EDUCATIONAL TECHNOLOGIES

Enhancing the learning of scientific inquiry skills for bioscience students in Australian universities

Final Report

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The University of Melbourne
Kristine Elliott
Anna Boin

Monash University
Helen Irving

La Trobe University
Elizabeth Johnson

The University of Queensland
Victor Galea

http://www.scientificinquiry.meu.unimelb.edu.au
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Executive Summary

The changing nature of contemporary scientific practice means that broad employment opportunities exist for appropriately skilled bioscience graduates. The challenge for higher education in Australia is ensuring that students develop skills during their undergraduate studies such as problem analysis, information seeking, critical appraisal, hypothesis formulation, experimental design, data analysis and interpretation, collaboration and the ability to communicate and defend the outcomes of an investigation.

This project adopted a qualitative approach to examine current teaching practice in bioscience disciplines in Australian universities. Twenty-six cases were identified where educators considered they were intentionally teaching scientific inquiry. The cases were identified from nine universities, across 11 bioscience disciplines, and were developed for all three years of undergraduate teaching.

The 26 cases represent a diverse range of teaching practice. Each case has been described using a framework based on the degree of inquiry inherent in student tasks, the degree of independence expected of students in performing tasks, the learning objectives educators were expecting students to achieve, and the learning environment in which tasks were carried out. Visual representations of cases have also been made so that educators can thumb through them for easy comparisons. It is intended that these snapshots contain enough information to act as triggers for educators wishing to change traditional practice towards approaches that increase student learning of scientific inquiry skills.

The use of educational technologies in supporting the development of students’ scientific inquiry skills was also investigated by the project. Generally, technology played three broad roles. Firstly, authentic online databases, software, and hardware allowed students to utilise technology in the same way they would as future professional scientists. Secondly, technology provided guidance for students in the process of their learning. Thirdly, technology was used to enable communication amongst student peers, and between students and educators. Frequently technology was one of many tools incorporated into a learning experience and many of these were delivered through the university online course management system.

In consulting educators about their teaching practice, insights were also gained on their views of the nature of scientific inquiry. In general educators’ views aligned with those reported by contemporary scientists, although scientists placed lesser emphasis on hypothesis driven research, and a greater emphasis on the importance of creative thinking in all stages of investigations. However, the fact that contemporary science is rarely pursued in isolation from technology, and the social context of science were themes reported by scientists, which were generally not raised by participants in this study.

Detailed learning designs have been created of six cases, which were innovative, made some use of educational technologies, and represented the diversity of practice studied. Educators wishing to adopt practices to enhance scientific inquiry skills can use the learning designs as exemplars to adapt and implement at their own institutions. The learning designs provide visual representations of each case, the motivation and background behind the innovation, learning objectives, tasks presented to students, teaching strategy, demands on educator resources, and evidence of improved student performance. Implementation requirements of the six
innovative cases vary greatly: from simply making extra use of a university’s course management system, to redesigning the undergraduate science curriculum.

Finally, recommendations have been made about the varied ways educators might evaluate student learning of scientific inquiry skills. Examples are provided on how to measure students' perceptions of scientific inquiry and their ability to perform scientific inquiry. Moreover, an exercise has been developed to measure science critical thinking skills in students at second year, tertiary level. Observation of students’ engagement and enthusiasm is another likely indicator that a teaching approach has been successful.

Overall the key outcomes of the project are as follows:
- a framework to describe the diverse range of practice used to teach scientific inquiry skills in bioscience disciplines
- a snapshot of practice in Australian universities drawn from an analysis of 26 case studies
- visual representations and descriptions of each of the 26 cases
- insights into educators’ views of the nature of scientific inquiry
- specification of the roles educational technologies play in supporting the development of scientific inquiry skills
- learning designs of six cases of innovative practice
- recommendations on how educators might evaluate student learning of scientific inquiry skills.

The key outcomes of the project have been published in a handbook *Teaching scientific inquiry skills: A handbook for bioscience educators in Australian universities*. The handbook has been specifically designed for educators and contains practical ideas for adopting improved teaching practice that explicitly targets scientific inquiry skills as learning outcomes. The handbook will facilitate wider adoption of improved teaching practice across the higher education sector, which is one way to ensure that bioscience graduates entering the workplace are equipped with the skills to successfully conduct scientific research.

The handbook and other project resources are available to download from the project website: [http://www.scientificinquiry.meu.unimelb.edu.au](http://www.scientificinquiry.meu.unimelb.edu.au)
1. Project Aims

Recent commentaries have highlighted growing concerns that Australia will be unable to meet future demand for suitably skilled scientists. A number of different factors are behind such concerns including:

- the trend in developed countries towards a decreasing number of students opting to study science at school and university
- a shortage of qualified secondary school science teachers, which Tytler (2007) argues affects the quality of classroom practice, leading to student disenchantment, and ultimately fewer students continuing on with science at a tertiary level
- the changing nature of contemporary scientific practice emphasising non-traditional skills
- studies indicating that in general young people are not sufficiently prepared to effectively participate in and contribute to life in a rapidly changing society (de Jong, 2006).

Given this background, one of the challenges facing higher education in Australia is identifying the best way towards developing appropriately skilled bioscience graduates. The literature describes many innovative examples of how this can be achieved during the early years of bioscience degrees:

- providing students with inquiry learning experiences in undergraduate laboratory classes (Adams, 2009; Weaver, Russell & Wink, 2008)
- providing students with the opportunity to contribute to original research in undergraduate laboratory classes (Weaver et al., 2008)
- providing students with opportunities to interact with practising scientists (Boyer Report, 1998; Hunter, Laursen & Seymour, 2007)
- providing opportunities for students to improve their conceptual understanding of scientific thinking and inquiry processes (Collins & Bell, 2004; Paxton, 2009; Wood, 2009)
- enhancing scientific inquiry learning through the use of educational technologies (de Jong, 2006; van Joolingen, de Jong & Dimitrakopoulou, 2007).

Within the Australian higher education sector, the extent to which bioscience educators explicitly teach scientific inquiry skills to their students is presently unknown. Furthermore, it has been acknowledged that within Australian universities there has been little adoption of the innovative teaching and learning developments made in science over the years (Rice, Thomas & O’Toole, 2009). Therefore, the project sought to clarify this situation with two broad goals:

1. To examine current teaching practice in bioscience disciplines in Australian universities and identify innovative approaches used by educators to enhance the scientific inquiry capabilities of their students.
2. To investigate the role of educational technologies such as highly interactive computer programs, computer simulations, collaborative tools, communication tools, and support tools that help students gather, organise, visualise and interpret data, in supporting the development of students’ skills.

The project adopted a versatile definition of scientific inquiry proposed by the National Research Council (1996).
Scientific inquiry refers to the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work (p. 23).

However, for the purpose of establishing a shared vocabulary between project team members and educators, a set of basic scientific inquiry skills was developed and organised into stages of scientific inquiry as follows:

- problem analysis (information seeking, critical appraisal, hypothesis formulation)
- inquiry planning (generation of a prediction/model, experimental design)
- hypothesis testing (conducting experiments, technical competency, data generation, analysis and interpretation)
- evaluation (testing accuracy of results, draw conclusions)
- review (cyclic refinement of hypothesis)
- collaboration and communication (display and defend outcomes of an investigation).

In order to achieve its goals, the project was conducted in four phases; investigation, identification, evaluation and dissemination. The aim and planned outcomes of each phase are summarised below.

**Investigation phase:** This phase examined and documented 26 cases where the priority to teach scientific inquiry skills to students had influenced the design of the teaching approach. Visual representations of each case were created to act as triggers for educators wishing to change traditional practice towards practices that enhance student learning of scientific inquiry skills.

Project outcomes:

- a framework to describe the diversity of practice
- a snapshot of teaching practice in Australian universities
- visual representation of 26 cases.

**Identification phase:** Data collected during the first phase was critically analysed to identify innovative cases of practice. Six innovative cases were subsequently described using learning design notation so that bioscience educators wishing to adopt practices to enhance scientific inquiry skills could use and adapt them to fit their own educational context. During this phase, the role of educational technologies in supporting the development of students’ scientific inquiry skills was also investigated.

Project outcomes:

- specification of the role of educational technology
- a set of six reusable learning designs describing innovative practice.

**Evaluation phase:** This phase examined and described evidence of evaluation across the 26 cases. Recommendations were written to assist educators in developing methods to evaluate the effectiveness of practice towards teaching scientific inquiry skills.

Project outcomes:

- evidence of evaluation across the 26 cases
- recommendations.
**Dissemination phase:** A number of strategies were employed throughout the life of the project to engage the wider community of bioscience educators with the project, and to disseminate the project’s findings.

Project outcomes:

- a handbook of findings written specifically for bioscience educators with practical ideas for adopting improved teaching practice
- a project website
- academic publications and presentations.
2. Methods

The project adopted qualitative methods to investigate the approaches taken by educators towards teaching scientific inquiry skills (Patton, 2002). Snowball sampling was used which began with four team members (Elliott, Irving, Johnson and Galea) each suggesting several educators whom they were aware had been taking innovative approaches to teaching scientific inquiry. These contacts led to further cases of interest. In addition, talks and posters were presented by team members at conferences and meetings early on in the project, which were designed to promote awareness of the project and invite participation from educators.

As a result, a list of 42 potential participants was attained. From these 26 case studies were selected where the priority to teach scientific inquiry skills had influenced the design of the teaching approach, and where educators agreed to describe their teaching practice.

The 26 cases examined by the project were identified from a broad range of universities across five states:

- Charles Sturt University
- Flinders University
- La Trobe University
- Monash University
- The Australian National University
- The University of Adelaide
- The University of Melbourne
- The University of Queensland
- University of Southern Queensland

Study participants taught across 11 bioscience disciplines, including agricultural sciences, biology, biochemistry, biomedical science, botany, immunology, microbiology, molecular biology, pharmacology, physiology and zoology. The overall strategy was therefore to obtain a wide variety of approaches to teaching scientific inquiry skills rather than a statistically representative sample of popular trends.

2.1 Data Collection and Analysis

Data collection began with the intention of recruiting participants via telephone. Initial contact was made by email with an attached plain language statement to notify participants to expect a phone call. Phone conversations asked educators what approaches they were taking to teach scientific inquiry skills to their students. If educators asked what was meant by scientific inquiry, the question was reflected back to them to define before progressing. Educators were then asked to describe their approach with the interviewer prompting for details on:

- discipline
- cohort
- year level
- student numbers and student educator ratios or indications of the educator time required per student
- learning objectives and motivations for taking this teaching approach
- method and details of learning design
- any evidence of success in achieving the learning objectives
- the presence or absence of educational technologies in the approach.
Telephone interviews were recorded using field notes that were sent back to participants for verification. Supplementary data was collected from student handouts, practical manuals, and recordings of lectures.

As part of this process, many educators discussed their views of scientific inquiry with the interviewer. Therefore, data collected from 14 educators was analysed to determine the priority given to teaching particular skills over others. We acknowledge that this sample may not accurately reflect the views of all educators in the higher education sector. It is recognised that there are many different educators, for example, university academics who combine teaching with scientific research, those who began careers as scientists and then moved into teaching roles, and those who specialise in science education. However, the themes drawn out of the analysis were widely represented in the sample and provide insights into general perceptions. To determine if the views of educators reflected those of practicing scientists, the literature was reviewed to ascertain contemporary bioscientists’ views of the nature of scientific inquiry.

Of the 26 case studies investigated, six were selected because they were innovative, made some use of educational technologies, and covered a representational range of the teaching practice studied in the project. To fully describe these innovative cases, face-to-face interviews were conducted with educators. Supplementary data was collected through observation of teaching sessions, student handouts, practical manuals, lecture recordings and publications. Face-to-face interviews were audio recorded.

All data was loaded and analysed using NVivo (www.qsrinternational.com) to identify themes. The nature of NVivo is such that it encourages the user to take a grounded theory approach to analysing the data, so analysis is at least partially influenced by the theories that are intrinsic to the data. This data, however, has been influenced by the background theories that the project team has brought to the project. Namely, the project started with a particular list of skills that constituted scientific inquiry skills, informed by the works of Bunge (1967); Chin & Malhotra (2002); Elliott, Sweeney & Irving (2009); Hatton & Plouffe (1997); de Jong & van Joolingen (1998); Kim, Hannafin & Bryan (2007); and Wenning (2007). Similarly, our analysis has been influenced by several recent publications that emphasise the development of scientific inquiry skills in first year and in the laboratory context (Adams 2009; Rice et al., 2009; Wilson 2008).
3. Project Outcomes

3.1 Investigation Phase

The aim of this phase of the project was to examine and document current approaches that tertiary educators take in bioscience disciplines towards teaching scientific inquiry skills to students.

3.1.1 A framework to describe teaching practice

The project identified 26 cases where the priority to teach scientific inquiry skills had influenced the design of the teaching approach. Cases were designed for all three years of undergraduate teaching.

A framework was developed to describe the diverse range of approaches that educators take towards teaching scientific inquiry skills (see Figure 3.1 below). The framework was based on four themes that were common to all cases: the degree of inquiry inherent in student tasks (Brown, Abell, Demir & Schmidt, 2006), the degree of independence expected of students in performing tasks (Brown et al., 2006; Buck, Lowery Bretz & Towns, 2008), the learning objectives educators were expecting students to achieve, and the learning environment in which tasks were carried out.

![Figure 3.1 A framework to describe teaching practice](image)

3.1.2 A snapshot of current teaching practice

Educators used a wide range of physical settings to teach scientific inquiry skills (see Table 3.1). Cases ranged from practice environments, such as wet laboratories and the field, to lecture and tutorial settings where teaching focused on conceptual understanding of the process of scientific inquiry. A number of cases, which we identified as blended learning, utilised multiple settings for a mixture of face-to-face and online interactions. We found more educators used out-of-class assignments and inquiry tasks in the laboratory as the vehicles for teaching scientific inquiry.
Assignments in this context were taken to mean any task where students were required to work independently of their educator, outside the classroom.

**Table 3.1 Learning environments used to teach scientific inquiry**

<table>
<thead>
<tr>
<th>Physical setting</th>
<th>Learning context</th>
<th>No. of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Informal, out-of-class</td>
<td>Students work alone or in groups independent of educator on a variety of assignments</td>
<td>11</td>
</tr>
<tr>
<td>Laboratory</td>
<td>Practical classes where students perform an inquiry task to varying degrees</td>
<td>6</td>
</tr>
<tr>
<td>Authentic research laboratory/ fieldwork</td>
<td>Practical classes where students participate in authentic research projects</td>
<td>4</td>
</tr>
<tr>
<td>Virtual laboratory</td>
<td>Online modelling of inquiry components for students</td>
<td>3</td>
</tr>
<tr>
<td>Lecture/tutorial</td>
<td>Inquiry tasks are embedded into the class experience</td>
<td>1</td>
</tr>
<tr>
<td>Unclassified</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

The degree of inquiry used in scientific inquiry tasks is summarised in Table 3.2. In 10 cases, educators concentrated on developing specific skills or components of the scientific inquiry process. Three components were readily identifiable: critical appraisal of information, appreciation of diverse views and interpretations, and mastery of technical skills such as bioinformatics analysis. Four cases combined a number of components to create a partial inquiry for students to conduct. Educators involved in these cases commented that it is not always feasible to have students perform a full inquiry. Partial inquiry offers a solution for large group teaching where expensive elements such as generation of complex data, can be omitted or replaced with information from the literature or *in silico* studies. Eleven cases offered students the experience of a full scientific inquiry. These cases have the advantage of duplicating more authentic research environments.
Table 3.2 Degree of inquiry inherent in scientific inquiry tasks

<table>
<thead>
<tr>
<th>Degree of inquiry</th>
<th>Task characteristics</th>
<th>No. of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discrete component of scientific inquiry</td>
<td>Critical appraisal of information</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Practice of laboratory skills</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Appreciation of diversity of views and approaches</td>
<td>2</td>
</tr>
<tr>
<td>Most of an inquiry</td>
<td>Task requires multiple skills with one or more steps from the inquiry cycle omitted</td>
<td>4</td>
</tr>
<tr>
<td>Full inquiry</td>
<td>Student completes a scientific inquiry cycle</td>
<td>11</td>
</tr>
<tr>
<td>Unclassified</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

The degree of guidance used in scientific inquiry tasks are summarised in Table 3.3. Seven cases were identified as teacher-driven inquiries where either educators modelled the scientific inquiry process (two cases), or students worked through set exercises (five cases). There were seven cases of guided scientific inquiry tasks, requiring students to exercise some judgement without complete independent control. Students undertaking these inquiries were asked to critically assess information from scientific literature, the work of peers, or their own work. Eight cases were identified which allowed students to move from a guided stage or framework towards independent investigations as students became more proficient. Four cases were identified where students performed independent inquiry, taking full responsibility for all stages of their investigation.

Table 3.3 Degree of guidance provided in scientific inquiry tasks

<table>
<thead>
<tr>
<th>Degree of guidance</th>
<th>Task characteristics</th>
<th>No. of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed inquiry</td>
<td>Educator models a component of scientific inquiry and students observe</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Students work through an exercise set by the educator</td>
<td>5</td>
</tr>
<tr>
<td>Guided inquiry</td>
<td>Educator defines the task but students exercise judgement (e.g. critical appraisal)</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Student begins with a guided experiment set by the educator but then progresses to increasingly independent work</td>
<td>8</td>
</tr>
<tr>
<td>Independent inquiry</td>
<td>Students develop and perform independent study</td>
<td>4</td>
</tr>
</tbody>
</table>
Educators were expecting students to achieve a broad range of outcomes from their teaching approaches. Learning outcomes ranged from specific skills (e.g. conduct statistical tests) to broadly defined outcomes such as collaboration. Overall, learning outcomes could be divided into those with an emphasis on conceptual understanding of the process of scientific inquiry, and those with an emphasis on the practice or application of scientific inquiry (see Table 3.4). Teaching approaches designed to develop conceptual understanding tended to emphasise components of the scientific inquiry process, for example, hypothesis formulation or critical analysis. Practice tasks emphasised experimental inquiry and relied on students learning by doing. A number of cases concentrated on both conceptual understanding and practice, providing students with opportunities to work through a full scientific inquiry and then reflect on the process.

<table>
<thead>
<tr>
<th>Type of outcome</th>
<th>No. of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developing conceptual understanding</td>
<td>11</td>
</tr>
<tr>
<td>Developing practice in scientific inquiry</td>
<td>11</td>
</tr>
<tr>
<td>Developing both conceptual understanding and practice</td>
<td>4</td>
</tr>
</tbody>
</table>

### 3.1.3 Visual representation of 26 cases

Visual representations of each case have been created to allow educators to thumb through them for easy comparisons; these can be found in section 4.3 of *Teaching scientific inquiry skills: A handbook for bioscience educators in Australian universities*. It is intended that the snapshots contain enough information to act as triggers for educators wishing to change traditional practice towards practices that enhance student learning of scientific inquiry skills.

### 3.1.4 Educators’ views of scientific inquiry

Three major themes emerged from interviews with bioscience educators about the nature of scientific inquiry. Firstly, scientific inquiry was viewed as a process guided by well-established principals. In its most basic form it was seen as the creation of a hypothesis and subsequent testing of the hypothesis. Secondly, educators viewed scientific inquiry as a way of thinking that was critical, objective, analytical and lateral. Thirdly, educators placed a great deal of emphasis on questioning as a way of seeking information during an investigation.

In general educators’ views aligned with those reported by contemporary scientists, although scientists placed lesser emphasis on hypothesis driven research, and a greater emphasis on the importance of creative thinking in all stages of investigations (Charlesworth, Farrall, Stokes & Turnbull, 1989; Schwartz & Lederman, 2006; Tytler & Symington, 2006; Wong & Hodson, 2008). The fact that contemporary science is rarely pursued in isolation from technology and the social context of science were themes reported by scientists (Charlesworth *et al.*, 1989; Darby, 2009; Tytler & Symington, 2006; Wong & Hodson, 2008), which were generally not explored by the educators in this study. Given the reasons that educators cited for not using technology in their teaching (e.g. it was unnecessary or had no advantage, it was no substitution to genuine laboratory experiments at the bench, it hindered attainment of tacit skills in scientific inquiry) it appears that in
some cases educators were unaware of the significant contribution of technology towards advances in contemporary bioscience, and the opportunities it affords for innovative teaching practice.

Interpretive discussion and illustrative quotes from educators are presented in section 3.3 of *Teaching scientific inquiry skills: A handbook for bioscience educators in Australian universities*.

### 3.2 Identification Phase

The aim of the second phase of the project was to identify innovative practice used by bioscience educators to enhance the scientific inquiry capabilities of their students. Learning designs of these cases were developed, which describe pedagogical strategies, tasks students are required to perform, resources and supports to help students complete tasks, and expected cognitive outcomes for students. The learning designs also describe the sequence in which events take place, when particular resources and supports need to be made available, time lines and recommendations for implementation.

During this phase, the role of educational technologies in supporting the development of students’ scientific inquiry skills was also investigated by the project.

#### 3.2.1 The role of educational technology

The diversity of educational technologies and how they were used in teaching scientific inquiry in the Australian context are summarised in Figure 3.2 below.

Although educational technologies were widely used, there were exceptions where educators did not incorporate technology into their teaching of scientific inquiry. When used, technology played three broad roles. Firstly, authentic online databases, software, and hardware allowed students to utilise technology in the same way they would as professional scientists. Secondly, technology provided guidance for students in their learning. Thirdly, technology was used to enable communication amongst student peers, and between students and educators. Few cases were identified where technologies were being used to enhance conceptual understanding of the scientific inquiry process. Instead, technologies were frequently one of many tools incorporated into a learning experience and many of these were delivered through the university online course management system.

Descriptions of specific educational technologies used in cases can be found in section 4.2.1 of *Teaching scientific inquiry skills: A handbook for bioscience educators in Australian universities*. 
Educational technologies: Enhancing the learning of scientific inquiry skills for bioscience students in Australian universities

The role of technology is defined on the horizontal axes. The technologies listed on the left provide guidance, those in the middle are authentic resources used by professional scientists, and those on the right are technologies used to facilitate communication. Scientific inquiry skills are listed on the vertical axes. The boxes are positioned on the vertical axes in relation to the scientific inquiry skills being developed and the long thin boxes spanning all the skills refer to technology approaches that enable the teaching of scientific inquiry as a process. The clouds illustrate why educators do not incorporate technology.

3.2.2 Six cases of innovative practice
Learning designs have been created of six cases, which were innovative, made some use of educational technologies, and represented the diverse range of teaching approaches studied. In adopting practices to teach scientific inquiry, the ease of implementation is an important consideration particularly where educators are working within existing curriculum constraints (Wood, 2009). For example, relatively simple interventions such as shifting from a didactic monologue in a lecture to a constructive debate can change student perceptions of how scientific inquiry is performed. However, transforming a traditional laboratory class to a suite of research projects embedded in authentic laboratories requires considerably more resources and reorganisation. Therefore the six learning designs range from adaptations requiring relatively little revision of existing work practices, to one that requires redevelopment of an undergraduate curriculum.

The learning designs, including visual representations of the case, the motivation and background, learning objectives, tasks presented to students, teaching strategy, demands on educator resources, and evidence of improved student performance, are provided in section 5.0 of Teaching scientific inquiry skills: A handbook for bioscience educators in Australian universities. Instructions are also provided on how to interpret the learning designs.

The main features of six learning designs of innovative practice are summarised below.
Case 1: Online discussion groups
This learning design describes an exercise for first year students where small and open-ended questions are introduced in lectures, for example, regarding a biological process: what conditions are needed for this process to take place? The questions are examinable, but the educator does not answer them in lectures. Instead, students are organised into online discussion groups to discuss plausible answers with their peers in out-of-class time. The educator can provide guidance, but does not directly answer the questions.

The method of learning is introduced to students in lectures and the educator clearly explains the motivation and philosophy behind the approach. Learning objectives are explicitly defined: to use discussions with peers to develop understanding of an issue; to critically appraise information from a variety of reliable and less reliable sources; to use scientific principles to solve a question that has no definite answer. This case requires little extra class and educator time. The only assessment is a short answer question on the final exam.

Case 2: Constructing flowcharts
This learning design describes an exercise for second year students, although a similar activity has been implemented with a first year cohort. Prior to a traditional laboratory class, students are required to create a flowchart that visually describes the sequence of tasks they will perform during an investigation. This introduces students to the notion of scientific inquiry as a process and is intended to convey the message that it is a process that needs to be designed.

The process of creating the flowcharts is demonstrated by the educator in the first lecture of the subject. With class participation, the educator draws the flowchart on a Tablet PC and the drawing is captured in the lecture recording. Thereafter students independently construct their own flowchart before each laboratory session. Learning objectives are to develop an understanding of the methodology behind experimental design and to conceptualise practical processes. Flowcharts are assessed by a quick inspection signature by the educator, which is recorded when students hand in their completed laboratory report. The case adds little extra time for the educator, but alters the way students participate in weekly labs.

Case 3: Online experimentation
This learning design describes an in silico laboratory session designed for third year students that replicates authentic discipline specific experimentation, “like how we do it in the field”. Students are required to complete prescribed tasks, but also have to understand the functionality of the authentic online databases, which they are able to explore. Questions asked towards the end of the session require students to compare and debate their findings against arguments in the literature. This provides students with the context of the theory behind the content of the laboratory session.

The learning objectives are listed on the assignment sheet given to students and are: to introduce students to a variety of analysis tools; to understand a discipline-specific experimental design and analysis; and to become skilled at data interpretation. Assignment questions worth more marks require students to research their own answers. They therefore have to “go find some of the literature” and the educator makes it clear that there is not always one right answer.

Case 4: Invent an organism
This learning design describes a semester long assignment for first year students. It runs closely in parallel with the more traditional course curriculum where students
study structure and function in classes. Students apply these principles to create a plausible organism that could live in a fictitious set of environmental variables.

The assignment is informed by principles of inquiry based learning, where the aim is to take students on a journey guided by teachers and peers. Students are therefore formulating, researching, and answering questions. Moreover, students are encouraged to be creative and have fun with the process. Learning objectives are defined as the ability to:

- apply the core principles learned to novel situations
- ask relevant questions
- identify important issues
- evaluate evidence
- use critical reasoning to formulate conclusions.

Teaching ratios vary because contact with educators occurs through lectures, group discussions, laboratory sessions and online. However, time spent giving feedback to students replaces three tests that students used to complete throughout the semester.

**Case 5: Authentic research**

This learning design describes a module that first year students self select to participate in. It is run in collaboration with the Center for Authentic Science Practice in Education (CASPiE) at Purdue University and enables students to contribute to an authentic scientific investigation. Students investigate a currently unanswered scientific research question while collecting data to a professional standard. A laboratory report book is submitted for assessment and students are required to write and submit abstracts to summarise the work achieved.

The module enables students to participate in a full inquiry, provides online access to advanced instrumentation and creates a collaborative research environment in the laboratory. Learning objectives are to: increase technical capabilities of students regarding a suite of instruments relevant to the research question; develop research skills; and to give students the knowledge and experience of collecting and recording data to an internationally accepted standard. This case alters half a semester of curriculum for first year students who self-select to be involved in authentic research. Therefore it is quite resource intensive because twice the number of laboratory classes are held and the lab books each take an hour to mark. Moreover, the CASPiE modules are run with slightly higher educator to student ratios than traditional laboratory sessions.

**Case 6: Vertical Integration**

This case is an alternative approach to undergraduate curricula with scientific inquiry teaching vertically integrated across all three years of the course. In this curriculum, inquiry forms the basis of the entire laboratory schedule with students concentrating on designing their own experiments, writing research proposals, and reporting their final results in the style of a scientific journal paper. In first year, students are taught to read, form questions and hypotheses. They use an electronic laboratory book, LabTutor®, which gives access to results displayed on a computer graph. In second year, students learn to refine hypotheses, validate and collect data. The learning design describes the second year of this curriculum.

This curriculum immerses students in a culture that encourages them to think and act like real scientists. Learning objectives are explicitly explained to students and include:
• hypothesis and method development (being able to break down a complex question into testable hypotheses and to develop methods to match hypotheses appropriately)
• validation and manipulation of data
• performance of statistical comparisons and derivation of key findings
• writing of scientific laboratory notes, proposals and reports.

Assessable tasks include written research proposals and papers. Implementation of this case would require significant support and resources from an institution, in particular for curriculum transformation and tutor training.

3.3 Evaluation Phase

The aim of the third phase of the project was to develop an evaluation framework to assist educators to develop methods to evaluate the effectiveness of their approach towards teaching scientific inquiry skills. Prior to developing recommendations, data collected during the Investigation phase was analysed to determine what evidence was already available to show that a particular case had achieved the desired learning outcomes for students.

3.3.1 Evaluation framework

The majority of learning evaluation conducted by educators consulted in the project occurred at Kirkpatrick’s (1975) first level, students’ reaction to the learning experience. Data indicating that students agreed that tasks helped them improve, were relevant, or had given them insights were examples of students’ reactions. So too were positive student reflections. It was not surprising that this was the main type of evaluation performed since it is quick and easy to obtain, and inexpensive to collect and analyse.

Although in several case studies, educators claimed their teaching approach resulted in increased competency in students’ skills or more students completing tasks to a higher level, these outcomes were based on educators’ perceptions rather than pre- and post-tests measuring changes in student capabilities. No cases were identified where evaluation had been conducted and documented at the third level i.e. long-term changes in student behaviour. The observations and interviews required over many months, means that this type of evaluation is time intensive and costly. At the fourth level of evaluation, several educators claimed that their subject had become increasingly popular, and assignment grades had improved over the years. However, at this level it is difficult to separate these effects from normal external factors such as cohort differences from year to year.

While many educators aspired to collect controlled evidence, the lack of evidence reflects the complex nature of what educators were trying to achieve, and a lack of understanding of the use of tools used for measuring these changes.

3.3.2 Recommendations

Recommendations have been made about the varied ways educators might evaluate student learning of scientific inquiry skills. Suggestions are provided on how to measure students’ perceptions of scientific inquiry and their ability to perform scientific inquiry. Moreover, an exercise has been developed to measure science critical thinking skills in students at second year, tertiary level.

The recommendations include examples and practical advice about:

• questionnaires that measure student perceptions of scientific inquiry and their
ability to perform scientific inquiry
- administering questionnaires (time, cohort size)
- developing items for questionnaires
- terminology used for items
- exercises that measure science critical thinking skills
- administering pre- and post-tests
- open-ended questions for focus groups
- observation of students.

These resources are available in section 6.2 of *Teaching scientific inquiry skills: A handbook for bioscience educators in Australian universities*. 
4. Dissemination

A number of dissemination strategies were used throughout the life of the project to engage the wider community of bioscience educators in Australia.

Early in the project in 2008, talks and posters were presented by team members at conferences and meetings to raise awareness of the project and invite participation from educators (e.g. ComBio2008 Conference, Canberra, September 2008; ALTC Assessment & Standards Forum, Adelaide, November 2008; ascilite Conference, Melbourne, December 2008).

During participant recruitment in early 2009, direct contact was made with 42 bioscience educators throughout Australia to inform them of the project and discuss its aims, methodology and planned outcomes.

Throughout 2009, ongoing correspondence about project outcomes was maintained with educators involved in the 26 cases described in A Snapshot of current teaching practice. At this time, team members also presented preliminary findings at conferences (e.g. Science Learning and Teaching Conference, Edinburgh, June 2009; Educate09 Conference, Melbourne, September 2009) and gave seminars at their local institutions. Later in 2009, project findings were presented at the UniServe Science Conference, Sydney, October 2009; ascilite Conference, Auckland, December 2009; and the ComBio2009 Conference, Christchurch, December 2009.


The major project deliverable is a 72 page handbook written specifically for bioscience educators in the higher education sector, entitled Teaching scientific inquiry skills: A handbook for bioscience educators in Australian universities.

The handbook gives a comprehensive account of current definitions of scientific inquiry, contemporary scientists’ views of scientific inquiry and compares them to the views of scientific inquiry held by educators consulted for the project. The handbook then describes 26 cases where scientific inquiry skills are explicitly being taught in Australian universities. Educators can browse through these snapshots for ideas on adaptations to traditional practice, which can change student perceptions of how scientific inquiry is performed. For example, through the incorporation of educational technologies, changes to the degree of inquiry inherent in student tasks, or the degree of independence expected of students in performing tasks. Detailed learning designs of six cases of innovative practice are provided for educators to adapt and implement at their own institution. It also provides resources to assist educators’ to develop methods to evaluate the effectiveness of their teaching approach.

The handbook is currently available for downloaded from the project website: http://www.scientificinquiry.meu.unimelb.edu.au

Printed copies of the handbook will be distributed to the Australian Council of Deans of Science and their member universities providing science programs, deputy vice-chancellors (teaching and learning) in Australian universities, and project participants.
4.2 Project Website
A public website has been established that provides general information about the project, its aims, methodology and outcomes. Details are also given about the project team members and how they can be contacted. The website URL is: http://www.scientificinquiry.meu.unimelb.edu.au

4.3 Academic Conferences, Seminars and Invited Presentations
Project findings have been published in conference proceedings and presented at various events:


5. Project Impact

5.1 Use and Advancement of Existing Knowledge

5.1.1 Scientific inquiry

In examining approaches to teaching scientific inquiry skills, it was essential that project team members and study participants held a shared understanding of the process of scientific inquiry and associated skills. A literature review was conducted to determine current understanding of scientific inquiry in general, and more specifically in the biosciences. In addition to examining the works of science philosophers, science education experts and university academics, we reviewed published accounts of contemporary scientists' views of scientific inquiry. The project built upon existing knowledge by comparing published scientists’ views to the views of educators interviewed in this study (see section 3.1.4 of this report). The major findings of the literature review are presented in section 3 of *Teaching scientific inquiry skills: A handbook for bioscience educators in Australian universities*, however, the key messages are summarised below.

There is general agreement in the current literature that there is no one method of scientific inquiry, and that the ways of doing science are very diverse (Charlesworth, Farrall, Stokes & Turnbull, 1989; Hatton & Plouffe, 1997; National Research Council, 1996). Earlier authors had proposed one method of scientific inquiry (Bunge, 1967), however, this is no longer considered applicable to contemporary science. There are indications, however, that perceptions about the nature of scientific inquiry differ amongst scientists from different science disciplines, for example physics, chemistry and the life sciences (Schwartz & Lederman, 2006; Wong & Hodson, 2009).

Within the bioscience disciplines, practicing scientists report several key themes about the nature of contemporary science (Schwartz & Lederman, 2006; Tytler & Symington, 2006; Wong & Hodson, 2009):

- Research is not always hypothesis driven, and indeed step-wise methods are not relevant to the process of ideas generation.
- It is impossible to conduct scientific inquiry without some theoretical speculation, therefore, scientific inquiry is not absolutely objective.
- Creative thinking and imagination play an important role in all stages of an investigation - planning and designing, data collection and data interpretation.
- Scientific thinking (e.g. scientific reasoning, research skills, lateral thinking, objective, analytical thinking) plays a critical role in scientific inquiry.
- Science is rarely pursued in isolation from technology, and technology has had a major impact on the design of scientific research.
- Collaboration and teamwork are significant factors, which highlight the important role of communication and other 'people skills'.
- Scientific research is closely connected to a social context, and consideration needs to be given to social and ethical issues.

5.1.2 A framework to describe teaching practice

The literature was also examined to inform the development of a framework to describe teaching practice (see section 3.1.1 of this report). It became apparent that there was lack of agreement about definitions and criteria for inquiry as a mode of instruction, and inquiry as a process for solving scientific problems, and general confusion between the two uses of inquiry (Brown, Abell, Demir, & Schmidt, 2006; Buck, Lowery Bretz, S & Towns, 2008; Weaver, Russell, & Wink, 2008; Wood, 2009).
The project sought to clarify this situation by characterising pedagogical approaches that were intentionally designed to teach scientific inquiry skills. Some of the approaches documented by the project were inquiry-based modes of instruction, but this was not considered a prerequisite. Therefore, the project has advanced existing knowledge in this area by providing a framework that defines the characteristics of pedagogical approaches to teach scientific inquiry skills. Furthermore, it has defined the roles of educational technology as part of this characterisation.

5.1.3 Evaluation of learning
In developing the evaluation recommendations (see section 3.3.2 of this report), the literature was searched for tests that measure science critical thinking skills in students. However, few examples were found. Fraser (1979) had previously developed a test to measure inquiry skills of junior high school students, but this test was not pitched at a level of achievement expected of tertiary students. The project has advanced existing knowledge in this area by developing a test to measure science critical thinking skills in students at second year undergraduate level.

5.2 Implementation in Other Institutions or Locations
The major impact of this project will be an increased awareness amongst bioscience educators of the possibilities of directly teaching scientific inquiry skills in undergraduate classes. Project team members have already implemented some of the innovative cases into their own teaching. Although excellent examples of teaching scientific inquiry appear in the tertiary education literature, most educators contacted for this study had limited knowledge of the innovative work of colleagues in this area. A recent ALTC study (Burke da Silva et al., 2009) confirmed that academic scientists are more likely to maintain active surveillance of their scientific research field rather than research into teaching and learning and educational innovation. The same study also found that academic scientists are more likely to engage with educational innovation presented by scientific colleagues and especially if it relates directly to their own field of study.

Engagement with curriculum revision is a constant challenge for science academics. The strengths of this project lie in the practical examples and advice that it has generated and presented in Teaching scientific inquiry skills: A handbook for bioscience educators in Australian universities. The handbook is written specifically for bioscience educators planning to change their teaching approach to one that explicitly targets scientific inquiry skills as learning outcomes. The learning designs contained in the handbook, are derived from six in depth case studies and capture key principles and elements. The learning designs are widely applicable to undergraduate bioscience courses. The snapshot of practice and the detailed learning designs both offer a wide range of solutions, which can be tailored to local circumstances.

A second challenge for science academics lies in genuinely measuring student achievement in understanding and using scientific inquiry. Generally, the effectiveness of approaches documented by the project were not well described. Therefore, the development of evaluation tools that can be used to effectively evaluate learning outcomes will lead to more evidence-based teaching practice in this area.

Finally, conference attendance by team members resulted in interest in the project at national and international levels. In terms of advancement of science education, the project team produced two fully written refereed conference papers and one fully
written un-refereed conference paper. It is intended that these papers will form the basis of further refereed journal publications.

5.3 Evaluation Outcomes
As this was a small project, a formal independent evaluation was not undertaken, however, evaluation was carried out at key stages during the project. To ensure that appropriate methodology was used and to maintain scholarly rigour, a half-day qualitative research workshop was held for team members prior to data collection. The workshop was conducted by Assoc. Professor Rosalind Hurworth, Director of the Centre for Program Evaluation, Melbourne Graduate School of Education, The University of Melbourne. As data collection began, the project team consulted an independent expert in qualitative evaluation of educational technology from the Centre for Program Evaluation, to review recruitment, sampling, interview strategies and data analysis used in the project.

An iterative approach was used to evaluate materials produced by the project. For example, all telephone interviews were recorded using field notes that were sent back to participants for verification. Also, drafts of learning designs were sent to educators for feedback, which was then incorporated into the final versions. In this way, high fidelity data informed the production of resources by the project team. Moreover, team members held on-going conversations with colleagues at their universities to make sure that the resources being developed were useful.

The handbook, Teaching scientific inquiry skills: A handbook for bioscience educators in Australian universities, has been reviewed positively by other educators, including Professor Trevor Anderson (Head, Science Education Research Group, University of KwaZulu-Natal, South Africa) who commented: “I have been going through your handbook and must congratulate you on an excellent project.” This feedback demonstrates that the handbook is working as it was designed to do and meeting a need in the educational literature. Further evidence of the impact of the project has been the acceptance of peer-reviewed publications of the project findings (see section 4.3 of this report), and invitations to present workshops at future special interest forums at the international biochemistry meeting OzBio2010 (26 September - 1 October 2010) and at the ascilite2010 conference (5-8 December 2010).

5.4 Success Factors and Challenges
The major factor critical to the successful completion of the project was a dedicated team, committed to the advancement of science education in Australia. All team members had research backgrounds in science and engineering, and three of the team members were science academics currently involved in both research and teaching. Their contributions ensured that the resources were designed in a manner that was more likely to capture the attention of scientific colleagues. This was also the reason why the project presented its findings at educational symposia of scientific conferences, in addition to teaching and learning events.

Communication between team members was very important to the project, particularly when the team was working across four institutions and two states. Significant time was invested in the early stages of the project in setting up project management processes to facilitate good communication. Interestingly, the team relied on email, telephone conferences and face-to face meetings to exchange information. These processes were particularly beneficial when it come to writing the handbook, resulting in a streamlined, collaborative production.
A further success factor was the enthusiasm of educators to participate to the project. Without the willingness of educators to describe their teaching practice, it would not have been possible to collect the rich data set that eventuated. The large volume of data collected was not originally anticipated, but provided a more extensive picture of current approaches that tertiary educators take in bioscience disciplines towards teaching scientific inquiry skills to students.

The short time lines of the project were a challenge, particularly as data collection needed to fit around educators’ teaching schedules. Consequently there were short time periods when large volumes of data were collected (e.g. semester breaks). The short time lines also meant that opportunities to observe teaching sessions were sometimes missed, particularly when the teaching schedules of participants from different states, clashed. The majority of data was collected by a research officer who was employed part-time. In retrospect, the project may have benefited from a full-time researcher with the flexibility to respond to educators’ teaching schedules.

5.5 Links to Other Projects in ALTC Priority Areas
The project was particularly interested in the findings of the ALTC project, ‘Re-conceptualising tertiary science education for the 21st century’ (2006). Although its specific focus was on laboratory learning it shared similarities with the current project in the area of generic skills in the laboratory and the role of multimedia and simulation in laboratory teaching. Interestingly, two of its recommendations have been addressed to some extent by the outcomes of the current project, namely that:

- The Australian Council of Deans of Science (ACDS) sponsors a project that provides models for the explicit identification, support and assessment of group work and problem solving skills in the laboratory context.
- The ACDS sponsors a project to identify a small suite of exemplers of the use of multimedia and simulation for first year science laboratory teaching and learning.
6. References


