Elements of experimental work in the Sciences.
Which are essential to Chemistry?

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Abstract

25 project reports from the second semester, labelled "Theory, Model, and Experiment" of the Natural Sciences Basic Programme at Roskilde University were analysed. The analysis concentrated on the elements of experimental work performed by the students. The assessment tool used was formulated in broad categories of elements of practical work, common to all the natural sciences in order to embrace all different traditions of "good scientific performance". The majority of the reports revealed the students' engagement in most stages of experimental work, including the formulation of the contribution of the practical work to the solution of the problem under study. The Chemistry-dominated problems seemed not to be better off in this respect than projects from other areas of the natural sciences. Experimental training of general relevance to the study of Chemistry actually takes place for the majority of students in their second first-year project. However, since the assessment tool was formulated in general terms, it does not discriminate between practical work which is central in most chemical investigations, and that which is of less importance.

Introduction. Practical work is a characteristic element in science teaching at all levels. Intuitively, it appears justified to most science teachers, because observation and manipulation of isolated parts of "the physical world" is part of the very nature of science. European university teacher's objectives for labwork have been studied recently[1], while the reasons for having practical work in school science teaching have been much discussed[2]. Whatever the reasons, at tertiary level it is essential both "to learn science, to learn about science, and to do science"[3]. To include practical work or not in a modern curriculum leading to a science degree is a matter beyond any reasonable discussion. Since practical work, however, is not a single, well-defined category it looks differently and plays different roles in different science disciplines. Many universities have curricula with "practicals" or "exercises" as the dominating form of practical work in the earlier parts, while "experimental work" or "investigations" may be included in thesis-work. In new science curricula, problem-oriented project work may be introduced from day one, and experimental work will be included when relevant. The Natural Sciences Basic Programme (NSBP) of Roskilde University[4] includes such proj-

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[1] EU-project PL 95 2005 "Labwork in Science Education (1996-1998). WP6: Teachers' Objectives for Labwork. Research Tool and Cross Country Results" (available at http://www.physik.uni-bremen.de/physics.education/niedderer/ projects/labwork/ papers.html)

[2] KIRSCHNER, P.A. (1992)"Epistemology, Practical Work and Academic Skills in Science Education" *Science &Education* (1) 273-299, HODSON, D. (1993)"Rethinking Old Ways; Towards a More Critical Approach to Practical work in School Science" *Stud. Sci. Educ.* (22) 85-142.

[3] HODSON, D. (1992)"Assessment of practical work: some considerations in philosophy of science" *Science & Education* (1) 115-144.

[4] a. JOSEPHSEN, J. (2000)"Wissenschaftliches Arbeiten in Projekten für Studienanfänger" *MNU*, (53/6) 367-371; b. JOSEPHSEN J., (1985)"From Freshman Students to Upper-Secondary School Teacher in Chemistry" *J. Chem. Educ.* (62) 426-427

ects occupying half of the study load. This two years programme serves as the first part of a number of degree-programmes.

From a Chemistry point of view it is obviously important that the two first years (the NSBP) include introductory Chemistry and give qualifications relevant to Chemistry. Among these, genuine experience of experimentation is essential to any Chemistry degree programme. Some experimental training is included in the Chemistry and other courses in the programme, but the project work certainly should also contribute to this training. It is supposed that the general experience of experimentation obtained through research-like projects (on problems involving any natural science subject) actually gives the students qualifications of importance in Chemistry or any other subject with a characteristic experimental dimension. But is this assumption correct? To address this question is relevant for the assessment of the NSBP as the first part of a Chemistry degree.

The first issue is to describe the characteristic elements of experimental work. The actual formulation could be different and more or less detailed[5,6] and specified in relation to the single subject, i.e. Chemistry or physics or…. It appears, however, that in the first place a moderate degree of specification is more useful, when experimental work from very different parts of science is to be described and compared (geo and environmental sciences, life sciences, the physical sciences, computer science and mathematics). The next problem is to assess to which extent the students get adequate experience of experimentation (experimental investigation) during their projects. One method may involve the knowledge of what they actually did. A source for this information is the project reports. Such reports may reveal whether the students during the project have experienced a specific element of experimental work. A question is, of course, if the reports themselves give sufficient information to assess this. If it is assumed, that the reports give such information to an acceptable degree, the top question could be elucidated: does experimental work of any science tradition contain the same elements as chemical experimentation or to which extent is this true? The present work deals with one of the steps in this chain of possible investigations: the analysis of the experimental work of the students' projects as brought to light by their reports.

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[5] HELLINGMAN, C.T. (1982)"A Trial List of Objectives of Experimental Work in Science Education" *Europ. Sci. Educ.* (4/1) 29-43

[6] JOSEPHSEN, J. (1998) "Elements of Experimental Work in Freshman Projects" Abstract, 1st ECCE, Budapest p 70.

Method The project reports[7] produced by the latest total population of first year students[8] in their second semester with the common theme "Theory, Model, and Experiment" were studied and labelled according to an area of teaching and research at the university (see Table 1). The reports were analysed using the five fairly general categories of most scientific experimental work (Objectives, Design, Experimental, Results and Interpretation) as a template. The general formulation was intended to allow for a fair assessment of activities from quite different traditions of observation and experimentation that is characteristic of the different natural science disciplines:

1 The formulation of **OBJECTIVES** for the investigation:
Argumentation for studying the detail in question. Accounts of possible outcomes and expected results.

2 Choice and **DESIGN** of methods and equipment:
Choice and design of principle of investigation. Choice of standard techniques or a new design.

3 **EXPERIMENTAL**:
Standardisation, optimisation, calibration, safety measures. Reproduction of procedures and measurements.

4 **RESULTS:**
Evaluation of accuracy and precision. Processing and presentation of data.

5 I**NTERPRETATION** and discussion:
Comparison of results with expectations. Fitting of results into existing knowledge.

The analysis focuses on which of the five categories that seemed to have been subject to intellectual challenge to the students. In the report it should be discussed **how** the particular element is handled and **why** the actual handling was chosen. At best this discussion should refer to the (international) literature. When not discussed it was anticipated that the handling was mostly due to the supervising teacher and taken as granted by the students without further notice. The assessment was not graded, since the study is preliminary and the method of assessment was actually on trial. The analysis of all the reports was repeated with a pause of at least a month between the first and second time and the results compared. When deviations were found, an extra analysis was performed, and the deviations were settled.

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[7] The students are asked to consider "Models, theory, and experiment" during their second first year project.

[8] NSBP students enrolled September 1999 performed their second project in 25 groups of on average 5.2 students during the spring term 2000. Such a project corresponds to half of the study load for one half year - 15 ECTS-credits.

Titel/area of study	Subdisciplin/subject
The dynamics of the boomerang	Aerodynamics
Restoration of Lake Borup	Aquatic ecology
Classification of Danish freshwater streams by microinvertebrates	Aquatic ecology
Faunaanalysis of Watercourses. An evaluation of the environmental status of X before and after restoration	Aquatic ecology
Monitoring ponds	Aquatic ecology
Unilamellar vesicles	Biophysical Chemistry
Protein folding monitored by IR-spectroscopy	Biophysical Chemistry
UV radiation of Tardigrades in cryptobiosis	Biophysics
The neuro impulse as a function of temperature	Biophysics
Transient chaos in a closed Belousov-Zhabotinsky reaction	Chemical kinetics
Albedo in the desertification in the Sahel	Climatology
Implementation of different sorting algorithms in different computer environments	Computer science
Automatic chategorisation of home pages	Computer science
Hedgerows in biological pest control	Conservation biology
The [Cu] in sediments due to antifouling	Environmental Chemistry
Flowdirection in a closed elastic circuit	Fluid dynamics
Alcohol and the nerveous system	Human physiology
Natural microbiological degradation of oil	Microbilogy
Yeast test of estrogen-like compounds in plastics	Molecular biology
The treatment of cancer cell lines with platinum drugs	Molecular biology
Coloured shadows	Optics/colour vision
Eqiulibrium for a charge transfer complex	Physical Chemistry/spectroscopy
The migration of metal ions in soil	Soil science
Roundup in different soils	Soil Science
The retension of nitrate in soil	Soil Science

Table 1: 25 Reports from 132 students, Spring term 2000. NSBP, 2nd semester

Results of the analysis

1. The practical work described in the reports seemed in almost all cases to be relevant to the problem formulated, taking also literature results into account.

The theme for the students formulation of the problem in the second semester is "Theory, Model, and Experiment", so it is not an unexpected finding, that the practical work was an integrated part of the project from the beginning. Only in a few cases was the practical work "added on" and was in fact more or less a "practical" that could have taken place during an ordinary course. A few projects are based mostly on a single reference in literature, where an experimental result may have been limited, uncertain, or inaccurate. Thus the main aim was to reproduce and extend such investigations under specified conditions and to get new or better results. A driving force for the students to include practical work in the projects is to solve a problem not being solved before. This is in contrast to most ordinary first year "practicals" and exercises in the laboratory, where the result of the experiment is known (by the teacher) or could be looked up in a book or in the literature, and of no use *per se*.

2. Only one third of the reports explicitly discuss the possible outcomes (results) of the experiments, although in some cases this aspect was implicit in the arguments for performing the practical work.

The students are offered instructions for setting up and formulate their reports. In this guide it is not underlined that it is useful to explicit one's expectations or predictions on print. As can be read between the lines in the reports, such considerations have not been absent, but their role in designing the methods or specifying the conditions is not clear.

3. About half of the project groups seemed to have adopted a standard experimental technique (or combination of techniques) and to have used a straightforward principle of investigation without further arguments. In the other half of the cases different possible methods have been (more or less thoroughly) discussed and criteria for preferring one over the other given.

This feature undoubtedly reflects the quite different number of available standards normally used in different scientific fields. For example, in experimental physics a specially designed method is often used; such experiments are not burdened by time consuming standard techniques, requiring skilled performance, as many molecular biological investigations are. In Chemistry both extremes are met.

4. Two thirds of the reports witnessed that standardisation /calibration procedures and safety measures have been addressed in some way or another and that the principle of reproduction of results had been obeyed.

When considering that a great deal of the actual practical work couldn't have been done without using standard procedures with built in standardisation /calibration the fraction of 2/3 ought to be higher. Only a small number of projects contained practical work with a moderate level of safety problems. In many typical Chemistry procedures safety issues are important and should be considered carefully.

5. The evaluation of accuracy and precision of results and further processing of data may be more relevant in some cases than in other. It was found only in about half of the reports.

It is obvious that this aspect is important in analytical Chemistry and other fields, where numbers are to be compared with numbers from other studies and where conclusions are based on such comparisons. In other types of Chemistry the accuracy is not necessarily the most import thing. This was not studied further.

6. The general lack of confrontation of results with expectations is consistent with the above finding that such expectations were not formulated generally in the first place (cf. 2. above).
7. Half of the reports revealed a proper discussion of the results obtained in relation to existing knowledge available in the literature.

Investigations by freshman students seldom produce "water proof" and publishable results right away. Some are actually not very conclusive. The discussion of results in relation to literature is not easy in such cases, and one of the bad habits from school, instead to list a lot of possible sources of systematic and random errors, was seen in some cases.

Discussion. Most of the projects were "single-subject" projects, where the problem studied matched the expertise of the supervising teacher rather well. The projects identified as "Chemistry projects" seemed in the first place not to reveal better experimental training in the above sense than the average.

However, the above analysis does not catch and highlight the special characteristics of experimentation in Chemistry. What was believed in the first place was that the general formulations also embrace the typical experimental work in Chemistry. They actually do. It may be a trivial finding since the analysis tool was strongly biased by the designer's background in Chemistry. Using a general assessment tool does not necessarily reveal the presence of central elements in experimental Chemistry, leaving out elements of minor importance to Chemistry training.

Two types of conclusions may be drawn:

Firstly, about the assessment tool:

1. The proposed assessment tool probably does have a potential when project reports from science projects are analysed with respect to contents of elements of general experimental training in the sciences.
2. The proposed assessment tool does not discriminate between experimental training, which is central to Chemistry, and that which is of less importance.

Secondly, about the contribution to the training in practical work during the second first year project of the NSB programme, seen from a Chemistry training point of view:

1. Not all the students get experimental training in that semester being central to Chemistry. (And certainly not all the students choose Chemistry after the first two years).

2. A major fraction of the students gets, however, experimental training, which is of general relevance to Chemistry (as well as to the other natural sciences).

This second type of conclusion is in line with the qualifications obtained through the Natural Sciences Basic Programme, which could be divided[4a] into

A. General academic qualifications (not including practical work)

B. General natural science qualifications (including practical work)

C. Special qualifications including supporting subjects (e.g. mathematics) and basic training in the subject (here Chemistry)

The next step of the present study would be to identify and specify the elements of experimental work essential to Chemistry in a way that allows an analysis using the project reports as a source of information.