Higher Education 17: 81–98 (1988)

The laboratory in higher science education: Problems, premises and objectives

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Abstract. A university study in the natural sciences, devoid of a practical component such as laboratory work is virtually unthinkable. One could even go so far as saying that it is extremely rare for anyone to question the necessity of laboratory work in either high school or university science curricula. Laboratory work is simply part of the science game. This article discusses the problems concerning the use of the laboratory as didactic tool in the educational process, the premises underlying its use in science education and different approaches to its implementation as described in recent literature. This article is primarily directed at a clarification and explicitation of objectives and of their implementation in laboratory work at the Dutch Open University. The effective and efficient use of time spent in the laboratory is a necessity for all educational institutions, but especially for an institution for distance education.

Introduction

The Dutch Open University is an institution dedicated to providing higher distance education to all those above the age of 18. Because it is an institution for distance education, whereby an attempt is made to offer the student maximal freedom to study where and when she or he wants, those aspects of the educational process which require the student to spend a great deal of time in a specific place (and at specific times) must be kept to a minimum. This philosophy poses a large challenge for the Faculty of Natural Sciences which offers diploma programs in both Environmental Sciences and Nutrition and Toxicology. Laboratory work traditionally requires that students spend a great deal of time working in a laboratory.

In an attempt to keep compulsory attendance in the laboratory to a minimum without sacrificing the learning objectives which can only be reached in a laboratory setting, the Department of Educational Technology together with the Faculty of Natural Sciences are engaged in a research project whose goals are fourfold:

- The elucidation and enumeration of the problems, premises, and objectives of practical work as found in recent literature;
- The selection of those objectives which the Faculty of Natural Sciences aspires to impart to its students;
- A well founded allocation of educational media (printed matter, computer

assisted learning and simulation, audiovisual media, tutoring and laboratory work) for maximum effectivity and efficiency;
- Testing and maximization of the allocated media.

This article hopes to signal the achievement of the first goal and in doing so attempts to review the problems with (and facing) laboratory instruction, and the premises employed by those espousing experimentation and labwork as a didactic technique for students in the natural sciences. The drafting of a list of (global) objectives, which teachers aspire to reach with practical work, turned out to be a very difficult task. A great many different objectives are attached to practical work, formulated from very general to very specific and from student-oriented to teacher-oriented. One of our goals in writing this article was to inventory and catalogue all these objectives. It concludes therefore with an appendix in which possible specific behavioral objectives for practical work in the natural sciences as found in the literature are enumerated.

Methodology

This paper reviews recent literature dealing with the objectives or aims of science laboratory use in the natural sciences. As stated in the introduction, it is a first step along a path that will hopefully lead to the implementation of well thought-out, effective and efficient laboratory education at the Dutch Open University. When we first began with this project, we expected to easily find a wealth of literature containing an exhaustive explication of aims and objectives for this didactic tool. This was, sadly enough, not the case.

An on-line literature search in ERIC (Educational Resources Information Center), Dialindex, Biosis (Biosciences Information Service) and INSPEC, with as limiting factor a publication date not earlier than 1970, yielded more than thirty sources of information dealing with the aims and objectives of science laboratories in one way or another. The bibliographies of this literature led to other literature also dealing with this subject. None of the literature, however, produced an exhaustive list of objectives. This fact was in essence the birth of this paper.

The laboratories and laboratory types described in these article are primarily freshman and sophomore university science laboratories in the United States, the United Kingdom and Australia. The articles report either on practical problems encountered in the laboratory, experimental research on the attainment of certain objectives, or theoretical articles on the laboratory as didactic tool. Our paper is a systematic bundling of these practical experiences and theoretical exercises into one.

Finally, one last comment on terminology. We use the term "practical work" for any activity relating to experimenting, such as demonstrations, real laboratories, pen and paper experiments, computer simulations, etc. "Laboratory work" is that subset of practical work performed in the laboratory itself (Henry, 1975).

Problems

Laboratory work is intrinsic to science in general and to the scientist in particular. But how this same laboratory can best be used in the instruction of future scientists is still an unanswered and, sometimes hotly disputed, question.

Flansburg (1972) found that, while new curricula stress the processes of science, emphasizing higher cognitive skills such as concept attainment, problem solving and critical thinking, students completing science courses involving laboratory work can do little, if any, better on examinations than students completing equivalent courses not involving laboratory work.

As a matter of fact, though experiments may aid in postulating a problem, they sometimes prove not only to be superfluous but actually harmful in achieving those skills which they hope to be helpful in attaining. Kreitler and Kreitler (1974) attribute this harmful effect to the diversion of the learner's attention from the essential theoretical features of the problem with a concurrent fixation of attention on "salient aspects" of the concrete situation. It seems that we are confronted with a *paradox*. A degree in the natural sciences (physics, chemistry, biology) that does not include a rather large amount of laboratory work (measured mostly in time spent in a laboratory) is considered at best a "second-rate" degree. At the same time, it sometimes seems that the only skills which this laboratory work appears to excel in achieving are the lowly-regarded manipulative skills (Aspden, 1974). Why then do we insist on long hours of laboratory work?

Although this problem is particularly salient at institutions dedicated to distance education, it is quickly becoming current at regular universities and (poly)technical colleges and universities. There is a move among administrators to either discontinue or cut back on laboratory instruction in undergraduate science courses. The basic arguments for this movement are:

- Laboratory instruction is very expensive, both for personnel and for material.
- The laboratory and laboratory instruction is not generally perceived of as a worthwhile learning experience.

Our review of the literature yields the following criticism (both from students and staff) of practical work.

- There appears to be an overall agreement that laboratory work at present provides a poor return of knowledge in proportion to the amount of time and effort invested by staff and students. This does not mean that laboratory work is not important, but rather that the skills and knowledge gained from this work is small in comparison to the time and effort spent to gain this knowledge. This criticism is compounded by the earlier stated tendency towards the emphasis of higher order cognitive skills such as concept attainment. Whether one is an adherent of the discovery method (Bruner) or the expository method (Ausubel, Carroll) of concept attainment, one feature common to both approaches is the necessity of repeated exposure to instances of a concept. An experiment may provide a demonstration of a concept, but it is only one, single demonstration. Since concept formation requires exposure to a maximally wide range of instances, it follows that performing an experiment, which is costly in both the time and resources, can scarcely be considered an economical and efficient means of achieving concept formation (Kreitler & Kreitler, 1974).

- All too often, the work done in a laboratory simply verifies something already known to the student. Most agree that work of this type tends to reduce or eliminate the motivation to investigate, providing a disservice to both the student and the discipline (Thomas, 1972; Flansburg, 1972).
- Allied to the preceding is the criticism that schools (both at the secondary and tertiary levels) waste too much time having students perform trivial experiments (Tamir, 1976).
- It is not at all uncommon to find a student who shows absolutely no understanding of the processes and techniques which he or she applied even a day earlier in the laboratory. It is actually quite easy to perform practical work which does not involve any (sic) thinking at all (Tamir, 1976; Moreira, 1980).
- Exercises are sometimes of a nature which tend to overwhelm the student. Non-trivial experiments tend to expect the student to solve problems beyond their comprehension in a period of time much too short to allow for completion. The abundance of information necessary to assimilate inside the laboratory along with the burden of reporting (writing up) outside of the laboratory tends to result in laboratory journals evidenced by minimal thinking (Thomas, 1972).
- Students almost never have the chance to spend time watching an expert (a scientist) do an experiment. There is thus a painful absence of a model which might set tangible standards as well a clear concept of how a well-done experiment progresses (Conway, Mendoza & Read, 1963).
- The supervision of laboratory work is often inadequate,
  - assessed work is not marked and returned within a period of time so as to have an effect on learning,
  - assessment (and penalization) is often arbitrary and has little teaching value,
  - constructive feedback is often lacking (Reif & St. John, 1979; Court, Donald & Fry, 1976; Fowler, 1969).

- Finally, practicals are often seen as isolated exercises, bearing little or no relationship with earlier or future work (Thomas, 1972).

All in all, with our present system of teaching natural, and thus experimental science, it is not hard to understand why it is necessary to review and revise our approaches to the science laboratory as a didactic tool within the natural sciences curricula. The question then is: How can experiments be used in science education to further, instead of to hamper, the attainment of educational goals? In order to arrive at and formulate even a tentative answer to this question, a careful analysis of the premises and didactics underlying practical work and the general objectives aspired to by science curricula is required. This must be coupled with a search for the optimal means available for achieving these objectives which, as stated in the introduction, is planned by us for the not all too distant future. Such an analysis could function as a framework into which laboratory work can be used as an efficient, effective and scientifically meaningful educational tool.

Premises

Those involved in the educational process in tertiary education, be that higher technical education or university education, hope to achieve a *wide spectrum of aims*. Educators expect that during the educational experience, students for example should acquire a body of knowledge, should develop the ability to learn independently, should be able to solve (complex, non-trivial) problems, should exhibit an academic and critical attitude towards that which they read, hear and do, should be able to express themselves, both in writing and orally, and should develop an appreciation of the subject area studied in general and the techniques and methodology of a subject in particular (Kay, O'Connel & Cryer, 1981). Each aim aspired to must be matched by appropriate teaching methods on the part of the educators, study activities on the part of the student, and evaluation and observation by both.

Although curricula tend to differ from one another in structure, sequence, content, underlying ideologies, and explicit, declared objectives, they almost all have one major thing in common: they almost all share a traditional *emphasis on concrete demonstration* of theories and principles in general and on *experimentation* in particular. Kreitler and Kreitler (1974) postulate that this emphasis is highly reminiscent of the old functionalist dictum "we learn by doing" and reflects the nineteenth century conception of the scientist as an ingenious inventor and skillful performer of experiments. Thomas (1972) was even more critical when stating, "that scientists do laboratory work is one of the fundamental tenets of our dogma; rarely does anyone question its necessity".

A thorough review of available literature on laboratory instruction collaborates the four major rationales or premises which are posited by Tamir (1976) for the emphasis on and extensive use of the laboratory in the teaching of the natural sciences. Firstly, scientists and educators in the sciences posit what can be called the *illustration and concretization rationale.* This rationale states that science is by nature a highly complex and abstract subject matter area. Students are generally not able to grasp these complex and abstract concepts without the concrete materials and possibilities for manipulation which the laboratory offer. Although it is not our intention to dispute this premise here, it is necessary to place a critical question mark as to the viability of such a premise.

Toothacker (1983) points out that according to Piaget (1964) the ability of a student to design and carry out an open-ended, inductive laboratory experiment is dependent upon the student's ability to carry out formal reasoning operations. Toothacker goes on to state that recent reports show that only one third of beginning university students are actually in the formal reasoning stage. Another third of the students can be classified as being completely in the concrete, operational stage. The remaining third is in a period of transition between those two stages. If this is the case, approximately two-thirds of those students making use of the opportunities offered are not intellectually ready for or capable of inductive experiments. At best then, these experiments are a waste of time and money, at worst they are a demotivating experience for the student.

The second rationale deals with both *cognitive and affective aspects* of science education. It implies that student participation in the laboratory experience, that is in the actual collection of data and the analysis of real phenomena, gives the student an appreciation of the spirit (sic) and methods of science. This participation also promotes problem solving behavior as well as the ability to analyze, synthesize and elaborate that which is learned. This rationale also implies that participation in enquiry develops important attitudes and provides confidence in acquired scientific knowledge (Henry, 1975). Here too is a need for a critical remark. This rationale implies that the acquisition of such attitudes is also "learned by doing" or just magically happens.

There are science educators who tend to repudiate vehemently such an assumption. Read (1969) charges that "scientific attitudes of mind must be taught, both by criticisms of students efforts and by examples. The sooner this is taught, the better since these attitudes are the essence of experimentation".

The third rationale, which we will call the *psycho-motor skills rationale,* states that practical experiences are necessary for the learning and development of the techniques necessary for fruitful laboratory work and that these skills have a wide range of generalizable effects. It is quite possible that these skills could be acquired by a means other than the traditional laboratory. The fourth rationale, a *motivational rationale,* states that students enjoy activities and practical work. This enjoyment consequently leads to a greater motivation towards and interest in science. Fowler (1969) in an unpublished paper on objectives for the introductory physics laboratory goes one step further. He posits two axioms for the laboratory as educational medium. Axiom 1 states that it is in the lab and only in the lab that the student can experience physics as it actually is. Axiom 2 states that for learning to take place most effectively, the student must be motivated through interest. We must assume that those espousing this rationale vehemently oppose the programming of trivial, verification experiments.

General objectives of laboratory instruction

As stated in the introduction, the first goal which our research project hopes to achieve is the clarification and enumeration of the premises, problems and objectives of laboratory instruction as found in recent literature. The problems with and premises underlying the use of the laboratory as educational venue have received explicit treatment in the preceding pages. Many implicit objectives intended to be reached through practical, especially laboratory, work have also passed the review. The time is now ripe to explicate those implicit objectives and bring them into the light.

Any attempt to assess to what extent student practical work achieves the objectives it is hoped to achieve is thwarted by two very serious problems (Toothacker, 1983). Problem one is that most faculties have a (historically and culturally) deep-seated belief that laboratory work is necessary and, if called upon, will produce reasons for this need. Problem two is that there is no universal accord as to what the objectives of (introductory) practical work are.

In our review we have found that most agree that the laboratory should be used to teach some general intellectual skills likely to be useful to students in their future work. These skills should be those which practicing scientists and professionals commonly use, and which can be effectively taught and practiced in the laboratory context. However true this may be, it does not help us in getting any further. Other points of major agreement are that:

- Using laboratory work to illustrate a lecture (theory) is inefficient use of the laboratory.
- Measurements themselves are often less important than learning to recognize, estimate, eliminate and analyze errors.
- Teaching laboratory skills through detailed instruction is an admirable way to train technicians, but is of little value for (the training of) scientists.

Attempts to organize the objectives of the science laboratory are hindered because the stated objectives are either so *detailed* that they can only be of use in specific laboratories in specific disciplines or are so *general* that they can include almost anything one can think of (i.e. imparting information, training basic processes and building up adequate motivation). We have catalogued more than

120 different specific objectives for science practical work which we have divided into eight, student-centered general objectives.

These general objectives are:

- To formulate hypotheses.
- To solve problems.
- To use knowledge and skills in unfamiliar situations.
- To design simple experiments to test hypotheses.
- To use laboratory skills in performing (simple) experiments.
- To interpret experimental data.
- To describe clearly the experiment.
- To remember the central idea of an experiment over a significantly long period of time.

These general instructional objectives as well as the specific behavioral objectives which they cover can be found in the appendix.

Didactics

The unique contribution of practical work in science instruction should be its ability to aid in the development of conceptual thinking, stir the imagination, whet the appetite and hone the methodological sharpness of those taking part in the experimental experience. We have however noted, that experiments are sometimes useless – let alone harmful – in achieving these sometimes far reaching sometimes more mundane goals as problem solving, concretization of theory and the acquisition of conceptual knowledge. Many researchers have also noted that laboratory work appears only to excel in transmitting psycho-motor, manipulative skills which are more at home in professional schools than in academic environments. Let us now turn to look at some didactic aspects of practical instruction which aim to increase the value of laboratory work as an educational strategy. As we have already noted, teachers in tertiary education have a wide diversity of objectives which they attempt to achieve or, better said, have their students achieve.

The teaching of basic general (intellectual) skills requires caution for the instructor with respect to an overemphasizing of details or formalism. Such details, without the presence of global insights as to the value setting of those details in relation to other details (be they facts, laws, theories, techniques, etc) are all too often applied by rote, sometimes wrongly, and quickly forgotten. What is necessary, and useful, is stressing the qualitative (and semiquantitative) aspects of that which must be learned in order to provide essential insights, which can easily be applied, elaborated upon and transferred to other situations so as to facilitate the learning of more detailed information.

This problem led Reif and St. John (1979) to the conclusion that to attain the higher level intellectual (laboratory) skills (for example: developing hypotheses or performing, describing or modifying experiments) it is crucially important that the relevant information be efficiently organized in a person's mind. They operationalize this efficient organization as hierarchical, goal oriented, multi-session work with explicit judgement criteria, flexible formatting and a timely weaning of instruction. It is quite possible that these principles may form the foundation upon which the didactics of laboratory instruction or the use of the laboratory as educational medium at the Dutch Open University will be constructed. A future article will cover this topic.

In their attempt to include the laboratory in the daily experience of distance education, the British Open University has for the most part abandoned the idea of doing standard experiments or long projects which are supposed vaguely to aim at contributing to all objectives simultaneously. Instead, according to Aspden (1974) they have produced a range of practical experiences. These experiences vary form "string and sealing wax" experiments that emphasize fundamental principles of instruments to the "thought" experiments on the computer where there is no real experiment at all but the emphasis is on the theoretical concept. In between come experiments to train students to make accurate measurements, and experiments where it is the *handling* of data once taken that is important. They believe that their future lies with "experimental experiences" tied to specific and perhaps limited objectives. This is a policy that they intend to pursue more purposively.

Laboratory assessment must not be forgotten when discussing the didactics of the laboratory as educational method. Court, Donald & Fry (1976) took time to scrutinize *assessment problems* with respect to teaching experimental physics. They conclude that a practical examination should not form a part of a course dedicated to the teaching and application of laboratory skills in performing experiments. Examination, they state, has little teaching value and is unreliable in assessing the formative objectives of such a course. They argue that there must be a clear separation of the functions of teaching and assessment. Penalization for mistakes does not advance learning where skills and techniques are learned. Assessment of experimentation should occur only after the student has completed the experimentation to his or her *own* satisfaction.

Approaches to laboratory instruction

Student laboratories can be roughly divided into three distinct approaches to learning and instruction.

First, we can distinguish the *academic or formal laboratory*. Other names for this didactic approach are traditional, structured, convergent or cookbook laboratories. These laboratories function primarily to verify the laws, principles, concepts and facts taught in lectures and given in textbooks. In such laboratories the student is told exactly what to do. The student must complete her or his experiment in a rigidly set time and should arrive at the (implicitly implied or explicitly stated) expected results. Since the experiment is a mere extension of the lecture or textbook, often very little attention is paid to the apparati in the lab. Lab reports made by students are seen as mere obligations and bear little resemblance to reports made by professional scientists. Experimentation is "de facto" forbidden in the academic or formal laboratory.

A second approach is what can be called the *experimental laboratory.* Other names for such an approach are open ended, inductive, discovery oriented, unstructured project or undergraduate research laboratories. In the experimental laboratory, in contrast to the academic laboratory, the student is presented with problems in experimentation meant to challenge her or his understanding and creativity without being so complex as to be unresolvable. Instructions are general except in cases where a mistake would be costly or dangerous. The student learns to solve problems, use more modern equipment (due to the research character of such a lab situation) and analyze results. She or he is also encouraged to consult the literature, question, think and initiate. The experiments themselves are often designed to show the limitations of theory while at the same time showing the necessity of theory in carrying out meaningful experiments through illustration of "the profound differences as well as the complex interdependency between theoretical and experimental" science (Robinson, 1979).

The last approach can be regarded as a realistic compromise between the experimental and the academic laboratories and is called the *divergent laboratory* (Lerch, 1971). In the divergent lab, there should be parts of the experiment that are predetermined and standard for all students, but there should be many possible directions in which the experiment can develop after the initial stage. The divergent lab would provide the student with tasks similar to those encountered in an open ended or project (experimental) lab within a framework that is compatible with the various restrictions imposed as a result of the wider system of instructional organization.

An example of such a divergent laboratory was encountered in a university chemistry practical for chemical synthesis by H. de Jager (1985) at the University of Utrecht, the Netherlands. Chemical synthesis requires the student to integrate theory, laboratory work and reflection upon the achieved results. Detailed instructions in the form of "chemistry cook books" are not particularly useful in that they leave the student no choices as to what they must do. Because of this closed quality, students are not stimulated into thinking about the theoretical aspects of chemical synthesis. De Jager drafted instructions in which the selection of starting materials, reaction conditions and synthesis techniques are posed, either partially or totally, as problems which the students must solve.

A fourth approach

Some researchers have become proponents of a totally different approach to practical work. They propose that experimentation can be taught as a distinct subject in the same way as theory courses such as mechanics, physiology, electrodynamics etc. It goes without saying that it is necessary that there be a correlation between experimental and theoretical courses. This, however, does not mean that the function and role of the laboratory is subservient to the theory/lecture material (Robinson, 1979). Such an alternative approach for undergraduate students is the "Experimental seminar" (Conway, Mendoza & Read, 1963) where students cooperate in the performance of an experiment collectively or by watching an expert perform an experiment whereby they also gain a clear concept of how a well-done experiment progresses. After collective experimentation or demonstration, discussion in a group follows, where necessary stimulated by an "expert" (teacher/lecturer/professor), 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. Those interested in a description of how such a laboratory functions are referred to Conway, Mendoza & Read (1963). Such an experimental seminar can of course be "modernized" to make use of newer techniques such as video, interactive videodisc or CD-ROM.

Toothacker (1983) expanded on the seminar idea in proposing an undergraduate course on "Experimentation". He proposed that: "at the end of the sophomore year (physics) students should take a course on "Experimentation". This course, which would take place in a classroom and not in a laboratory, would teach such topics as data analysis, experimental graph plotting, curvefitting, accuracy, precision, significant digits, estimation and propagation of uncertainties, the difference between random and systematic errors etc. (through demonstrations, films, audio, video and computer simulations). After these introductory topics higher-level thinking skills related to designing and carrying out a real experiment should be stressed culminating in a carefully done group experiment led by an instructor (seminar experiment). 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. After this comes upper-level lab work; long, project-type self-directed investigative experiments. Such upper-level lab work should probably be reserved for those (few) students whose goal it is to do experimental research.

Discussion and conclusion

Much has been written about the objectives and implementation of laboratory work in the natural sciences. Despite the fact that the results achieved in the laboratory setting are not always in proportion to the time, energy and money spent, and that they are seldom in accordance with the expectations of those who designed them, it is very rare that one asks fundamental questions as to the use of the laboratory as an educational tool. The Dutch Open University, an institution for open distance education, is however compelled to question this "fundamental tenet of our dogma" (Thomas, 1972). This need to question has not been forced upon us by our superiors and is not based upon cost-efficiency motives, although the problem of recurrent costs for the use of laboratory space is quite real. A much more important reason for our search for a more effective and efficient laboratory experience is that the requirement of laboratory attendance, being at a certain place at a certain time, is diametrically opposed to the philosophy underlying the Dutch Open University. This philosophy holds that students should be given maximal freedom to decide where and when they choose to study.

Constructions which impinge upon this freedom should either be limited (obligatory attendance at lectures or workgroups) or avoided (semesters, academic year).

The implementation of innovative techniques in education can be much more easily accomplished at the Dutch Open University than at traditional universities, simply because of its youth (it opened its doors to students in 1984). The Dutch Open University has no "tradition", no history, no large investments in laboratories and laboratory equipment, no faculties which must give certain courses in order to share in the budget. We also have the advantage of being able to use (comparatively) large amounts of audio-visual media and computers (for simulation and computer assisted instruction) in our curricula.

The Dutch Open University, at its inception, was actually mandated by the Minister of Education to be innovative in her didactic approach to higher education and to develop and be innovative in the use of electronic media.

The implementation of laboratory work at the Dutch Open University, keeping in mind our philosophy of openness and our need for efficiency and effectivity, will be based upon a list of explicitly chosen global and specific objectives which are deemed both necessary for those completing their study at our institution and which are unable to be equally (or more efficiently) achieve by the other media at our disposal. The proper implementation of these chosen objectives derived from the list in the appendix to this article, is the goal of the rest of the research project outlined in the introduction. Our goal is thus a laboratory which achieves "real" laboratory objectives, alongside practical work which achieves other objectives.

Acknowledgements

The authors wish to thank prof. dr. H. C. de Wolf, professor of education at the Dutch Open University and prof. dr. A. P. Zuur, professor of chemistry at the University of Leiden, the Netherlands, for all their helpful ideas, comments and criticism. Without them this paper would have been a much lesser product.

Appendix

General and specific objectives

All objectives found in the reviewed literature dealing with biological, chemical and physical practical work are listed in this appendix.

Objectives can be specified along a number of non-exclusive dimensions. These dimensions can be teacher-oriented or student-oriented, process-oriented or product-oriented, general or specific. Sometimes they are based on the rationales for practical work and sometimes they are based on the end terms of the total study program.

The objectives here have been (re)formulated in such a way that they all have the same form. As guideline for this work we used Grunland (1970, 1977) who postulated that objectives should be formulated so as to be both student- and product-oriented. That is, they should provide a learning outcome for the student. Moreover all objectives must start with an active verb.

After completing this work a number of objectives still remained. These objectives are more rationales for than objectives of the practical work (van Lieshout, 1986). These rationales have also been (re)formulated so as to be both student- and product-oriented.

Another postulate of Grundland is that one should start by formulating general instructional objectives. These objectives are consequently (re)defined in more specific, behavioral objectives. We also used this method here. The eight general objectives found are partly in agreement with the successive steps in performing an experiment: idea (problem) formulation – model generation – verification of the model (laboratory work) – results – readjusting of model if necessary – verification of a new model – results – interpretation – evaluation report.

In performing this redefinement of objectives we came across a large number of objectives or statements, describing end terms of a study program. The practical work is a means for reaching those end terms while for attaining the general and specific objectives, practical work is the goal in itself.

We arranged those statements according to the following two end terms:
- to obtain good (scientific) attitudes
- to understand the scientific method.

Other parts of the study program can also serve as a necessary condition to reach these general aims. Applying this method we succeeded in categorizing all the objectives. (Many other classifications are of course possible). This appendix both subdivides the end terms into the two previously stated end terms (attitudes and scientific method) as well as enumerates the general and specific objectives.

End terms:

I. *To obtain good (scientific) attitudes*
   - to formulate a problem
     - to identify the nature of a problem
   - to survey the literature

- to choose and evaluate useful literature

- to make decisions
  - to make personal investigative decisions
  - to show self-confidence using these decisions
- to demonstrate a critical attitude
  - to demonstrate the critical and questioning approach which must be adopted by any scientist doing original research work
  - to apply a logical reasoning method of thought
- to exhibit self-confidence and independence
  - to exhibit confidence in the subject
  - to exhibit confidence in one's own skills
- to take initiative
- to tackle a problem alone
- to plan ahead
  - to use time efficiently
  - to organize work and work space
  - to be orderly
- to interpret the reliability and meaning of results in the widest sense
- to elucidate theoretical work as an aid to comprehension
- to apply principles and attitudes of experimental science (physics, biology and chemistry)
- to apply one's own insights, discoveries and conclusions
- to formulate generalizations and models
- to define limitations
- to display an open mind
- to work in groups when necessary
- to work independently when necessary
- to fulfill an active role in the scientific process
- to exhibit skills inherent to professionals in a chosen field.

II. *To understand the scientific method*
- to deduce the relation between science and nature
- to show an intuitive understanding of the nature of a variety of phenomena
- to show an analytical understanding of the nature of a variety of phenomena
- to relate theory and experiment
- to test simple theories to their limits of applicability
- to make phenomena more real through experimentation using models
- to explain the facts, theories and principles discussed in the lectures
- to verify facts and laws
- to build a framework for facts and principles occurred in the theory (lectures)
- to use the laboratory work as a process of discovery
- to simulate the conditions in research and developments laboratories
- to operate from a scientific point of view
- to experience the intellectual challenge of the experimental method
- to experience the joys and sorrows of experimenting
- to experience a kinship with the scientist
- to have a laboratory experience like that enjoyed by scientists in the past and in the present
- to experience a deeper understanding of the discipline studied
- to show the spirit of scientific enquiry and the essence of scientific thinking
- to show interest in the subject area or in science.

General and specific objectives

1. *To formulate hypotheses*
   - to formulate hypotheses using theories
   - to translate a conceptual definition of a quantity into a set of measurement procedures

2. *To solve problems*
   - to solve problems by identifying and defining the nature of smaller problems contained in a larger problem
   - to solve problems in a multi-solution situation
   - to derive and evaluate relationships
   - to use experimental data to solve specific problems
   - to solve difficult problems involving the use of scientific facts in laboratory situations
   - to understand what an experiment is, what is to be measured and how
   - to approach a (physical, biological, chemical) system by identifying variables and using experimental methods to determine empirical relationships
   - to solve problems by critical evaluation of the results of the different steps

3. *To use knowledge and skills in unfamiliar situations*
   - to apply knowledge in solving new problems
   - to apply existing principles in new situations
   - to recognize and define problems
   - to construct and test complex models based on experimental findings in simple models of phenomena
   - to construct new models which fit the evidence instead of confirming more complex theories
   - to work oneself out of tight places
   - to apply the common place as well as the fundamental

4. *To design (simple) experiments to test hypotheses*
   - to design an experiment to test or verify the theory
   - to properly plan an experiment
   - to design observation techniques
   - to design measurement techniques
   - to design new or subsequent experiments involving the phenomena
   - to recognize hazards and appropriate safety precautions

5. *To use laboratory skills in performing (simple) experiments*
   - to understand and follow instructions
   - to exhibit manipulative skills
   - to set up laboratory equipment quickly and correctly
   - to manipulate apparati
   - to conduct experiments making use of the phenomena without endangering the apparatus
   - to know and apply some generally useful measuring techniques for improving reliability and precision
   - to exhibit basic laboratory techniques
   - to handle modern equipment
   - to calibrate instruments
   - to carry out accurate measurements
   - to observe phenomena both qualitatively and quantitatively

- to observe substances both qualitatively and quantitatively
- to be flexible in modifying experiments
- to handle waste in relation with safety and environmental aspects in a proper way

6. *To interpret experimental data*
   - to collect and process experimental data
   - to apply operational definitions to relate symbolic concepts to observed quantities
   - to analyse experimental data
   - to apply broadly based principles rather than computation of formulae in the theoretical analysis of the lab experiment
   - to apply elementary notions of statistics (e.g. random errors, systematic errors, mean values, uncertainty and confidence limits)
   - to decide how errors in direct measurements may contribute to errors in a derived measurement
   - to deduce answers form experimental data in a logical way
   - to reliably estimate the outcome of the experimental measurements within a given precision
   - to evaluate the outcome with regard to the hypothesis
   - to make estimates and order-of-magnitude calculations
   - to incorporate unexpected results in the new theory
   - to generalize from data

7. *To clearly describe the experiment*
   - to summarize the important aspects of an experiment based on observations and collected data
   - to articulate the central goal of an experiment, its underlying theory and its basic methods
   - to define the scope and limiting conditions of the experimental techniques used
   - to communicate in written form
   - to communicate in oral form
   - to keep a day-to-day laboratory diary in such a way that a third person can repeat the experiments
   - to discuss results and suggest follow-up work

8. *To remember the central idea of an experiment over a significantly long period of time*
   - to present the essentials of an experiment in a written form, without using the lab notes
   - to use the gained knowledge and skills in interpreting more recent literature data
   - to design future experiments in the same field of research

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