# Scientific abilities in undergraduate projects and laboratory

**David R Mills**
**School of Physics**
**Monash University**
**Melbourne**
**Australia**

**david.mills@sci.monash.edu.au**

*Experimental projects are, by their nature, the best way of preparing students for future work as scientists, engaging students and providing scope for their creativity*

**Abstract**
*Projects are being increasingly used to provide a richer experience in physics teaching laboratories, and in the higher years, these may well approximate to the real world of industry and research. In first year, however, a wide range of approaches are utilised, from projects to open-ended experiments, yet questions remain about how students can best acquire a range of desired scientific abilities. Recent physics education research has suggested tools and approaches to help develop and measure the abilities such as needed to design and implement an experiment. Examples from several countries illustrate the need for matching the task with students' capabilities, and how various goals may be achieved for student learning in the laboratory.*

**Enquiry skills and laboratory**
Skills of scientific enquiry have gained the attention of university physics educators in an unprecedented way in recent years. The May 2007 issue of European Journal of Physics has a special section dedicated to undergraduate laboratory and project work, in which several papers incorporated scientific enquiry. A similar emphasis is found in the other sciences. Some advances in research and effective practices will be outlined.

A study of learning and teaching in Australia's 34 university physics departments completed in 2005 showed a tenacious commitment to laboratory work in the face of substantially reduced academic staff and inadequate budgets[1]. Across first to third year, laboratory work accounted for between 25 - 40% of both student contact time and assessment weighting for most departments, with a few below 20%, and several more than 40%. Students' views of the abilities they gained in their undergraduate physics were obtained from focus groups comprising 118 students in 7 selected representative institutions, spread across first and third year and early postgraduate years. The majority of these students believed that they had obtained a lot or some of the following (in rank order, highest first): laboratory skills, problem solving, experimental design, written communication and teamwork. Since these skills are largely developed in the laboratory, it is reasonable to say that laboratory work was performing a useful role. Nevertheless, partly as a result of physics education research, partly by networking with others, many departments are undertaking initiatives to improve the effectiveness of their teaching laboratories[2].

In Europe, laboratory work in chemistry, physics and biology was mapped in a major study in the late 1990s, covering upper secondary and university levels[3]. The mapping was of content and processes, context, what students were expected to do in terms of actions and in terms of ideas, and included the degree to which students were required to take initiatives. Compared to chemistry and biology, the physics laboratory involved ideas and relationships between quantities to a greater extent, but had less diversity in the range of features. Physics laboratories were similar across national borders, causing the authors to speculate that this may not necessarily aid reflection, research and innovation today. On the degree of openness (open-endedness and student initiative), physics was the lowest, although all three disciplines were low at university level and close to zero at senior secondary level.

**Projects and other possibilities**
Experimental projects are, by their nature, the best way of preparing students for future work as scientists, engaging students and providing scope for their creativity. The piCETL project reported recently by Lambourne[4] and by Raine[5], are excellent examples of what can be achieved when a laboratory programme is transformed as part of a wider innovation.

Many Australian universities offer projects as part of their physics laboratory component, or as the whole of the laboratory programme for one or more semesters at higher years. Projects are also common as stand-alone subjects in third year, providing invaluable preparation for students intending to undertake further study at fourth year honours or higher degree. Such projects typically are added on after a traditional first and second year laboratory programme.

A major consideration in deciding on how to run a first year laboratory programme is the size of the class. The larger physics departments in Australia typically have between 200 and 500 students enrolled in mainstream first year physics, dropping to say 60-100 in the second year. Generally students take four disciplines in first year and narrow down to one or two disciplines at third year, so competition exists between disciplines to attract students, the better ones in particular. A balancing act is required, since the majority of first year physics students will not continue to third year, whilst on the other hand students may drift to other disciplines if laboratory work is uninspiring. In some Australian departments, project work at first year, which was considered highly valuable, has been dropped because of the cost and effort involved. Projects which have survived at first year typically involve teams in the construction of a particular device and take a large part or all of a semester's laboratory work.

Solutions to this dilemma include an advanced laboratory programme for selected students or an honours stream starting in first year. Mini-projects or open-ended experiments offer an alternative which may be offered to the whole cohort[2]. The Australian study noted that the current generation of students, who have grown up with technology and the internet, are likely to expect greater engagement and sense of contributing personally.

**Scientific abilities and projects**
Policies for secondary science curricula have raised the profile of scientific enquiry and both experts and teacher-researchers have looked at enquiry from many angles; useful mappings of scientific enquiry have been made[6]. Millar has reviewed the role of practical work in secondary science and cautioned against pinning too much on open-ended investigations. He warns that "attempts to include investigative practical work in the mainstream curriculum often result in practice that is disappointingly different from that intended, especially when students' performance of investigative tasks forms part of the course assessment"[7].

*Policies for secondary science curricula have raised the profile of scientific enquiry and both experts and teacher-researchers have looked at enquiry from many angles; useful mappings of scientific enquiry have been made*

In higher education, fewer are engaged in learning and teaching research. The curriculum, which has usually evolved from within the department, is likely to be less critically evaluated than at the secondary level. In addition, academic content and its level is a significant factor in student scientific enquiry. For these three reasons, it is understandable that scientific enquiry in higher education has been less thoroughly charted than in school science. A comprehensive survey of advances in (university) physics teaching across the international physics community in 2003 mentioned the need for 'discovery' in laboratory work, but none of the 392 references explicitly addressed inquiry skills[8].

A pre-requisite for successful outcomes in projects is an appropriate match of students' abilities to the set tasks, with useful guides for implementing project laboratory at first year by Planinšič[9], and suggestions for 'scaffolding' from students prior knowledge and experience by Neumann and Welzel[10].

Our expectations for projects or open-ended laboratory need to be realistic. A long term study of student thinking and learning was observed in a range of university physics laboratory classes (by video-recoding of actions and conversations)[11]. To the surprise of the researchers, they found that "students in *all* studies rarely talked about physics concepts … rarely explicitly stated the principles … nor hypotheses". Rather the students typically search for a formula which leads to a suitable result. This is consistent with the typical novice approach to problem solving, and reminds us that scientific enquiry is a form of problem solving. They also noted that "the more open-ended the laboratory instruction, the less likely that students' activities will make explicit reference to physics concepts". Whilst this may arise from a weakness in the design of the activity and associated requirements (in terms of what is valued, what is to be discussed, or presented in a report), it is helpful to remember that students are finding their way through unfamiliar territory. The experiment and measurements are the concrete know-ables, so that working out the relationship between their observations and concepts may occupy only a small part of the time, but may be the most significant in terms of thinking and understanding.

**Developing and assessing scientific abilities**
We can consider two broad avenues for developing scientific abilities. One, akin to problem-based learning, is for the students to recognise the skills needed as they tackle the project or experiment (and acquire those skills). The other is to provide a sequence of structured small activities designed to cover the range of skills.

Etkina, van Heuvelen and colleagues[12] have over some years, generated an approach of the latter type for developing students' scientific abilities, and have produced tools for formatively assessing these skills. Their approach places a high value on experiments in learning physics[13], not simply as a better way for students to learn concepts, but as the way in which scientists actually work. The abilities are not restricted to the laboratory situation, but are developed in a holistic way through large classes and small group tutorials (recitations). They name the following abilities: "(A) the ability to represent physical processes in multiple ways; (B) the ability to devise and test a qualitative explanation or quantitative relationship; (C) the ability to modify a qualitative explanation or quantitative relationship; (D) the ability to design an experimental investigation; (E) the ability to collect and analyse data; (F) the ability to evaluate experimental predictions and outcomes, conceptual claims, problem solutions, and models, and (G) the ability to communicate".

*The 'Challenge Experiment' is one activity used over the past six years for first year main-stream students at Monash University which is specifically designed to extend students' enquiry skills and to inject some fun and interest.*

Some of the model tasks provided by Etkina and colleagues are intentionally simple in order to suit students with no prior physics background; for first year students with good physics backgrounds other more appropriate tasks are available. The effectiveness of the approach for various abilities were tested in four projects, each across university large classes with different backgrounds, different reasons for taking physics and in different institutions.

Integral to their approach is the consistent form of tasks and processes which students work on throughout the semester. The experiments typically cover core topics in the introductory physics syllabus and students design an experiment to observe, or to test, or to apply, a given phenomenon. Student initiative is central, the tasks are relatively simple but often posed in an interesting way, for example, an exploration of how an object can be electrostatically charged without making contact, or the angle at which a toy truck can ascend a slope without slipping. The approach may be described as open-ended in relation to the experimental method, whilst the aim and equipment tend to be given. Students are required to reflect on what they did and learnt[14]. The rubrics used by instructors for formatively assessing students' work are also a tool for students' own self-evaluation.

In relation to their ability to design an experiment, little improvement occurred in students' recognition of underlying assumptions and awareness of the effect of experimental uncertainties. For these areas, further formative assessment tools are planned. It is worth commenting, however, on the imperative of addressing key skills within the laboratory class itself. If students' formative assessments are being written or discussed after the laboratory and away from the experimental environment, students are much less likely to appreciate tacit assumptions (e.g. that the floor is flat, in the case of one experiment cited). During the laboratory activity students are able to see the consequences of an unmet assumption (the ball not round or the table not horizontal or flat enough). The opportunity to make predictions and test assumptions is best utilised in the laboratory rather than in later imagination.

**Steps toward improving enquiry skills**

There are several ways in which scientific enquiry skills can be enhanced by relatively simple steps. One is to raise the level of student initiative in experiments which are otherwise basically unchanged in terms of equipment and conceptual content, by requiring students to make decisions about appropriate aspects of the method and the analysis of data. We have carried this out across most of our first and second year experiments[15]. In particular this can target the nature of the discussion, reflection or report required as part of the experiment, and address matters of science enquiry (for instance as utilised by Etkina et al). In addition to using this as a formative assessment tool (between demonstrator and student) we have expanded it as a follow-up exercise within small peer groups, the effectiveness of which is currently being evaluated. Recognition of the importance of formative assessment and self-evaluation has prompted us to replace a hands-on, end-of-semester practical test with formative assessment feedback throughout the weekly laboratory classes.

The 'Challenge Experiment' is one activity used over the past six years for first year main-stream students at Monash University which is specifically designed to extend students' enquiry skills and to inject some fun and interest. Numerous other universities have used special experiments designed to achieve similar goals. Our students have two hours in teams of 3 or 4 persons, to experiment with physically interesting systems such as the precession of a gyroscope subject to an external torque; the rolling or slipping of a cable or cotton reel pulled by an attached string, and the oscillation of a magnet in an external magnetic field. They are in their second semester, and have had some 50 hours of laboratory prior to the Challenge. In their reflections written two weeks later, they responded to questions about what was special about the Challenge, and what they got out of it. Their open-ended responses showed a high level of appreciation of working out their own method, wrestling with a novel situation and achieving something themselves. They came to a more satisfying understanding than in a conventional experiment. In short, this two-hour experience achieved many of the positive aspects of an extended project, though clearly not to the same extent. Among the students who continued to second year Physics after its inception, the Challenge experiments (including a simpler semester 1 activity) stood out as the favourite components of first year physics[16], and has probably been a positive factor in our increased number of students continuing in the second year.

**References**


1. Sharma, M., Mills, D., Mendez, A. and Pollard, J. (2005) *Learning Outcomes and Curriculum Development in Physics* (Australian Universities Teaching Committee, online at http://www.physics.usyd.edu.au/super/AUTC/).
2. *Snapshots - Good Learning and Teaching in Physics in Australian Universities* (The Carrick Institute for Learning and Teaching in Higher Education, Sydney, 2005. Online at http://www.physics.usyd.edu.au/super/AUTC/).
3. Tiberghien, A., Veillard, L., Le Maréchal, J-F., Buty, C., and Millar, R. (2001) An analysis of labwork tasks used in science teaching at upper secondary school and university levels in several European countries, *Sci. Educ.*, **85**, 483-508.
4. Lambourne, R. (2007) Laboratory-based teaching and the Physics Innovations Centre for Excellence in Teaching and Learning. *Eur. J. Phys.* **28** S29-S36.
5. Raine, D. (2006) From Projects to Problems, *New Directions,* **2**, 81-84.
6. Ahlgren, A. and Wheeler, S. (2002) Mapping the steps towards basic understanding of scientific inquiry, *Science & Educ.*, **11**, 217-230.
7. Millar, R. (2004) The role of practical work in the teaching and learning of science, (Paper prepared for the Committee, High School Science Laboratories, National Academy of Sciences, Washington DC. Online at http://www7.nationalacademies.org/bose/Robin_Millar_Final_Paper.pdf ).
8. Thacker, B. A. (2003) Recent advances in classroom physics, *Rep. Prog. Phys.*, **66**, 1833-1864.
9. Planinšič, G. (2007) Project Laboratory for First Year Students, *Eur. J. Phys.*, **28**, S71-S82.
10. Neumann, K. and Welzel, M. (2007) A new labwork course for physics students: devices, methods and research projects, *Eur. J. Phys.*, **28**, S61-S69.
11. von Aufschnaiter, C. and von Aufschnaiter, S. (2007) University students' activities, thinking and learning during laboratory work, *Eur. J. Phys.*, **28**, S51-S60.
12. Etkina, E., Van Heuvelen, A., White-Brahmia, S., Brookes, D. T., Gentile, M., Murthy, S., Rosengrant, D. and Warren, A. (2006) Scientific abilities and their assessment, *Phys Rev ST PER,* **2**, 020103-1 – 15.
13. Etkina, E., Van Heuvelen, A., Brookes, D. and Mills, D. (2002) Role of Experiments in Physics Instruction — A Process Approach, *Phys. Teacher,* **40**, 351-355.
14. May, D. B. and Etkina, E. (2002) College physics students' epistemological self-reflection and its relationship to conceptual learning, *Am. J. Phys.*, **70,** 1249-1258.
15. Feteris, S. M. (2007) PhD thesis to be submitted, (Monash University.
16. Mills, D., Feteris, S., and Greaves, T. L. (2005) Developing Investigative Skills through a 'Challenge' Experiment, *Proceedings of The 16th Congress Australian Institute of Physics* (Canberra ACT: Australian Institute of Physics.