Integrating Inquiry and Technology into the Undergraduate Introductory Biology Curriculum

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Abstract

The challenges facing educators of introductory science subjects include instilling in students a sense of discovery and inquiry instead of just transmitting content knowledge, and integrating assessments that are authentic and worthwhile. In addition, implementation of technology into the curriculum must both engage students and support effective teaching in the context of ever-increasing class sizes. The abstract, and sometimes counterintuitive, nature of biology, for example at a cellular scale, necessitates innovative pedagogical strategies that integrate varied avenues for inquiry-based experimentation and research-led teaching. In this paper, we present a revised curriculum for introductory biology that provides a scaffolded environment where students are encouraged to explore and develop their scientific reasoning skills in authentic theory and practical sessions. We describe and evaluate the design of this scaffolded curriculum, with reference to the integration of theory and practice, a productive failure-based structure of engaging with experimental design, and authentic research-contextualised assessment grounded in critical analyses and application of the primary literature. We also describe the use of technology-enhanced teaching strategies that promote collaborative and active learning, timely feedback for formative and summative assessments, and the integration of online and multimedia resources that support student-centred pedagogy. Our integrative curriculum emphasises developing independence and critical thinking so that students are better equipped for future study in an ever-changing world.

Introduction

Challenges for biology educators – diverse student expectations and experiences

Introductory biology courses are often comprised of diverse student cohorts. Students in first year biology bring a range of life experiences and prior knowledge of biology as well as a diversity of future career aspirations (Rice, Thomas, O'Toole, & Pannizon, 2009). For students who will not major in biology, introductory biology courses may be the only opportunity for them to engage in learning experiences with rigorous scientific reasoning and evidence-based inquiry approaches (Brewer & Smith, 2011). Although the learning and teaching of biology has the potential to be a rich and rewarding experience, in reality a more 'traditional' mode of teaching biology is dominant in many of our Australian institutions.

More often, content is didactically delivered in lectures and basic principles are confirmed in ‘cookbook’ lab experiments. Such approaches fail to address the learning needs of the diverse student cohorts in biology, and provide a fundamentally dry and static picture of the discipline (Handelsman, Ebert-May, Beichner, Bruns, Chang, DeHaan, Wood, 2004; Rice et al., 2009; Wood, 2009).

Perhaps one of the most disruptive mechanisms forcing curriculum change across the science disciplines is technology and the internet (Bahner, Adkins, Patel, Donley, Nagel, Kman, 2012). Massive open online courses and sites such as the Kahn academy deliver content which was previously available only in voluminous biology textbooks. Additionally, student engagement requires an integrated curriculum design in which course structures and supporting technologies play a key role in building engaging, collaborative experiences that support student growth (Krause, 2007; Bovill, Bulley, & Morss, 2011). Students, having grown up immersed in technology, are accustomed to and even expect that technology will be infused into their learning (Oblinger, Oblinger, & Lippincott, 2005; Krause, 2007; McNeill, 2011). Although it is commonly acknowledged that effective implementation of technology can offer significant gains in efficiency, creativity, collaboration, and deep learning (Bower, Hedberg, & Kuswara, 2010; Lee & Tsai, 2013), students can also perceive their teachers’ use of technology to be inadequate and therefore a challenge for their learning (Oblinger, 2003).

As a result of both a critique of science curricula and the disruption caused by technology, curriculum design has shifted to focus on the conceptual understanding and scientific reasoning in biology, grounded in relevant contexts and based on evidence. Such an approach is more pedagogically and developmentally fruitful (Lawson, 1990; Handelsman et al., 2004; Wood, 2009). Students too have suggested that introductory biology curricula should focus on applying scientific thinking rather than content memorisation in contexts which are real-world and provide opportunities for connections both within the discipline and to other disciplines (Wood, 2009; Brewer & Smith, 2011).

To do this, educators have used a number of strategies (reviewed in Allen & Tanner, 2005; DiCarlo, 2006; Wood, 2009; Bovill et al., 2011). These include focussing on student-led inquiry in laboratories (McKenzie & Glasson, 1998; Luckie, Maleszewski, Loznak, & Krha, 2004; Weaver, Russell, & Wink, 2008; Herron, 2009; Rissing & Cogan, 2009; D'Costa & Schlueter, 2013), grounding content and concepts in real-world contexts (Smith, Stewart, Sheils, Haynes-Klosteridis, Robinson, Yuan, 2005; Coker, 2009; Herron, 2009), integrating biology theory and practice (Lawson, 1990; Smith et al., 2005) and promoting active learning in lectures (Burrowes, 2003; Smith et al., 2005; Stein, Challman, & Brueckner, 2006; Ross, Tronson, & Ritchie, 2008). Another key theme in the recent biology education literature has been the infusion of research-enriched practices in undergraduate biology laboratories (Brew, 2010). These experiences range from the processes of working like scientists (McCune & Hounsell, 2005; Rice et al., 2009) to involving students in simple practical activities on academics’ research (Kloser, Brownell, Chiariello, & Fukami, 2011). The literature provides overwhelming evidence for the positive efficacy of these pedagogies, both in terms of student engagement, and learning (Burrowes, 2003; Luckie et al., 2004; Rissing & Cogan, 2009; D'Costa & Schlueter, 2013).

Case Study: A scaffolded, inquiry-based, technology-infused curriculum

We re-developed our introductory biology course from a content-focussed curriculum to inquiry-based learning, integrating research-enriched experiences and technologies to engage students, enhance collaboration, and better support the learning needs of a diverse cohort. Our large-enrolment introductory biology course ($n \geq 800$ students) comprised a mixture of students in major (approximately 40%) and non-major pathways across 15 degree programs, with a range of science backgrounds in which a majority of students may have prior studies in chemistry and physics but only 50% have prior exposure to biology.

As is generally the case with introductory biology courses, the course covered a wide range of biological concepts, from cell and basic molecular biology through to genetics, evolution, and biodiversity. In order to focus the content and provide opportunities in laboratory classes for scientific inquiry, we reduced from three to two 50-minute lectures per week, and increased from six to 11 three-hour laboratory sessions over a 13-week semester. The laboratory and lecture programs were tightly integrated to allow reinforcement and application of key concepts. The laboratory included experiences for students from guided inquiry to open inquiry to test hypotheses and critically analyse scientific data and the primary literature, in the context of real-world scenarios (Weaver et al., 2008). Such a program scaffolded the development of student skills. Our goal was to cultivate students who are able to scientifically reason and understand fundamental biological concepts, while developing a suite of essential lab skills through being exposed to authentic research-based experiences. Technology played a key role in supporting the laboratory experience and enabling forms of collaborative and student-centred learning. Previous studies on similar courses demonstrated that online resources improve learning (Peat, Franklin, Lewis, & Sims, 2002; Peat, Franklin, Devlin, & Charles, 2005). We built on these courses when designing activities to encourage independent thinking and learning.

Course Design: Structure and Evaluation

Student-centred learning experiences

In detail, the course was divided into three modules, reflecting levels of biological organisation: molecules and cells, genetics, and evolution and biodiversity. To promote active learning in a typically passive lecture theatre environment (White, 2006), interaction was achieved through group exercises interspersed between other activities often supported by student response systems (Caldwell, 2007; Lantz, 2010; Liu & Taylor, 2013). We used this strategy to explain and review abstract biological concepts, particularly in the molecules and cells module. Many lectures were supported with animations from the Walter and Eliza Hall Institute and Harvard University/XVIVO. Students commented that this "*helped bring textbook work into the 'real world'*".

We integrated technology in the form of formative 'online tutorial worksheets' delivered via a learning management system. Immediate feedback was provided on student misconceptions based on individual student responses. This process allowed students to revisit concepts and encouraged them to address shortcomings in their understanding, instead of providing the answer directly (Sadler, 1998; Nicol & Macfarlane-Dick, 2006). Students were allowed unlimited attempts to get the 'right' answer and statistics on how many times students revisited questions determined the concept areas to be covered in subsequent face-to-face revision sessions (Nicol & Macfarlane-Dick, 2006). Studies have found that applying knowledge to solve problems shortly after a learning activity, such as a lecture, improves students understanding and performance (Klionsky, 2008).

We also developed student independence and confidence with biological concepts using the *PeerWise* system (http://peerwise.cs.auckland.ac.nz). *PeerWise* is a web-based platform where students create exam-type multiple-choice questions evaluating other questions created by peers (Denny, Luxton-Reilly, & Hamer, 2008). Students were motivated to contribute, and a small proportion (less than 10-15%) of *PeerWise* questions were used in summative examinations. When *PeerWise* was first introduced into the course in 2012, the ratio of staff- to student-contributed questions was approximately 50:50. By 2013, 98% of the questions (n = 286) were student-contributed and only 2% or five questions were authored by staff. This occurred partly because short sessions on how to write multiple-choice questions (particularly about effective distractors) were introduced into lectures. This provided a rich space for collaborative student learning (Purchase, Hamer, Denny, & Luxton-Reilly, 2010). Students commented that *PeerWise* "*helped in finding weaknesses in my understanding which I could then relearn*", and that "*PeerWise is a good practical way to improve and review knowledge*".

The difference between student performance and understanding before and after the introduction of the changes to the curriculum and *PeerWise* was measured by analysis of students marks in the mid and final semester exams. Overall there was a shift to the right of the normal distribution of marks on the mid-semester exam from 2010 to 2013 (Figure 1). Intra-cohort analyses also suggested a positive trend between assessment performance and engagement with these resources (Figure 2 and Figure 3). This occurred even though the nature of these assessments was similar, although the questions were not identical. Nevertheless, these results support studies which have shown enhanced conceptual retention by students due to the repeated application of knowledge to test questions (Karpicke & Roediger, 2008). Throughout the study, a proportion of students did not engage with *PeerWise*, and yet the overall student performance in examinations shifted from an average of 48.0% (0.38 s.e.m.) in 2010 and 2011 to 58.6% (0.41 s.e.m.) in 2012 and 2013. Although more data are required before a causal link can be established between these strategies and student performance, data from other studies also suggest that student engagement in these formative activities improve learning outcomes (Peat et al., 2005; Cliff et al., 2008; Denny, Hanks, & Simon, 2010; Denny, 2011; Bates, Galloway, & McBride, 2012).

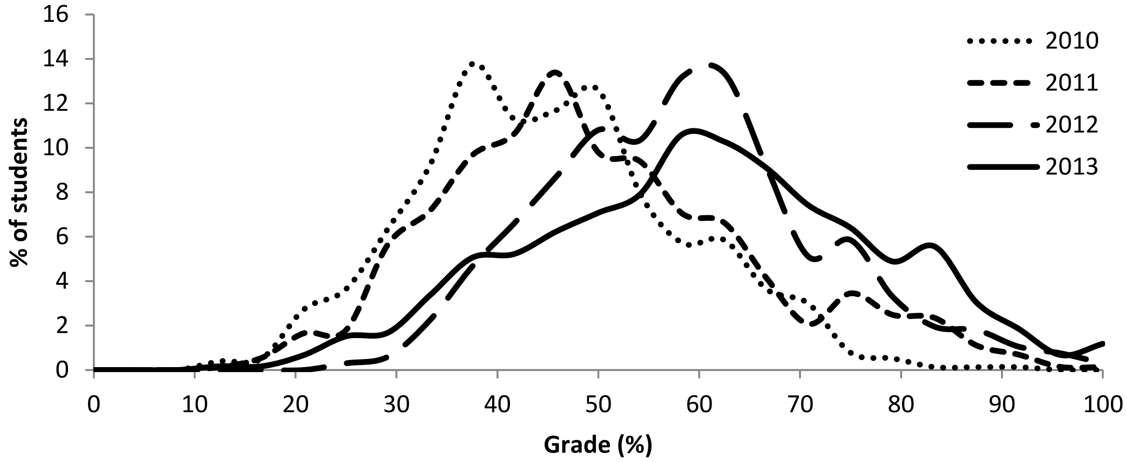

Figure 1 – Student performance in mid-semester tests from 2010 to 2013. The new curriculum and *PeerWise* was introduced in 2012. Online tutorial worksheets were introduced in 2013. Student numbers were 770, 726, 667, and 594 from 2010 to 2013 respectively.

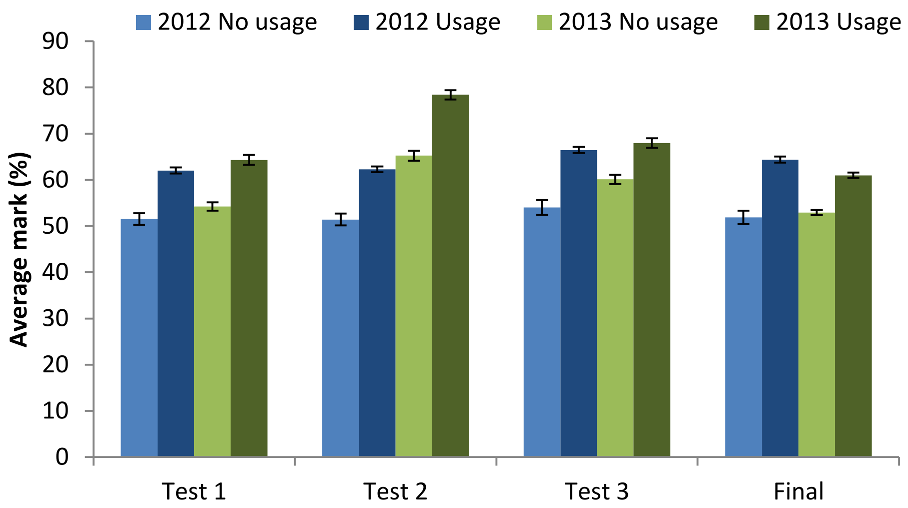

Figure 2 – Comparison of marks between students who did ('Usage') and did not use *PeerWise* ('No usage') in 2012 (74%, n = 863) and 2013 (36%, n = 727). Average marks shown for three in-semester tests and the final exam. Error bars show ± standard error.

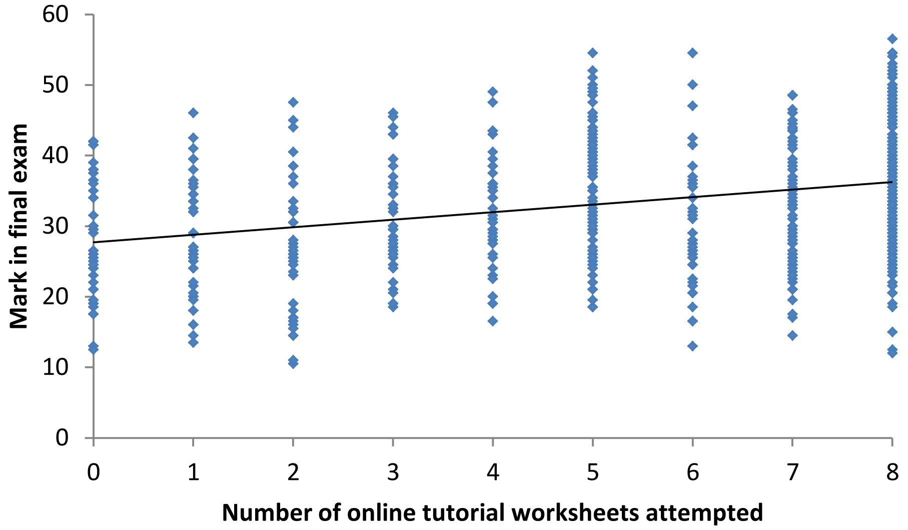

Figure 3 – Comparison of final exam marks to the number of on-line tutorial worksheets attempted in 2013 (n = 727).

Our course was supported by the university learning management system integrating the face-to-face and online activities (Garrison & Kanuka, 2004; Wood, 2009; Bovill et al., 2011). To support lectures and laboratory classes, we linked to numerous open-access multimedia and interactive resources, including selected YouTube videos, explanatory animations, and links to external websites providing further study resources (e.g., the Berkeley evolution site, http://evolution.berkeley.edu). An online discussion board provided another avenue for collaborative learning, and recently we have been experimenting with more modern forum software, Piazza (http://piazza.com; Topi, 2013), with encouraging preliminary outcomes (unpublished data). The provision of these online resources allowed students to engage with learning at their own pace and in their own space (Krause, 2007). Through this we were able to provide immediate feedback and increase time on task (Wilson, 2004; McCabe & Meuter, 2011). Student collaboration was possible as the resources encouraged students to think more deeply and allowed for the exchange of ideas between peers, especially in responses to questions (Figure 4).

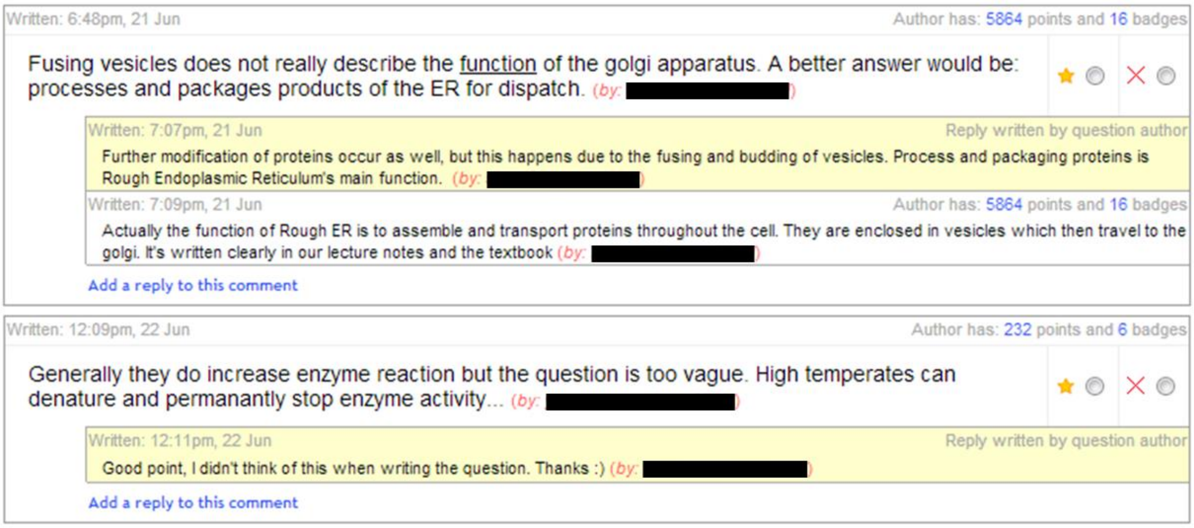

Figure 4 – Examples of students collaborating in two different *PeerWise* questions.

Investigative laboratory experiences

Laboratory classes are an integral part of introductory biology education, primarily because through practical work, students appreciate and learn the processes of science (Rice et al., 2009). Central to our curriculum review was the drive to expose students to authentic research environments (Brew, 2010). The research and inquiry process, however, can be daunting for students, who are not familiar with directing their own experiments (Weaver et al., 2008). In order to ease this transition for students and to help them develop sound scientific reasoning skills, we designed a scaffolded laboratory program that integrated with lectures to improve students' understanding of theoretical biological concepts (D'Costa & Schlueter, 2013).

A key behaviour integral to biology is effective record-keeping. In our new curriculum, first-year, first-semester biology students kept a laboratory notebook. A resource manual was provided to students which provided examples of relevant notebook entries. There is currently much discussion about the efficiency and possible disadvantages of electronic notebooks, as scientists trial their adoption in their research laboratories (Butler, 2005). We nevertheless, encouraged students who wished to keep entirely digital records to explore this themselves, and were pleasantly surprised with the quality of these elementary 'electronic notebooks' and the seamlessness with which laboratory data (such as spreadsheets, microscopy images, gel photographs, and even videos) were integrated with other records. Students predominantly used word-processing programs such as Microsoft Word or Apple Pages, or specialised note-taking software such as Microsoft OneNote, to keep their notebooks.

A range of laboratory and inquiry thinking skills were introduced over six weeks (Table 1). The first practical encouraged students to explore microscopic biodiversity. This was selected as an activity to provide genuine investigative choice and nurture the curiosity of incoming first-year students (Brewer & Smith, 2011). It was coupled with an introduction to scientific record keeping. During this practical, students explored a range of possibilities for making and recording their observations on the organising principles of cellular movement and subcellular architecture. To do this they used digital cameras attached to microscopes and cameras on their mobile phones to capture images and videos. Following the learning cycle instructional methodology (Lawson, 1990), these biological phenomena were then explored in subsequent lectures on cells and organelles where lecturers used student images and videos. Student videos were also uploaded onto our official YouTube channel. These strategies engaged students, who commented they benefitted from "*the ability to decide which organism to examine*" and "*finding the structure and taking an awesome picture*". We also held a microscopy competition for the best scientific still image and best video, as incentives for students to explore different ways of visualising and communicating the complexity and diversity of the biological systems they were investigating. These were sponsored by the microscope suppliers and students were recognised for their achievements at an official prize night.

Subsequent practical sessions, contextualised in real-world scenarios, scaffolded further laboratory techniques and experimental design principles (Table 1). Hypothesis generation and testing are central to the practice of biology and the critical features of these processes have been demonstrated to provide significant challenges both for teachers and learners (Taylor, 2006; Taylor & Meyer, 2010). Our previous trials of diagnostic surveys of student misconceptions about hypotheses (Taylor, Meyer, Ross, & Tzioumis, 2013; Zimbardi et al., 2013) provided evidence to target key problems in thinking about hypotheses during review sessions. Initial guided-inquiry laboratories involved working in small groups to test instructor-led experimental designs and class hypotheses (Weaver et al., 2008). To motivate deeper student learning (Chin & Brown, 2000), relatively simple experiments were grounded in real-world contexts with a focus on engaging with the primary literature. For example, the influences of fruit ripening or rhizosphere microenvironment on enzyme activity in agricultural crops were used to contextualise an otherwise 'confirmatory' practical experience (Rice et al., 2009). The relatively simple nature of these earlier sessions allowed space and time for students to 'fall over' in their experiments and review the results, a process modelled on the ideas of productive failure (Luckie et al., 2004; Kapur, 2008). We found that students in this situation learnt not to strive for the 'right answer', but instead critically reviewed their procedures and experimental results. In keeping with the scientific inquiry themes, students wrote a brief scientific article outlining their class' results and integrated them with references provided from the primary literature.

As a result of this scaffolding, students were better equipped to handle less-structured, open-inquiry situations on photosynthesis later in the course (Luckie et al., 2004; D'Costa & Schlueter, 2013). Since the curriculum design had to take into account the constraints of the large enrolment, both in terms of assessment consistency and procedural practicalities, students were offered a constrained set of variables and materials upon which to base their experimental design (Kloser et al., 2011). Working in small groups, students developed their own question and hypothesis with minimal guidance from instructors, co-operatively arriving at a protocol with sound experimental design using principles learnt in previous sessions.

Together, students conducted their own experiment, analysed and assessed their data, using skills developed in previous sessions. By collaborating on this experiment, students built their scientific teamwork skills and increased independence (Smith et al., 2005; Bovill et al., 2011). This open inquiry project culminated in students writing a scientific paper based on their results. Other inquiry-focussed experiments included the identification of a fictitious viral outbreak using restriction digestion (Michigan State University, 2003), discussion of the impact of genetic drift on populations (Andersen, 1993), and collection of invertebrates and analysis of biodiversity in the local area. These activities maintained student motivation by addressing questions grounded in real-world contexts.

Table 1 – Progression of skills and inquiry learning, from guided to open, in the first half-semester of the practical curriculum, culminating in an independent student project on photosynthesis. Elements of inquiry (Weaver et al., 2008) were instructor-led (I+S), instructor-assisted (S+I), or student-led (S).

		Practical focus			
		Week 2 Cells	Week 3 Enzymes	Week 4 Respiration	Week 6 Photosynthesis
Elements of inquiry	Observation and questioning	S			S
	Experimental design		S+I	S+I	S
	Data collection and analyses	S	S+I	S+I	S
	Reporting and peer review		I+S		S
Skills	Microscopy	S+I			S
	Liquid handling		I+S	S	S
	Spectrophotometry		I+S		S
	Data analysis		I+S	I+S	S
	Primary literature		S+I		S

Similar frameworks for curriculum re-development have also focussed on more inquiry-based pedagogy (Willison & O'Regan, 2007; Brew, 2010). It has been shown that investigative laboratory experiences lead to deeper understanding of course material which is reflected in enhanced assessment outcomes (Luckie et al., 2004; Rissing & Cogan, 2009; D'Costa & Schlueter, 2013) and is positively received by students (Luckie et al., 2004; Herron, 2009; Wood, 2009; Beckman, Ferru, & Beckmann, 2013). Students within our courses engaged with the experiments (Figure 5) and commented that they were appreciative of "*being in complete control of our own experiment*" and "*thinking about the design of the experiment and coming up with our own – made me understand photosynthesis*". In their formative article, Chickering and Gamson (1987) wrote: "*Expect more and you will get more*"; indeed, we communicated high expectations of students in this re-developed course, and they were keen and able to take on this challenge. Additionally, deliberate contextualisation of their experiments (Smith et al., 2005) allowed students to see that "*there was a practical purpose for the course with real world applications*" and that it "*put into practice and reinforced concepts learnt in lectures*".

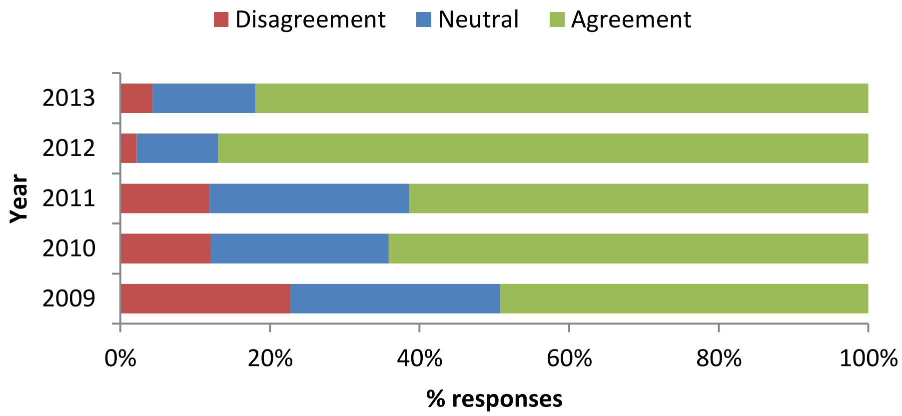

Figure 5 – Student responses to unit of study evaluation question '*The tutorial/practical classes were worthwhile*'. The inquiry-based laboratory curriculum was introduced in 2012. In 2009 to 2013, n = 365, 503, 557, 327, 568 respectively.

Throughout the laboratory course, various forms of technology were integrated to provide a blended learning experience. Before each session, students were required to complete a minimally-weighted summative pre-lab quiz based on their reading of the practical notes and interaction with online material such as videos that introduced equipment or presented alternate explanations of biological concepts. We used learning analytics on student performance from these quizzes to implement "Just in Time Teaching" (Marrs & Novak, 2004). Using this technique, laboratory supervisors addressed key student misconceptions before each session commenced. Similar to other reports (Gregory & Di Trapani, 2012), our teaching staff noted greatly improved student attitudes and aptitudes in laboratory sessions. Students commented that "*pre-lab work really stimulates the content and acts as tool of [sic] revision*". Students also found the pre-lab work useful; for example, a pre-lab video was used to explain how to use the micropipette. During an in-class demonstration students commented "*when the demonstrator was explaining it, I was going like, oh yeah, I can recall [this]*". Within laboratory sessions, technology was used to collect data (e.g., digital cameras attached to microscopes, students recording data on personal devices) as well as collate and analyse data (e.g., gathering class data on publicly-accessible Google spreadsheets; Herr, Rivas, Foley, Vandergon, & Simila, 2011). Post-lab videos were also used to deliver and present class data (e.g., screencasts of data analyses). The pre-lab and post-lab videos received high audience engagement, especially around assessment times (Figure 6). Together, these technologies have allowed us to engage students and meet their expectations of a technology-infused course (Oblinger et al., 2005).

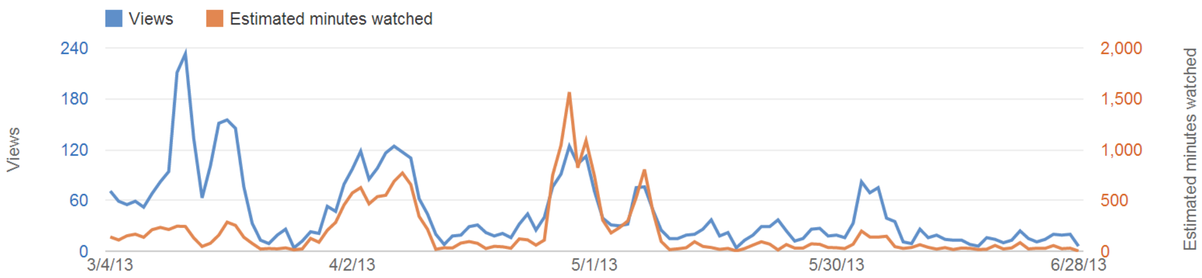

Figure 6 – Representative access analytics for YouTube videos from semester 1, 2013. Daily view counts (left-hand y-axis) overlayed with daily minutes viewed (right-hand y-axis). Mid-March peaks correspond to pre-lab instrumentation videos, and early-April and early-May peaks correspond to post-lab data analysis videos.

Authentic, continuing assessment and timely, personal feedback

It is critical that early on in a university education students are introduced to the primary literature and have opportunities to integrate it into their writing (Luckie et al., 2004), even though this may be seen as a primarily senior-year endeavour (McCune & Hounsell, 2005). In providing students with an authentic biology education, it is important that peer review should form part of this process (Brewer & Smith, 2011). Pragmatically, peer review is an efficient way for students in a large-enrolment course to receive feedback, whilst gaining valuable insight into their own and other students' writing (Luckie et al., 2004).

As with all other areas of the course, the scientific writing and peer review components were scaffolded. Students first wrote a short preliminary discussion paper with provided literature before writing their major paper and searching and selecting relevant literature. To start, students first wrote the results and discussion sections, based on the results from the enzyme experiment (Table 1, week 3). This required students to analyse, present, and describe data, and briefly relate their findings to the primary literature provided. This process was supported by lectures on information literacy and the use of scientific databases. It culminated in a guided peer review session. During this session, students were given two exemplars to assess in small groups, followed by instructor-led discussions of salient points in exemplars. These points were summarised into a series of criteria, which were then compared to a staff-prepared rubric. In most cases, the points raised by students readily assorted into the rubric, which was then used as a template for peer review. We chose to use peer review in our feed-forward process since the large class sizes precluded staff providing quality feedback for individual students, and previous studies on writing to learn (Ellis, Taylor, & Drury, 2007; Taylor, 2007) had shown that the process of reading and reviewing the work of others would lead to greater self-reflection on the writing process. Students worked in small groups to review de-identified papers from the same class, while instructors assisted where necessary. A subsequent class discussion brought together the main points, and allowed students to complete a reflection sheet documenting their planned improvements for their own paper (Taylor & Drury, 2007). This session also provided an opportunity to openly discuss the complexities of academic plagiarism in the context of the application of Turnitin similarity detection software (http://turnitin.com). Students were introduced to a number of Turnitin 'originality report' exemplars, and the various matches highlighted by the software were explained. These included false positives where the software detected a string of text that coincidentally or inconsequentially matched another source, as well as the distribution of appropriate and inappropriate sources. Students were permitted to see their originality report for the first submitted paper to assist them in determining the effectiveness of their paraphrasing efforts (Emerson, Rees, & MacKay, 2005). This whole process was conducted primarily as a formative learning exercise, and comprised a nominal summative assessment.

Table 2 – Summative assessments in the re-developed curriculum. Week designations are representative only of relative timing in a 13-week semester (MCQ, multiple-choice questions; SAQ, short-answer questions).

	Assessment	Timing	Assessment type	Feedback timeframe	Weighting (%)
Laboratory	Pre-lab quizzes	Each week	MCQ online	Immediate	5
	Laboratory notebook	End of semester	In-class	Immediate	5
	Draft papers and peer review	Weeks 5, 8	In-class	Immediate	7
	Final paper for independent project	Week 9	Submission	2-3 weeks	15
Laboratory + lectures	In-semester tests × 3	Weeks 5, 10, 13	MCQ paper	Same day	30
	Final exam	Examination period	MCQ & SAQ paper	None	38

Subsequent to this introduction to scientific writing and the use of primary literature, students were asked to write a draft paper on their open-inquiry project (discussed in the previous section). This required a deeper engagement with primary literature. The draft paper was peer-reviewed in a session that was less instructor-centric, and allowed students to review all components (introduction, methods, results and discussion) of peers' de-identified papers. This process of producing a draft paper of reviewable quality and participating in peer review again formed part of students' summative assessment. The final paper was created using feedback from peer review and was assessed by independent markers forming a substantial portion of the assessment (Table 2). For these papers, students were not permitted to view Turnitin originality reports for the draft or final versions, because the former might facilitate the dishonest rearrangement of phrases just to avoid detection (McKeever, 2006), while the latter would be of little instructional utility.

In addition to assessments based on scientific writing, student-centred learning was further promoted through a system providing personalised feedback for summative in-semester examinations. Using a customised version of bespoke software developed internally at the university (Bridgeman & Rutledge, 2010), results from multiple-choice examinations were processed and delivered to students via email approximately 4-6 hours after the conclusion of each examination. The personalised message contained specific feedback that addressed misconceptions and suggested explanations for the biological concepts being assessed, providing encouragement and offers of support for students with lower marks. The timeliness of feedback provision was vital in maintaining relevance and student interest and these directed comments helped learners improve (Higgins, Hartley, & Skelton, 2002; Nicol & Macfarlane-Dick, 2006). Students commented that "*getting the test back the night it's done maximised time to learn from mistakes*" and "*detailed answers catered to how you answered wrong were great*". Additionally, the personalised aspect of these messages promotes student engagement (Bridgeman & Rutledge, 2010), encouraging students to take responsibility for their own learning. An added benefit of this software was its ability to generate reports and question metrics which were used in curriculum review by academics and course designers to create more effective assessment questions (McAlpine, 2002; Crisp & Palmer, 2007).

Overall, the summative assessments in the course aimed to provide a balance between content and competencies (Table 2). Students' laboratory notebooks were formatively and summatively assessed based on a three-point rubric (satisfactory, incomplete, absent; Allen & Tanner, 2006). Students engaged with their laboratory notebook which was measured by the quality of records. They also engaged with peer review, writing, and pre-lab work. The weighting of these laboratory-based components was increased to emphasise the importance of competencies in biology education (Brewer & Smith, 2011), and the formal examinations included a number of skills-based questions from the laboratory curriculum (Table 2). Formative and summative assessments were distributed throughout the semester, primarily to set the expectation of ongoing engagement and to allow frequent opportunities for instructive feedback. Not only did students benefit from this, but ongoing assessment enabled us to evaluate our teaching effectiveness based on student feedback and performance analytics.

Cohesive and Engaged Teaching Team

Implementation of a new curriculum relied on a committed and collaborative teaching team comprising of academics who lectured and a large number of sessional staff who taught in the laboratories. Most of the lecturers also taught laboratory classes. As is typical in Australia, most of the laboratory-based sessional staff were PhD students, with a small number of Honours or Masters Students. Each laboratory has a student: staff ratio of approximately 15:1 and the laboratory supervisor was responsible for leading class discussions. Demonstrators rotated within their class every week to give students the opportunity to interact with a variety of demonstrators over the semester.

Demonstrators were selected only after a round of interviews, and training sessions were held twice a semester. At these sessions, course objectives and our teaching ethic were articulated and demonstrators performed key practical activities to appreciate the students' point of view (Lawson, 1990). New demonstrators were 'buddied' with experienced demonstrators to enable peer-mentoring. Moreover, some experienced demonstrators were given the opportunity to take on more responsibility as laboratory supervisors. In this way, course coordinators mentored supervisors, who mentored experienced demonstrators, who mentored new demonstrators. At the end of semester, the supervisors' and demonstrators' contribution to the course was celebrated at a large debriefing session where they were closely involved in reviewing the entire course. The co-operative and collaborative nature of this feedback loop meant the teaching team remained cohesive and engaged (Smith et al., 2005). As is often the case (Rice et al., 2009), our student evaluations (formal university and specifically designed curriculum review instruments) reported that the teaching staff in laboratories tended to be the most significant influence in students' learning. This was because of the amount of time spent in laboratories and the level of active engagement that occurs in these sessions. Students commented that the team provided an effective environment for student learning: "*The laboratory classes are really amazing. I learned a lot and had a lot of fun during the lab classes. I think it is really good that students can learn in such a good environment. Learning with fun can help students to learn better*". Students also commented that the laboratory sessions "*were educational and enjoyable. I felt like the class and the tutors were a community by the end that I was part of*".

Training and feedback for teaching staff extended beyond the laboratory classes. A large group of demonstrators was also involved in assessing the students' open-inquiry papers. We moved this process online to the Turnitin system for all paper submissions and operations. Demonstrators who marked papers for the first time received training, where the application of criteria and standards were assessed by team-marking of a number of student papers. Through this process, common student mistakes were identified, and a data bank of common feedback to be provided was created within Turnitin for all markers to use. This was done to promote consistency of feedback. When a large team of markers is involved in assessing a large number of student papers, marking inconsistency can be an issue. This was addressed by asking markers to randomly assess three papers, which were then audited by the course co-ordinators to ensure the level of grading and the provision of feedback were consistent. Each marker was provided with feedback to recalibrate their marking before students received their final grade. This training and mentoring process was crucial to ensure equity in our large enrolment cohort. It also created a cohesive and engaged teaching team, made more efficient because of the use of technology.

Conclusions and implications for practice

Large, diverse cohorts are typical of introductory biology courses. Our aim was to integrate inquiry-based learning, authentic assessments, and technology. These features were key facets in a re-developed curriculum, which had a scaffolded investigative laboratory course synchronised with lectures where concepts were developed through the use of active learning pedagogies. Technology supported the core of this curriculum, enabling students to flexibly collaborate and engage inside and outside of class. We have presented a descriptive account of the methodologies that we have found to be effective in promoting active, student-centred learning. Some of the strategies which are novel include *PeerWise* and electronic notebooks, and both were relatively easy to implement. Other strategies, such as videos, online tutorials, and interactive lectures, were more technologically and pedagogically challenging to implement but have the benefit of economies of scale. Once a video is made, an online tutorial is developed, or interactivity is thoughtfully integrated into a lecture, many students receive the benefits simultaneously. Moreover, technology affords significant gains in personalisation, immediacy, scalability, and consistency which are crucial in subjects with large-enrolments. Re-development of an entire practical curriculum requires substantial commitment from a range of teaching staff, but is necessary to engage students with inquiry. This current case study of our curriculum re-development adds to the growing body of work that describes inquiry-based reform that is supported by emerging technologies. Our collection of ideas and strategies of varying complexities serves as a foundation of investigation for other practitioners. However, we acknowledge the difficulty in collecting empirical data on the causal links of curriculum change and student learning. In the future, we plan to use student performance and engagement analytics as a basis to track student learning. Additionally, we plan to further leverage technology to shift the learning focus to be even more student-centred (Smith et al., 2005), so that the limited face-to-face class time can be used for context-driven active learning. Through these pedagogies, students will be better equipped to think through the biological questions that they will face, regardless of the career they pursue.

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