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ABSTRACT

The Prime Minister's Committee on Natural Science in Education in Great Britain reported in 1918 that "...in many schools more time is spent in laboratory work than the results obtained can justify." Seventy years later this conclusion can often still be drawn. This is particularly a problem in open distance education where laboratory practicals, due to philosophical and logistical reasons, must be kept to a minimum and where their implementation must be both effective and efficient. Many feel that laboratory experiments do not usually justify their costs because they are all too often used to achieve the wrong goals. They often focus on the illustration or affirmation of the substantive structure of science, whereas their strength lies in the teaching of the syntactical structure of that same domain. Three common but faulty motives for laboratory experiments were rejected and three new, more valid ones were presented in their place. Finally, three types of laboratory experiments were introduced and paired, on didactic grounds, to the three valid motives. (Author/MVL)

Practicals and the acquisition of academic skills

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Abstract

The Prime Minister's Committee on Natural Science in Education in Great Britain reported in 1918 that '... in many schools more time is spent in laboratory work than the results obtained can justify.' Seventy years later this conclusion can often still be drawn This is particularly a problem in open distance education where practicals, due to philosophical and logistical reasons, must be kept to a minimum and where their implementation must be both effective and efficient. Practicals do not usually justify their costs because they are all too often used to achieve the wrong goals. They often focus on the illustration or affirmation of the substantive structure of science, whereas their strength lies in the teaching of the syntactical structure of that same domain. Three common but faulty motives for practicals will be rejected and three new, more valid ones will be presented in their place. Finally, three types of practicals will be introduced and paired, on didactic grounds, to the three valid motives.

Preface

Practicals are one of the most expensive and time consuming elements of undergraduate science education. As budgets get tighter, the hours and facilities allotted to practicals become less and less. What usually happens is that institutions of higher education, having spent much money on infrastructure (laboratories and apparatus) and having many employees in many different departments (with vested interests and tenure), try to trim down their practicals. They look for 'fat' and 'bone' to cut away and when there is no more fat or bone left, they begin on the meat. The Dutch Open university, which only first opened its doors to students in 1984, doesn't have such an infrastructure. It also doesn't have a myriad of monodisciplinary science faculties but consists of one small interdisciplinary faculty of natural scientists, chosen as much for their educational expertise as their scientific expertise. Finally, the Dutch Open university does not have the mandate to turn out 'laboratory scientists' or 'technicans' but rather to turn out thinking, problem solving academics in the fields of Environmental Sciences, Nutrition and Toxicology, and Policy and Management in the Natural Sciences. With this in mind, the Dutch Open university has chosen to go a different route with respect to practicals. One reason is its philosophy of freedom of time, pace and place of study and the problems that this philosophy causes for practicals. A second, and weightier reason, is its desire (and mandate from the Dutch government) to innovate; to design and administer practicals which are more (and better) than copies of those of others.

In the law which governed the foundation of the Dutch Open university, parliament made clear that this institution was authorised not only to provide higher education to a wide segment of the population which up to then had been excluded from it, but also to act as a motor for innovation in higher education as a whole. The following contribution focusses on this.

This has as its consequence that I will not discuss practicals and the limits which open distance education puts on them. Certainly, I could argue that the constraints of freedom of time, place and pace make it necessary to find alternatives for the traditional laboratory in science education. It is also true that the development and exploitation of laboratories in study centres is a problem, both financially and logistically, for an institution such as the Dutch Open university; and that this forces us to look for new answers which minimise these problems. But that would be too easy an answer. I believe that all of these constraints only make us look harder for curriculum innovation. Practicals need to be revised and used 'properly' in all institutions of higher learning. In this respect, the Open university has a lead on the other institutions. What others usually call a restraint or constraint is actually freedom or latitude.

Practicing science or learning to practice science?

Practical work, usually in the form of a laboratory practical, is intrinsic to science in general and to the natural scientist in particular. How this practical work can best be used in the instruction of future scientists is an unanswered and sometimes hotly disputed question. The origi of this uncertainty may be the failure to distinguish between 'teaching/learning science' and 'doing science'. The aims of the former need not necessarily coincide with those of the latter. In my opinion, educators and curriculum innovators in the natural sciences have operated and reformed on the mistaken belief that the way science is practiced is also the best way to teach and learn science. Their mistake lies in overlooking that students do not practice science but are *learning about* science and/or *learning to* practice science.

Woolnough and Allsop (1985) summed this up by stating that in *teaching science* we should be concerned with introducing students to a body of knowledge and with familiarising them with the way a 'problem-solving scientist' works. The former, the substantive structure of science, is a vehicle in aiding in the understanding and enjoyment of science. The latter, the syntactic structure of science, is a vehicle in helping students to develop certain habits or skills and to use them. This is the crux of the problem: practicals are all too often used for teaching, affirming or illustrating the substantive structure whereas they are more suited for conveying the syntactic structure of a natural science.

There are many techniques available for the teaching/learning of the substantive structure of a knowledge domain. These techniques may be passive of active, may be based on reception learning or discovery learning (Ausubel, 1963), may be oral, written or electronic, etc. What binds the techniques together is that they have as goal the conveyance of the structure (the facts, rules, principles, concepts etc.) of a knowledge domain. This paper, although acknowledging that this is an important facet of education (or stronger still, is indispensable for learning the syntatic structure of a domain as is evident in the introduction of the cognitive phase in skill learning later in this paper) will not deal explicitly with this problem. This paper will further only discuss different aspects of the teaching/learning of the syntactic structure of (the habits and skills of those soon to be practicing in) a certain domain.

Academic skills

What we as educators should be trying to convey to students are certain habits and skills. Since the Open university is an institute for higher education, where the primary goal is to promote a critical, academic attitude in its students, we will limit our skills training to academic skills (as opposed to a vocational or technical institution whose aim is the promotion of technical and/or motor skills).

The statutes governing the Open university, ratified by the Dutch parliament in 1979, described these academic skills as: '..., those things a person can do with knowledge. Examples are general intellectual activities such as problem solving, evaluation and analysis or more specific behaviours such as the interpretation of research data or the writing of reports.' The Department of Natural Sciences, in their curriculum white paper in 1987, defined its goals in similar terms. Although no one denies that certain technical or motor skills may be necessary for achieving these goals, they are not in themselves goals of the educational programme.

Consequently, we define practical work very broadly as any activity relating to experimenting, starting with ascertaining that there is a problem which must be solved, through devising, evaluating, choosing and executing a solution, to reporting, discussing and ascertaining if the solution is satisfactory or if the process must be restarted on the basis of new ideas and conceptions. This definition puts practical work very close to the concept of 'problem solving'. Practicals may take the form of demonstrations, experimental seminars, real or wet laboratories, pen and paper experiments, simulations, etc.

In this light, academic skills are comparable to cognitive strategies as defined by Gagné in his 1977 revision of The Conditions of Learning (3rd edition). He defines cognitive strategies as 'learned skills which manage (the student's) own learning, remembering, and thinking ... certain techniques of thinking, ways of analyzing problems, approaches to the solving of problems.'

Teaching and learning of skills

Educators and psychologists tend to agree on the character of and the conditions necessary for the learning of skills, be they (psycho)motor or academic ones. A *skill* is characterised by a proficiency in a task, usually a specific task.

Skills refer to 'being able to do something' rather than to 'knowing something'. Skills are further characterised by a succession or sequence of activities, each of which is in itself a simpler skill or subskill. These simpler skills, when properly executed in the right order, combine into more complex skills. A typical example in natural sciences can be found in doing ethological research on animal behaviour. A student must recognise that a type of behaviour has been exhibited, discriminate between different types of behaviour, categorise the types, hypothesise about the relationships, statistically evaluate the hypotheses and draw conclusions. Although this may seem complex, it is a fairly simple skill because the preceding skills (determining whether or not behavioural research is warranted and devising an experiment) and subsequent ones (evaluation of the results aimed at redesigning the research) have not been taken into account. This is not to imply that the only measure of complexity of a skill is the number of relevant subskills which it entails, but rather that it is an often used and useful measure of complexity.

The quality of the relationships between subskills also plays a role in determining the complexity. The more intertwined or interrelated the subskills are, the more complex the skill tends to be.

Fitts and Posner (1967) define three phases in the acquisition of complex skills. The first phase, the early or *cognitive phase*, consists of the learner's orientation on the specific skill on the basis of instruction. The beginnen tries to understand the task and is often able to perform it in a crude fashion. In other words, a certain knowledge of the substantive structure of a domain is a prerequisite for the learning of a skill. He/she learns to observe and to understand what a task involves and how a task is carried out. What the learner knows determines what the learner sees. An empty mind 'sees' little and understands even less (Wellington, 1981).

In the second phase, the *intermediate* or *associative phase*, practice and feedback play a dominant role. New patterns of skill components are tried out and inappropriate actions are gradually eliminated. Gradually, the student learns to act in the required manner; the skill is gradually refined. Ample practice in phases makes skills more polished and easier to apply. Feedback should not be limited to informing the learner as to the 'correctness' of what he or she has done. It should explain how and why things went wrong or could have gone better. It should also allow for discussion or argumentation with others and for internal reflection.

In the third phase, the final or *autonomy phase*, the learner gains speed, control and coordination of the different subskills which make up the skill. The component process become increasingly automatic, less subject to interference from other tasks. The learner will eventually be able to carry out a complex skill as an uninterrupted unit instead of as a series of simpler subskills.

I will return to these phases later, when I discuss the three motives for practicals.

Currently held motives for practicals

I stated at the beginning of this paper that the currently held motives for implementing practicals in a science curriculum are primarily based upon the premise that practicals should be used for the acquisition, illustration or confirmation of the substantive structure of science. Gardner (1975) defines the substantive structure of the natural sciences as 'the network of related theories and laws and concepts that individual researchers bring to bear when they set out to solve problems in their discipline'. The premise that practicals should be used for the substantive structure is based upon the idea (or rather: the misconception) that the process of learning science is or should be equivalent to the process of scientific inquiry. This idea that learning science is equivalent to doing science is, in my opinion at best debatable and at worst faulty. Scientific inquiry is the systematic and investigative performance ability which incorporates unrestrained thinking capabilities after a person has acquired a broad critical knowledge of the particular subject matter through formal learning processes (Kyle, 1980). As stated above, teaching/learning science is something quite different. This (faulty) premise has led to the general acceptance of three motives for implementing practicals.

The first motive is that the value of a practical lies in its *service* (or possibly subservience) *to scientific theory*. In this way, it is almost solely used to illustrate or affirm theories taught in another setting. The problem is that students are not real scientists and their apparatus is often a weak derivative of real research equipment; so their attempts to affirm theories often end up as mere affirmations of nonexistant and wrongly inferred ineptness. This is not only didactically weak but potentially harmful to the student's motivation. Furthermore, it appears that even if the student succeeds in affirming a theory or viewing a phenomenon, that this does not usually add much to the already available written or verbal information. Mixing two chemicals and seeing a precipitate does not increase the learner's understanding of chemistry. It may, however, lead to a 'fixation' or 'stabilisation' of a theory. Finally, proponents of the first motive tend to also believe in the 'if-you-do-it-yourself- it-sticks' notion; a variation of this we shall see in motive two. The problem here is that students often are unable to explain what they did or why they did it, even immediately after the practical (Tamir, 1976; Moriera, 1980).

The second motive is based upon the belief that *discovery* (preferably in a laboratory) is the only way to achieve *meaningful learning*. This view has its origin in the misinterpretation of David Ausubel's ideas on the psychology of meaningful verbal learning. Proponents of this second motive equate reception learning with rote learning and discovery learning with meaningful learning (Novak, 1978; Summers, 1982). They see this as a one-dimensional continuum (see figure 1).

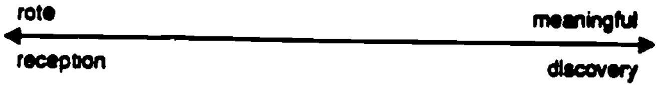

figure 1
A one dimensional misrepresentation of the ideas of Ausubel (Summers, 1982).

Ausubel (1963, 1968) actually went to great lengths to dismiss this myth, as can be seen in the following citations

> "The distinction between rote and meaningful learning is frequently confused with the reception-discovery distinction... This confusion is partly responsible for the widespread but unwarranted twin beliefs that reception learning is invariably rote and that discovery learning is inherently and necessarily meaningful (1963, p. 18). It should then be clear that verbal reception learning can be genuinely meaningful and that the weaknesses attributed to the method of expository verbal instruction do not inhere in the method itself but are derived form various misapplications" (1963, p. 17).

Thus Ausubel's ideas are actually better represented in a two-dimensional matrix, as shown in figure 2.

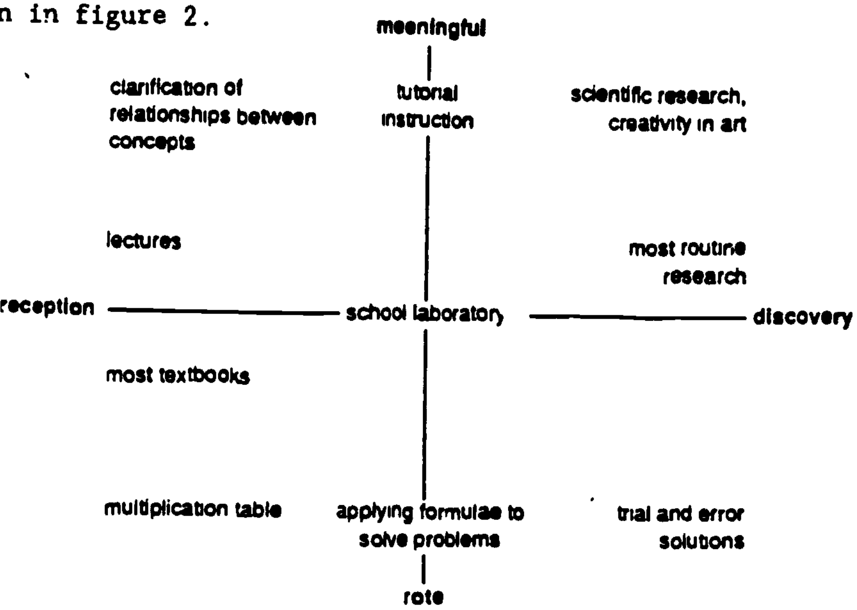

figure 2
The map of learning, after Ausubel (Elton, 1987).

To quote Ausubel (1963) for the last time:

> "In laboratory situations, discovery learning also leads to the contrived rediscovery of known propositions... Typically, however, the propositions discovered... are rarely significant and worth incorporating into the learner's subject-matter knowledge. In any case, discovery technics hardly constitute an efficient primary means of transmitting the content of an academic discipline" (p. 17).

The third, and final, motive is based upon the (mis)conception that the learner will *distill insight and understanding* from empirical work with phenomena. There are basically four problems with this conception. Problem number one is that the acquisition of understanding demands a *rich educational environment*. This is a prerequisite to all types of learning. Wellington (1981) called this his objection to the empiricist view of discovery learning. Observations and experiences do not give rise to knowledge and conceptual structures, but are rather determined by them. Without a good conceptual framework, meaningful observation (including the interpretation of those observations) cannot take place at all. Suchman (1966) in his model for the analysis of inquiry posited that the meaningfulness of an encounter (an experience with sensory data) depends on the kind of relevant information we already possess. Some kind of 'organizer' is required that allows us to select out and pattern certain aspects of an encounter. The application of an 'organizer' yields meaning. In science education, ideas and concepts are brought to bear on observations; they are not derived from them. In other words, what the learner knows determines what the learner sees. An empty mind sees little and understands even less.

Problem number two is that scientific theories are for the most part *abstract*; they deals with theoretical concepts and their interrelationships. Because they are abstract, they should also be considered and manipulated in the abstract (Woolnough et.al, 1985). It is essential that these concepts be separated from their concrete reality if the 'maturing scientific mind' is to gain mastery of them. Students are misled and their thinking is restricted when they are given the appearance of relating (or being able to relate) everything to lab experience. Furthermore, many scientific concepts have no observable instances at all so that they cannot be manipulated at all.

Related to the previous problem is problem number three (also documented by Woolnough et.al.), which is simply that reality tends to *clutter and distract*. Wrong or irrelevant observations thus waste valuable time and money. Because of this, basic theory can probably better be taught through lectures, workgroups, tutorials, written material, etc. than through practicals.

Problem number four is that even if the first three problems did not exist, the amount of experimenting and practice necessary to make enough observations to distill insight and understanding is so large, and would require so much time, energy and resources (both physical and monetary) that implementation would be impossible. A learner, even the most brilliant or highly gifted one, will not be able to derive meaning from a single instance of a phenomenon.

To recap, the in my opinion faulty motives[1] are based upon the notion or belief that because scientists discover new aspects of the substantive structure of science through the practicing of science, the logical conclusion should be that the teaching of this substantive structure should be done in the same way. What educators who adhere to this belief forget is that we are not *letting* students 'do science'. We are *teaching* students about 'doing science' and we should use our practicals to achieve just this!

A new basis for practicals

Practicals can better be used to introduce students to, and let them become proficient in the syntactical structure of scientific knowledge. Gardner (1975) defines this as 'what pathways of enquiry they [the scientists, PK] use, what they mean by verified knowledge, and how they go about this verification... Syntactical structure is concerned with issues such as the way in which new substantive concepts are formed, and the ways in which different kinds of knowledge statements generated by the discipline may be validated'. In the context of this paper, syntactic structure is those thinking and reasoning skills used by academicians within a discipine. This premise that practicals are best suited for the teaching/learning of the syntactic structure of science brings with it three new, more valid motives for implementing practicals in science education. The first motive is that practicals are best suited for helping develop *specific skills*[2].

Examples of the skills that could or should be developed are: discrimination skills, observation skills, measurement skills, estimation skills, manipulation skills, planning skills, execution skills and interpretation skills. This list is not exhaustive and I am sure that the reader can come up with a number of skills him/herself. The types of skills and subskills are varied in nature, but their attainment is based on two simple, underlying principles.

1: Insitutions for distance education add two extra motives which can be mentioned here. The first motive can be called an equivalency motive. Mora et al (1986) in an article on residential physics workshops (summer schools) state that the 'degrees awarded by UNED [Universidad Nacional de Educación a Distancia] represent the same level of achievement as degrees from other Spanish state universities. (...) Laboratory work is therefore compulsory ...' In other words, we do it like this because 'real universities' also do it like this. This is not a very relevant didactic motive.

A second, for distance education specific, motive can be called a social motive. Students at distance universities are geographically isolated. They are cut off from contact with faculty and each other. This (feeling of) isolation is in turn seen as a primary reason for high high drop-out rates. Practicals are thus seen as a vehicle for removing this feeling of isolation and lowering the drop-out rate (Mora et. al., 1986). This 'hidden objective' has nothing to do with the nature of learning science and may not be used as such.

2: Because this paper deals with practicals in an academic and not a vocational or technical setting, the skills discussed will be primarily of an academic nature.

Those principles are *practice* and *feedback*, the chief components of the fixation phase of skills attainment. Of course, this presupposes the attainment of certain skills and knowledge in the cognitive phase. This way, the practical is clearly not subservient to the theory but is complementary to it. Both are necessary for attaining the skill. In the following section I will discuss which type of practical is best suited for achieving these ends.

The second motive is that practicals are suitable vehicles for the learning of the '*academic approach*' to working (especially as a scientist). Scientists, but for that matter all academicians, are problem solvers. Their method of working entails (at least) the following skills:
- studying a situation and acknowledging that there is actually a problem to be solved
- defining the problem to be solved
- seeking alternative solutions/solution strategies for the problem
- evaluation of the alternative solutions/solution strategies for the problem
- specifying or choosing the 'best' solution strategy
- solving the problem
- evaluating the solution and studying the solution with respect to determining whether a new problem need be acknowledged, in which case the procedure starts all over again.

This iterative procedure, characteristic for problem solving, is graphically rendered in figure 3.

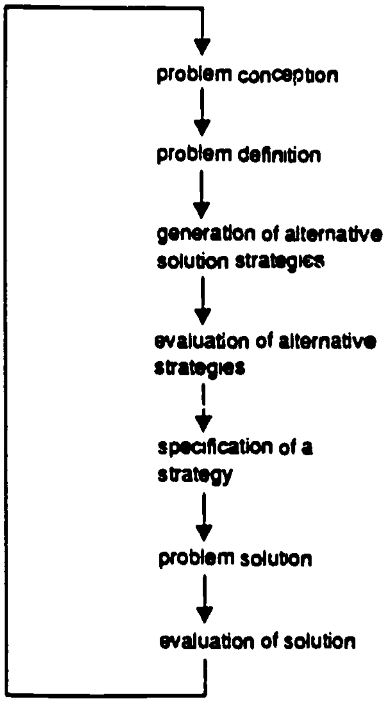

figure 3
Academic problem solving.

Here again, the practical has its own raison d'être. Expository, substantive knowledge, gained in the cognitive phase, is a prerequisite for attaining the desired ends. This knowledge is a knowledge of methods and techniques, a knowledge of one's own domain (theories, principles, concepts and facts) and a knowledge of related domains. As Kyle (1980) put it, 'prior to successful, productive and useful scientific inquiry a person must acquire a broad and critical knowledge of the subject matter (the learning of basic competences). After this the person can then learn to synthesise concepts rationally, inquire scientifically and solve problems via unrestrained inductive thinking.'

Practicals, on the other hand give practice and an opportunity to develop competence in learning to investigate; in learning to solve problems. Further, the ability to *discuss*, *reason* and *compare* what a person has done with others (be it a model, another student or an interactive electronic medium) is a necessity for attaining these (sub)skills.

The third motive for implementing practicals in science curricula is to allow students to *experience phenomena* and that which accompanies such pheromena, and in doing so to gain a *tacit know edge* of different scientific phenomena and their settings. This is quite different from the motive rejected in the previous section. What is attempted is not the gaining of insight or understanding of phenomena through practicals, but rather getting a feel for phenomena. This 'experiencing' of phenomenon is possibly best characterised by the German word 'Fingerspitzengefühl'. It is the obtaining of an implicit, often indescribable, feeling as to what is happening or what is supposed to happen, as opposed to the explicit knowledge of how something works or why. As a geologist, discussing the necessity of a mineral sample kit in an introductory geology course, once said to me: 'The student does not need the kit to learn to distinguish and identify minerals. The student needs the kit to feel, smell and taste the minerals.' This feeling or tacit knowledge often cannot be expressed in words, either to oneself or to others, but can be strengthened or directed through discussion with others.

Types of practicals, their characteristics and their relation to the new motivation

In a recent review of the literature, Kirschner and Meester (1988) distinguished three major types of practicals, namely simulations, experimental seminars and 'wet' laboratories. *Simulations* are, generally speaking, organised experiences where reality or a part thereof is imitated such that the experiences are more easily repeatable, safer and usually less expensive to achieve than reality itself.[3] Excepting real-time simulators, simulations also work more quickly than reality. Finally, simulations can usually be quickly redone and can be accompanied by immediate feedback as to the correctness and precision of what has been done and by explanations as to what has gone wrong (or right!).

Experimental seminars is an approach for undergraduate students in natural sciences first proposed by Conway, Mendoza & Read (1963). Here students cooperate in the performance of an experiment collectively or by watching an expert perform an experiment. This way they may gain a clear concept of how a well- performed experiment progresses. Collective experimentation or demonstration is followed by group discussion, where necessary stimulated by an 'expert' (teacher/lecturer/ professor) and in which the students can help each other. An experiment which is routine and uninteresting to one or two students can trigger a valuable discussion in a group. This provides the student with a model for problem identification, experimental design, assembling, testing and calibrating equipment, data collection, analysis, interpretation and reporting of results.

Characteristic for this type of practical is the possibility to practice, discuss, reason and compare methods and results with others. Such an experimental seminar can of course be 'modernised' to make use of more advanced techniques such as video, interactive video disc or CD-ROM.
'Wet' laboratories are the most common type found in science curricula; they provide hands-on experience in a laboratory setting. These laboratories can be formal laboratories (also known as convergent or cookbook labs), experimental laboratories (also known as open-ended or discovery labs), or divergent laboratories (a compromise between the two previous labs and often called guided-discovery labs).
Regardless of the type of wet laboratory, each of them is characterised by concrete, hands-on experiencing of phenomena.

Looking back at the three 'new' motives for practicals, it is not hard to pair each motive with a type of laboratory. This is not to say that each laboratory type is uniquely suited to that particular motive, but rather that a certain type of laboratory is better/best suited to a particular motive. Simulation is a reasonable vehicle for developing specific skills, where practice and feedback are of the greatest importance. Experimental seminars, where discussion, comparison and modelling play such an important role are well-suited for helping students achieve an academic approach to working. Wet laboratories, finally, are the best, and possibly the only way to experience phenomena.

Conclusion

Practicals are an essential part of the science curriculum. This is a truism which cannot be disputed. What can be disputed are the motives for their use. As vehicles for the teaching/learning of the substantive structure of the scientific domain, they are not very useful, and very poorly equipped. They can be likened to the use of a pushcart to move the family and all the household effects. A pushcart may indeed accomplish the job, but it will take an long time and enormous effort to do it this way; probably more time and more effort than is available.

On the other hand, practicals are the proper vehicles for the teaching/ learning of the syntactic structure of the scientific domain. Practicals then become the removal firm using a removal van and a crew of four to pack, load, transport and unload all of the family's household effects. They accomplish the job efficiently, effectively and with a minimum of problems.

The questions are not whether practicals should or should not be used, whether practicals are or are not effective, or whether more or less time should be spent on doing practicals. The questions are:
- Do we want to continue using practicals for the wrong motives?
- Can we afford, both in terms of lost learning and misused resources, to use practicals for the wrong motives?
- Are we bold enough to attempt to use practicals in a new and innovative way?

3: A warning for the reader. Although a computer will often play a role in simulations, the concept used here is much broader and can include groupwork (with or without a tutor) gaming, etc..

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