunities for investigation. INSIGHTS amd STC have also been adopted and adapted in several European countries. There is video material showing impressive implementation examples in the classroom, but such implementation is still relatively rare. Klentschy (2008) illustrates many examples of real inquiry work from K-8 student notebooks. Having elementary students involved in real investigation work is certainly possible, but most elementary teachers are still insufficiently trained and supported to realize this.

We saw that the ambitious 1960s secondary science curricula in the USA offered more prescriptions and less investigations than the authors intended and advertised (Tamir, Lunetta, 1981). However, there are lots of inquiry-based materials in circulation. Israel pioneered inquiry labs for High School Biology in the 1970s and even had national laboratory exams with a significant inquiry component (Tamir, 1974). Other countries require evidence of school-based research work. The Netherlands has required school-based research projects for science since the 1990s but this also led to the surprise of many teachers that their own laboratory programs did not properly prepare their students for research. Since then there has been a slow but steady change towards more investigation. Rens et al (2010) developed a very ambitious but also very pragmatic approach to get grade 11 students from the Netherlands and some other countries into real research in chemistry. The process starts with some focused exploration of a phenomenon, for example tooth decay. Then students read a poor quality research paper and are asked to design better experiments to study influence of various factors on the phenomenon (e.g. soft drinks and acids on tooth decay). Students from different schools exchange their research reports and comment on each other's experimental design and results just like happens in the world of scientists (Figure 1). In UK studies like those of Abrahams have triggered the Getting Practical Project of the Association for Science Education in which teachers are working on better focused objectives and teaching methods for laboratory activities and this project has spread to other countries.

At the University level the Free University in Amsterdam in the 1980s had students themselves design experiments to measure constants of nature or material properties, always with two different methods. Contrast between outcomes of two methods, for example, an optical and an electric way to measure an index of refraction led to useful comparing of two experimental designs. Lately Etkina et al (2006, 2010) have not only developed interesting lab activities but have also documented the outcomes carefully and extensively and their approach has spread to other universities. Goldberg and colleagues (2010) have long pioneered inquiry activities with a strong concept orientation and have recently (Goldberg et al, 2012) adapted activities for large enrollment courses with retention of concept gains. Both Etkina's and Goldberg's work can be adapted to secondary school level. Many other pioneers must remain unmentioned here. There is no shortage of examples of good and effective laboratory work, but there needs to be much more effective and wide spread implementation which we hope can be achieved through extensive professionalization projects such as Getting Practical (http://www.gettingpractical.org.uk).

Conclusions

Research on laboratory teaching shows disappointing results and these seem to be caused by mismatches between educational objectives, choice of activities and experiments, lab instructions, guidance, and assessment. Just like other teaching methods laboratory activities need to be carefully thought through and implemented properly. Some suggestions are:

1. Decide about a few main objectives for the activity.
2. *Concepts*: Which preconceptions are there? How can these be used productively to move towards the scientific concepts? What could the lab activity contribute? Choose experiments which are meaningful considering the preconceptions of students rather than "standard" experiments.
3. Practice *pre-requisite lab techniques* in a pre-lab or integrate a *check* of these skills in the activity.
4. Choose a few *investigation skills* from the Figure 3 to focus guidance on even if students do a complete investigation. Make sure that during the year all skills get attention.
5. For each activity formulate some teacher questions for:
    a) pre-lab discussion (without giving away the results);

   b) guidance during the activity, to force back-and-forth thinking between concepts and phenomena;
   c) 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? What is the evidence for our conclusions? How can validity and reliability of the experiment be improved?

6. Look for appropriate ways to evaluate student performance. For concept activities this could be a paper-and-pencil test or presentations; for investigation skills it could be observations and interviews during the lab, student worksheets describing proposed experiments or conclusions, a research report, or continuous assessment and portfolio, or performance assessments; lab techniques and measurement skill should be observed/checked during the activity.

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

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