Educating the next generation of bioscientists: the challenge for higher education in Australia

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Abstract: *Traditional science boundaries continue to be challenged, thereby creating broader employment opportunities for appropriately skilled graduates. However, many factors including limited time and resources, diverse student cohorts and large student numbers, may limit good practice when it comes to developing highly skilled bioscientists. Within this context, it is timely to examine the role of undergraduate teaching in educating the next generation of bioscientists. This paper describes preliminary findings from a project supported by the Australian Learning and Teaching Council, which is examining current teaching practice in bioscience disciplines. The project is using a qualitative research framework to identify innovative approaches used by educators to enhance the scientific inquiry capabilities of their students. Twenty cases have been studied where the priority to teach scientific inquiry skills has influenced the design of the teaching approach. Cases have been identified from nine universities across five states. In general, the approaches are variations of inquiry or problem-based learning, and have been delivered through online environments, laboratory classes and lectures. Skills that educators aim to develop include: formulation of research questions and hypotheses; experimental design; critical appraisal of literature and ideas; collaboration; communication of arguments and findings. Educational technology has been used to provide solutions for distance and asynchronous communication, collaboration, incorporation of immediate learner feedback, and has been used in numerous ways to enhance the learning experience. While the extent of implementation was diverse, there were some interesting overlaps in strategies.*

Introduction

The traditional pathway to becoming a bioscientist was via a PhD, following the completion of an undergraduate bioscience degree. This initiation into the practice of scientific research has been likened to entry into medieval arts and craft guilds, an apprenticeship model where PhD students enjoyed an extended, individual approach to learning their craft (Charlesworth, Farrall, Stokes & Turnbull, 1989). This model of gaining scientific research practice, however, is closely tied to the notion of academic science, the collegial system where disciplinary associations formed between universities to oversee the training and certification of new researchers (Whitley, 1984). Since the 1980s, the expansion of both industrial and state science has challenged traditional science boundaries. Scientific skills continue to be "…combined in novel ways for new intellectual goals so that results cannot be fitted into existing boundaries and reputational priorities" (Whitley, 1984, p.224). This trend has opened up broader employment opportunities for appropriately skilled graduates.

Today, only a minority of university science students will follow the traditional pathway via a PhD to become scientists (Harris, 2007). However, at the undergraduate level, many factors may work together to constrain good practice when it comes to developing appropriately skilled bioscientists. For example, bioscience education today is generally characterised by large student numbers, resulting in high student-teacher ratios, and diverse student cohorts with a wide range of knowledge, skills, motivations and aspirations. Furthermore, limited time and resources may change the nature of the laboratory experience for students. Consequently, fewer bioscience graduates will have the skills required for employment in a laboratory context.

A recent report from the UK on the role of first year practicals in developing future bioscientists, highlighted the fact that

> The laboratory classes experienced by first year students often do not represent an exciting and motivating experience and may deter some students from pursuing practically-orientated programs that may lead to laboratory based careers in bioscience. (Wilson, 2008, p.8).

This finding is reiterated in an Australian study, which interviewed staff and students from nine universities to determine their perceptions of first year laboratory classes,

> A consistent message heard from the academics and demonstrators in many of the subjects was that the really interesting work happened in second or third year, which of course, is too late for those who have no need of further years of study in science subjects or who have become disengaged (Rice, Thomas and O'Toole 2009, p.40).

A similar message was perceived by students

> Stuff I am learning now won't help me contribute. It is pretty basic and boring. Everyone is telling me that the fun doesn't start till second or third year" (Rice, Thomas and O'Toole 2009, p.40).

These observations suggest a mismatch between educators' traditional views of scientific training pathways, and the broad career possibilities for graduates.

The importance of "engendering first year students with enthusiasm" (Adams, 2009) underpins the argument for teaching basic bioscience knowledge alongside the fun stuff, the creative, problem-solving notion of science. The literature points to many ways this can be achieved during the early years of bioscience degrees. For example, Adams (2009) describes an extensive list of recent examples of innovative, inquiry learning in undergraduate laboratory classes. Inquiry learning is the process of solving problems through exploration of the natural world: asking questions, making discoveries, rigorously testing these discoveries in the search of new understanding (National Science Foundation, 2000). The examples come from most disciplines of biology, however, biochemistry, physiology and cell biology are well represented. Learning experiences that are designed to enhance student engagement, such as collaborative projects where small groups of students design and perform their own experiments, have resulted in higher scores in laboratory tests, enhanced reasoning skills and more enjoyable experiences for students (Adams, 2009).

Providing students with the opportunity to contribute to original research in undergraduate laboratory classes is another way of introducing students to the wonder of science. Adams (2009) describes over twenty examples extracted from the literature where students in undergraduate laboratory classes have participated in "entirely original and valuable research". The novel techniques and model organisms developed for molecular biology and gene technology make these disciplines more likely to incorporate authentic research activities into teaching classes.

Increasingly, universities are also providing opportunities for biology students to improve their conceptual understanding of scientific thinking and inquiry processes. One UK university for example, offers a second year, interdisciplinary module where students are taught about different definitions of science, introductory philosophy of science, basic logic, the use of authority in science, the scientific method(s), experimental design, rationale for using statistics, biases encountered by scientists and a little history of science (Paxton, 2009). The module was developed to address gaps in students' understanding, for example, why the philosophy underpinning their decision making is not always justified and why scientific literature should be more reliable than popular magazines. The focus of the module is on teaching day-to-day scientific thinking, rather than a philosophical perspective.

Scientific inquiry learning in undergraduate classes has been further enhanced by the use of technology. There are many examples in the literature of how computers are used for scientific inquiry activities including: Simulations (presenting a simplified version of a natural phenomena or processes); Support tools (helping students gather, organise, visualise and interpret data); Collaborative tools (allowing students to communicate and to share data and ideas); Modelling tools (allowing students to express their theories in models). More recently, efforts have been made to develop scaffolds or cognitive tools for computer environments, which support students through the inquiry process (de Jong, 2006). Evidence shows that supported, online environments are effective modes for scientific learning (van Joolingen, de Jong & Dimitrakopoulou, 2007).

Within this context, it is timely to examine the role of undergraduate teaching in developing the next generation of bioscientists. The purpose of this paper is to describe the findings of the first stage of a project that is supported by the Australian Learning and Teaching Council. The project is examining current teaching practice in bioscience disciplines in Australian universities, to identify innovative approaches used by educators to enhance the scientific inquiry capabilities of their students. It has a specific focus on the role played by educational technologies in developing students' skills.

Project methods

A qualitative research framework is being used to document teaching approaches currently used by bioscience educators to teach scientific inquiry skills. In this way the project is investigating a wide variety, rather than a statistically representative sample of popular trends. Human research ethics approval has been obtained.

Educators were recruited for the study by calling for participants at conferences, following up team members' professional contacts and snow-ball sampling, where participants suggest other potential participants. Forty potential participants were identified and sent an initial email describing the project and inviting participation. The email was followed up with a phone call to determine suitability, availability and willingness to describe teaching approaches. As a result, twenty cases were selected where the priority to teach scientific inquiry skills had influenced the design of the teaching approach.

Data collection began with semi-structured, phone interviews, which asked participants to describe what approaches they were taking to teach scientific inquiry skills. The plain language statement given to participants had suggestively defined scientific inquiry skills as: problem analysis, hypothesis formulation; prediction of logical consequences; inquiry planning; experiment design; hypothesis testing; generating, collecting and analysing data; drawing conclusions; communicating results. However, if a participant asked what was meant by scientific inquiry skills, the question was reflected back to them to define. They were then asked to describe the approach, with the interviewer prompting for details on: discipline; cohort; year level; student numbers; student-educator ratios; learning environment; learning objectives; motivations; method and details of learning design; presence or absence of educational technologies; attitudes to using technology; purpose of technology; details on integration of technology; evidence of success in achieving learning objectives. Phone interviews were recorded using field notes that were sent back to the participant for verification. Supplementary data was collected from student resources, practical manuals, lecture recordings and published documents.

Interview transcripts were analysed using the software package *NVivo* to identify emerging themes. A grounded theory approach was taken to the analysis, which was influenced by recent publications that emphasise the development of scientific inquiry skills in early undergraduate years and the laboratory context (Adams, 2009; Rice, Thomas & O'Toole, 2009; Wilson, 2008).

Results

A wide range of approaches for teaching scientific inquiry have been discovered from nine universities across five states: Australian National University; Charles Sturt University; Flinders University; LaTrobe University; Monash University; University of Adelaide; The University of Melbourne; The University of Queensland; University of Southern Queensland. These approaches have been used in a broad range of bioscience disciplines: agricultural science; biochemistry; biology; immunology; microbiology; pharmacology; physiology; plant molecular biology; plant science; zoology. In general, they can be described as variations of inquiry or problem-based learning, and have been delivered through online environments, laboratory classes and lectures. In order to present the reader with a snapshot of teaching approaches, we have synthesised five general categories from the literature: Conceptual understanding of scientific inquiry; Inquiry learning in undergraduate laboratory classes; Real-world research in undergraduate laboratory classes; Technology-enhanced inquiry learning; Integrated inquiry approaches. Below, each category is described using specific cases to detail major features and variations. Disciplines from where the teaching approach was identified, are also shown.

Conceptual understanding of scientific inquiry: Biology, Microbiology, Plant science, Zoology

Lectures are being used to explain the history and theory of scientific discoveries, to debate current scientific problems and to visualise the scientific inquiry process. One educator remarked,

> I like to give a little bit of the history to show the scientific inquiry that lead to this conclusion. And so if there is a really classic experiment that is appropriate for first years, I like to explain it, to show them what the hypothesis was at the time, with the equipment they had then, how they were able to support it. And then you might go on later with the sophistication we have got now, we have refined the hypothesis. And I think that is important scientific inquiry for the kids too. You don't have to always be in the lab.

In another case, team lecturing is used to present scientific problems, with each lecturer taking on a different perspective. The team challenges each others' assumptions and beliefs about the topic in front of the students, and demonstrate the justification of their position. These processes model the oral defence of a piece of research and illustrate the scrutiny of novel research finding by peers. In a third case, the educator creates flowcharts with input from students, as a way of visualising the overall inquiry process that students will perform in a subsequent laboratory session.

Inquiry learning in undergraduate laboratory classes: Biochemistry, Physiology, Plant molecular biology

Students conduct a full inquiry in the laboratory around a constructed scenario or an established bioscience phenomenon. Teaching may begin with a traditional practical session to familiarise students with the scientific problem and laboratory equipment. In this way, the approach is consistent with de Jong's (2006) assertion that sound curricula combine different forms of tuition, both inquiry learning and direct instruction depending on the purpose. Over the course of several weeks (e.g. five weeks), small groups of students then formulate a hypothesis, design an experiment to test the hypothesis, perform the experiment, collect preliminary data, refine experimental design if necessary and collect further data, which is analysed and conclusions drawn. Students write up their findings in a scientific paper format. Variations to this approach include students producing a poster of their findings and presenting an oral presentation to their peers. Online lab books, bioinformatics tools and statistical analysis software were used in these cases as support tools.

Real-world research in undergraduate laboratory classes: Agricultural science, Biochemistry, Chemistry, Immunology

One specific case in this category uses CASPiE (http://www.purdue.edu/dp/caspie/course.html), an American initiative adapted for the Australian context. Students contribute to an original research problem and conduct a full inquiry; analyse the problem, formulate a hypothesis, design and perform experiments, draw conclusions, contribute to international online discussions (communicating results) and collaborate with other researchers. The approach allows students to gain research experience, use advanced instrumentation and experience the accountability of real-world research. Variations include students spending time in real-world laboratories with a supervisor, reading the literature, taking ownership of a project, and writing up their laboratory experiences in a scientific paper format. In the agriculture science case, students carried out real-world research in the field.

Technology-enhanced inquiry learning: Agricultural science, Biochemistry, Physiology

The first case in this category was primarily designed to encourage critical thinking in students and to demonstrate the importance of communication for scientists. The educator said to the students

> …one of the skills you need to learn is to talk to other people about an issue and sort out the good stuff they are saying from the bad … a skill you have to develop is to be able to take in information and critically analyse it. Not just write it down. Not just get stuff from the web, copy it down and give it back to someone else, but actually have something going on in here between information going in and the coming out.

On-line discussion groups were used for the actual task, but it is introduced to students at the beginning of a lecture by the educator,

> I want you to use a bit of scientific reasoning. So you're only just starting on the course of becoming a scientist. Most of you will be in one way or another a scientist at the end of this. Or we hope that you will be. So what you need to start doing is using some scientific principles to solve in this case a question that's got no definite answer.

Students were assigned to debate groups and allocated a discussion topic. The educator suggests a few ideas to get started (i.e. What are the factors? What would happen if?) and then steps out of the process. Students were assessed on their understanding of the discussion topic in their exam. While this particular case focused on components of inquiry, such as critical thinking and communication, other cases were identified where students perform a 'virtual' full inquiry, online during a dedicated computer session.

Integrated inquiry approaches: Physiology

This category is similar to Inquiry learning in undergraduate laboratory classes, however, rather than running for several weeks, the laboratory program is vertically integrated over three years of the course, with scaffolding that is gradually reduced over this time period. For example, in first year, students read information, formulate hypotheses and generate research questions. During second year, students are required to extend their inquiry and design, perform, collect and analyse data, validate data, refine hypotheses and relate findings back to the published body of literature. There is also an emphasis on the critical analysis of literature – why do different research groups come to different conclusions? The educator remarks

> The other beautiful thing that has come up [is that the lecturer] has said that [the students] are asking questions. They'll come up to him at the end of a lecture and say, 'I need to know this for my experiment' … So he has been really impressed that they have been curious coming into his lectures. I'm pretty sure that helps them learn better if they are having a question coming in.

A variation of this approach is the implementation of a semester long, inquiry task for students, which is closely integrated with topics being covered in practical laboratory sessions and lectures.

Discussion and Conclusions

Australian educators are currently using various strategies to introduce scientific inquiry at early stages of the curriculum. In an effort to engage and retain first year students, some educators have reformed first year bioscience laboratory curriculum so that students gradually (with significant scaffolding) begin to actively participate in inquiry processes from the time of their first laboratory class.

Other educators are providing students with the opportunity to contribute to authentic research problems, in first and second years. Thirdly, educators are bringing aspects of the discovery process into lectures by either explaining the stages that a scientific discovery has been through, presenting unanswered research questions, or debating the scientific content of lecture in front of students. Some approaches have incorporated technology to assist students in inquiry-based tasks, and two universities are making fundamental changes to course structures to integrate the inquiry process over the three years of undergraduate study.

Overall, these findings parallel those of international studies examining the role of undergraduate education in the development of future bioscientists. Data collected by the project to date, suggests that the development of scientific inquiry capabilities in students can be viewed as a continuum, a process of gradually building up enabling skills (small, manageable components of scientific inquiry such as, hypothesis formulation, critical appraisal of information, handling of lab equipment), and then giving students the opportunity to practice these skills until they become proficient. The gradual progression towards creative, scientific problem-solving, supports the view that scientific inquiry should be introduced to students during the early years of bioscience degrees.

It is of interest to note the ways educational technologies are being used in the Australian context, to support the development of scientific inquiry skills in students. In some cases, specific technologies, for example, online discussion groups and flowcharts on Tablet PCs, are blended together with innovative strategies, into the traditional laboratory or lecture context. In other cases, inquiry learning in undergraduate laboratory sessions is being supported by online resources such as, lab books, bioinformatics tools and statistical analysis software. In cases where online learning environments were developed for the specific purpose of introducing students to the notion of scientific inquiry as an iterative, cyclic process, the use of technology as a delivery platform was also seen as part of the solution to high student to staff ratios, and to providing face to face communication in distance education.

Future project work aims to define scientific inquiry from the perspective of industry science employers and offer ways to evaluate the effectiveness of inquiry learning in developing scientific inquiry skills in students.

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