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Revisiting the Research-Teaching Nexus Framework: Two Case Studies Introducing Research into Program Level, Undergraduate Teaching

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Internal and external drivers have seen institutions of higher education place increasing emphasis on the links between teaching and research in their curricula. Despite the apparent positive trend towards research-oriented undergraduate programs, there are a number of documented challenges or "risks" to incorporating research into teaching and learning. This paper presents an adapted four-quadrant framework that maps student progression throughout a program of study from research-briefed learning to carrying out independent research themselves. The model is illustrated by two case studies of its implementation throughout entire degree programs (Natural Sciences at the University of Leicester and Integrated Science at McMaster University).

This paper sets out to offer a theoretical framework and accompanying case studies to explore the nexus between teaching and research on a program wide basis. The research-teaching nexus has been an area of interest and research for over 30 years (Barnett, 1992; Griffiths, 2004; Malcolm, 2014; Robertson, 2007). It is now widely accepted that Higher Education institutions (HEIs) endeavour to develop links between teaching and research within their curricula, and many institutions advertise their curricula as research-led (Brown & Smith, 2013; Hattie & Marsh, 1996). Studies have shown that students learn more effectively and find more relevance in what they learn when provided with a clear and direct link to current research (Cantor, DeLauer, Martin, & Rogan, 2015; Harland, 2016; Lopatto, 2007). The motivations for clearly linking research and teaching extend beyond just the students, however; they extend to the faculty and staff, the university, and society as a whole (Harland, 2016).

The increasing complexity of modern society (and its problems) requires graduates to be capable of critically evaluating information to develop creative solutions to the challenges that society faces. Students see the value of research within the curriculum, and although their understanding of research is variable, research is accepted as an integral part of university life and academic experience. Students also expect cutting-edge research to be referenced in their classes (Jenkins, Blackman, Lindsay, & Paton-Saltzberg, 1998; Zamorski, 2002) and see the involvement of research as an important component towards their employability (e.g., independent research and learning skills) (Healey, Jordan, Pell, & Short, 2010). Indeed, data from our own survey confirm this trend. Students entering the Honours Integrated Science Program at McMaster (2012-2017) rank research skills significantly higher than independent learning skills (Figure 1), with 86.5% of incoming students ranking research skills as highly important or important.

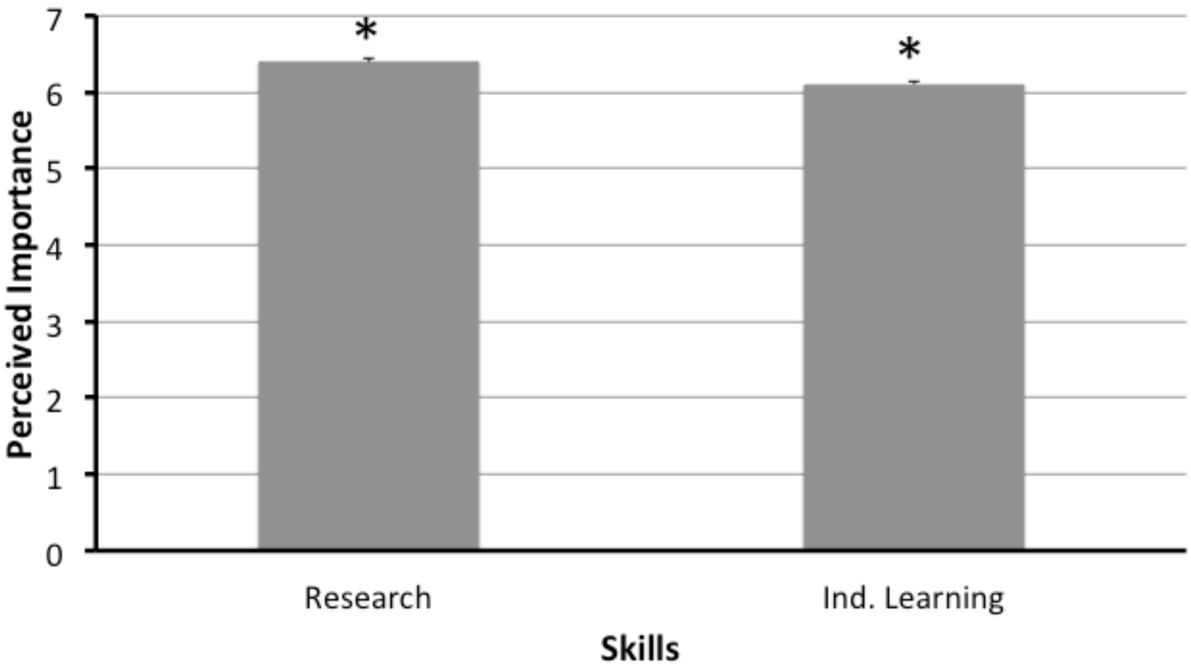
Thus, today's students appear more aware of, and have a desire to be involved in, academic research. Most academics are in agreement about the need for research to be included in the curriculum (Zamorski, 2002), having themselves argued the benefits of being taught by active researchers and being directly involved in the research process (Healey et al., 2010). Increased student awareness and high enrollment in HEIs because of teaching that includes research also offers a competitive advantage and reputational credit to those institutions (Schapper & Mayson, 2010). Indeed, there is a historical governmental demand for this linkage to occur. For example, an extensive review and analysis of the lack of research in undergraduate education in American research-oriented universities, The Boyer Commission noted:

> …they should take advantage of their research dimension and "bring undergraduates into the big tent". Undergraduates should be included in research endeavors, which are now primarily the province of professors and their graduate students. Undergraduates should be made part of research teams, and traditional lecture courses should be restructured to promote "inquiry-based learning", in which students explore a topic in much the same way that a researcher approaches scholarly work. (Wilson, 1998 pp. 2-3)

This has encouraged a shift in many HEIs towards evidenced-based teaching that assists students in the development of these research skills that will equip them to become creative problem-solvers (Brew, 2010).

This ethos summarizes the foundation and motivations for the two interdisciplinary science programs outlined in this paper. Yet, despite the apparent positive trend towards research-oriented undergraduate programs and external motivators for

Figure 1
Perceived importance of research versus independent learning skills



Perceived importance (mean ± 1 SE; N=327) of research versus independent learning skills by first year students, entering the Integrated Science Program at McMaster University 2012-2017, as ranked on a 7-point Likert scale. * Difference assessed with a two-sample t-test ($t = 3.9997$, $df = 642$, $p\text{-value} < 0.0001$; R v. 2.13.1).

HEIs, there are a number of documented challenges or "risks" to incorporating research with teaching and learning (Gresty, Pan, Heffernan, & Edwards-Jones, 2013; Pan, Murray, & Cotton, 2011). Generally, these initiatives have resulted in mixed results across institutions (Barrie & Prosser, 2004; Schapper & Mayson, 2010). Brew (2001), notes that "the belief that there is a connection is stronger than the statistical evidence" (i.e., quantitative evidence) when it comes to the relationship between teaching and research (p. 146). Zamorski (2002) reports that "formal institutional policies to manage a direct relationship between research and teaching are sometimes weak" (p. 413). This could be true, as most initiatives require champions at multiple administrative levels and a solid funding base to gain traction. The clear separation of funding for teaching (typically from tuition monies) and funding for research (typically from public or private external funding bodies) has often resulted in institutional organizational structures mirroring this dichotomy (Brew, 2010; Malcolm, 2014; Mayson & Schapper, 2012). Indeed, external research funding bodies in countries such as Australia discourage involvement of undergraduates in research (Brew, 2010). Add this to the ever-increasing undergraduate class size and cohort diversity (Brew, 2001) and it is no wonder that many academics are often hesitant to include more research opportunities for undergraduates. They perceive a lack in student skill sets, the need to relinquish control over the research process, and an inability to balance their time between their own research and that of the students to ensure a consistent level of student learning (Gresty et al., 2013). This perceived tension is also a major concern of the students (Henri, Morrell, & Scott, 2018). Conducting research is not easy, as it does not have defined answers and may not work exactly as one planned. These factors put more apparent responsibility on the student to learn: the learning must be more active and less passive. There is not necessarily one correct answer, so this is a method of learning that requires time as well as some experience to see the benefit (Spronken-Smith, et al., 2011). These factors are challenging for both faculty, staff, and students.

These risks, however, can be managed (Gresty et al., 2013). Awareness is the first step to addressing these risks. Change and innovation require time for adaptation, particularly at the higher administrative levels in an institution (Brew, 2010). There is a growing body of research identifying successful methodologies to incorporate a research-teaching link in undergraduate courses at the classroom level, yet few (if any) successful examples of administration-level implementations (Mayson & Schapper, 2012) across a whole program. This is likely due to varied interpretation of who is required to make the research-teaching linkage (Barnett, 1992) and a lack of clear mandates necessitating appropriate pedagogical change (Hattie & Marsh, 1996; O'Neil, Smith, & Brown, 1995). As communicated by Schapper and Mayson (2010), "establishing links between research and teaching at the level of academic departments can connect discipline-based research with student learning, thereby better integrating research and teaching" (p. 647). This middle administration level can establish a better integration of research and teaching, with some administrative pressure, yet avoid the more challenging levels of administrative "red tape" (Brew, 2006).

Malcolm (2014) points out that because "the research-teaching link is constructed and contingent, the next stage of research will involve moving beyond the illustrative and taxonomic" (p. 297). We agree with this view, but also see the importance of illustrative contexts to demonstrate the motivation and mechanism for how to make such a change. With this motivation, the two objectives of this paper are first, to present a more representative four-quadrant model that illustrates student progression to research-apprenticed learning (i.e., learning science by doing science) and second, demonstrate the quadrants of our model by providing two examples for how a progression to research-apprenticed learning can be implemented at the program and/or department level.

Research: Teaching framework

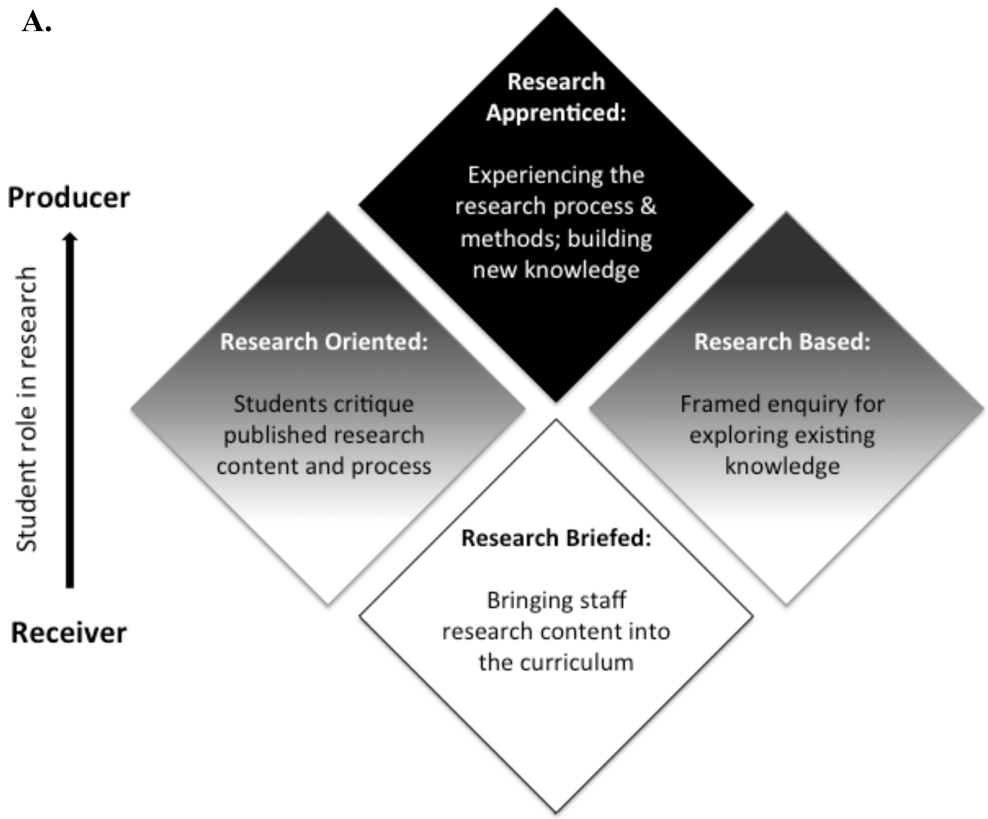
There has been a short history of research into mapping the teaching-research nexus. Hattie and Marsh extensively studied the necessity of research and teaching being linked, including a meta-analysis (1996) and decade-long summary (2004). That there is a clear linkage between research and teaching in higher education is, in our opinion, not debatable. As pointed out by Griffiths (2004), however, "there is a need to acknowledge that the nature of the possible relationships between research and teaching, and indeed the very meaning of these terms, will vary according to the discipline context or field of inquiry" (p.710). There have been many attempts to identify and characterize the research-teaching nexus to address the question of how to introduce, reinforce, and equip today's students with the background and skills to transition from being knowledge consumers to knowledge producers. This body of research starts with the simple observation that there is a difference between *knowledge discovery* and *knowledge application* (Boyer, 1990). Hattie and Marsh (2004) reinforce this with the overall result of their meta-analysis: "it would be difficult to imagine today's university teachers not being aware of recent research, although whether they have to also generate this research to be excellent teachers is questioned by the results of this and other studies" (p.11). Bringing this notion into teaching practice, Griffiths (2004) characterized this variation into four main teaching categories, namely:

- Teaching can be *research-led* in the sense that the curriculum is structured around subject content, and the content selected is directly based on the specialist research interests of teaching staff; teaching is based on a traditional "information transmission" model, where the emphasis is on understanding research findings rather than research processes; little attempt is made to capture the two-way benefits of the research-teaching relationship.
- Teaching can be *research-oriented* in the sense that the curriculum places emphasis as much on understanding the processes by which knowledge is produced in the field as on learning the codified knowledge that has been achieved; careful attention is given to the teaching of inquiry skills and on acquiring a research ethos. The research experiences of teaching staff are brought to bear in a more diffuse way.
- Teaching can be *research-based* in the sense that the curriculum is largely designed around inquiry-based activities, rather than on the acquisition of subject content; the experiences of faculty and staff in processes of inquiry are highly integrated into the student learning activities. The division of roles between teacher and student is minimized, and the scope for two-way interactions between research and teaching is deliberately exploited.
- Teaching can be *research-informed* in the sense that it draws consciously on systematic inquiry into the teaching and learning process itself.

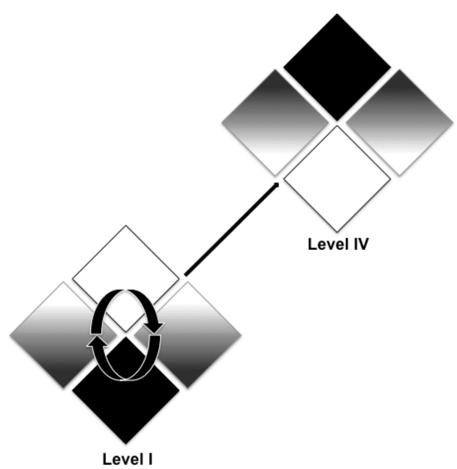
Even with this seemingly clear set of categories, much overlap and reiterated terminology has caused confusion and ambiguity in the literature, particularly with the interchangeable use of research-led and research-informed teaching along a continuum of involvement of students through to faculty and staff (Gresty et al., 2013; Trowler & Wareham, 2008). Here we present a further adapted version of a research-teaching model: including what we term research-briefed (towards students learning course content by actually doing research), and generation of new knowledge, termed research-apprenticed learning.

Figure 2
***A.** Research-teaching nexus portraying a continuum of student learning from the roles of research receiver to research producer*
***B**. Concentrations of learning occurring in Levels I to IV*

A.



B.



Progression through the quadrants is best approached in a constructivist manner with successive iteration through each quadrant to reinforce perspectives, review practices, and affirm research development. Both the Natural Sciences Program, at the University of Leicester, and the Integrated Science Program, at McMaster University, have used this framework with high levels of success over more than a decade.

This framework contains four quadrants as identified in Griffiths (2004), Healey (2005), and Levy (2009). We have re-positioned the quadrants into a diamond shape, which better illustrates student progression as a researcher (Figure 2), the general progression from receiver to producer, but emphasizes that this process is not necessarily chronological. The lowest quadrant contains activities that require the student to act only as a receiver of research knowledge. The two middle quadrants are both more student-centred, requiring engagement with the research process. In both research-based and research-oriented activities, students are involved in aspects of the research process but are not generating new knowledge themselves. These activities are a necessary step: by experiencing and understanding the research process, students will be more adequately prepared when they undertake a research project (Buckley, 2011) which requires the generation of new knowledge. In this framework, students benefit from both types of activities in the mid-section of the diamond, but they do not need to undertake them in a particular order and can pursue these activities concurrently. They are also presented as equal in terms of the level to which students are producing research. It is most beneficial for these middle activities to occur before the research-apprenticed stage, but the framework is not necessarily linear. Indeed, as with active research, learning can be enhanced by cycling through each quadrant, with students gaining greater depth of understanding with each cycle.

Program Descriptions

The authors of this paper come from two programs that share many design and pedagogical similarities: the Natural Sciences Program at the University of Leicester, UK and the Honours Integrated Science Program at McMaster University, Canada, and effectively collaborate at the student, faculty, and staff level (Hurkett et al., 2018). Most importantly, both programs utilize a central design based upon research-apprenticed learning. Students learn through interdisciplinary research projects motivated by modern issues relevant to society (e.g., nanoscience, sustainable energy, planetary exploration, drugs and disease). The projects require students to understand the links between scientific disciplines and to develop both the practical and communication skills necessary for the demands of post-graduate employment or studies. Each research project requires a high level of collaboration between students, and instructors, generating an environment in which highly motivated students can track curricular learning objectives, yet be free to explore creatively and discover. One of the main principles these programs share is a progressive and scaffolded pedagogical approach that leads students into research-apprenticed learning. By progressively exposing students to elements from each quadrant of the framework, the students gain a deep understanding and confidence in the methodologies, perspectives, and freedoms associated with a research-apprenticed learning environment.

The two programs employ a high proportion of teaching-focused academics conducting pedagogical research, and research-focused academics who embrace the scholarship of teaching and learning and pedagogical innovation. This combination establishes a learning environment in which students are presented with current, research-briefed content, yet are also well supported to progress towards becoming knowledge generators themselves.

The Natural Sciences (formerly Interdisciplinary Science) program was established at the University of Leicester in 2004 with funding from the Higher Education Funding Council for England. Both the three-year BSc and four-year MSci variations of the program offer an alternative approach to UK undergraduate science teaching. The synthesis of teaching and research, which engages students in the research process throughout their degree (Gretton, Raine, & Bartle, 2013) and the interdisciplinary nature of the content, which spans the entire degree program, distinguish the program within the UK HE environment.

The Integrated Science Program (iSci) at McMaster University was established in 2009 with a mandate from the Dean of the Faculty of Science to develop future scientific leaders. iSci is a four-year Honours BSc program specifically designed to engage students with all facets of the research-teaching framework within each course and across all years of the program. This is achieved by having only a single, large (with respect to credited units) course (module) for each year-level. Similar to the Leicester program in the UK, the four-year, integrated, interdisciplinary structure of iSci, with its emphasis on research-apprenticed learning, make it highly innovative in Canada.

Another commonality of the two programs is their initiation from a blank slate, which has provided the freedom to incorporate this research-teaching framework into their program and curricular design, with particular emphasis on pedagogies that facilitate student learning within a research-apprenticed environment.

Using all Facets of the Research-Teaching Framework

There is disparity as to the approach to teaching that most effectively links research with teaching (Malcolm, 2014; Spronken-Smith & Walker, 2010). All facets of the nexus come with pros and cons that span the instructor-student experience continuum (Gresty et al., 2013). Within our framework, research-apprenticed learning places the student in the most research productive role and therefore, we argue the most effective learning activity. We are very aware, however, that for students to learn effectively in a research-apprenticed environment, they need to acquire basic skills, approaches, and trust in their peers and instructors. That said, within our framework, this acquisition of skills can happen much more quickly than seen in more traditional models; students can be effectively engaging with research-apprenticed learning by the end of their first year of undergraduate study, as opposed to their third or fourth year.

Indeed, by exposing students to all the "lower" sectors of the research-teaching framework, we can take a scaffolded or constructivist approach (Vygotsky, 1978) to understanding the research process, ensuring the student can more effectively embrace the perceived challenges of a research-apprenticed experience, and concomitantly, that instructors feel that students are more prepared (Healey & Jenkins, 2015; Lips, 1999; Spronken-Smith et al., 2011). This contrasts with the experience of a significant number of undergraduates, who despite usually having a research-apprenticed element in the form of a capstone project or Honours thesis as the final summative assessment in their degree, have often been exposed previously only to research-briefed teaching. Zamorski (2002) notes that for some students, this left them not sufficiently taught or prepared for their research project work, which students noted: "for the dissertation we weren't given much guidance on how to actually do it. We were expected to just go and get on with it... But there's certainly room for improvement in that they could teach you better research skills" (p.423).

Using a framework similar to ours at higher administrative levels within an institution has been suggested as a way to achieve movement towards a greater degree of student engagement in active learning (Pan et al., 2011), but this is rarely seen as a priority outside single courses with teaching-focused instructors (Mayson & Schapper, 2012). As we will demonstrate below, we feel the administration of a research-apprenticed learning framework at a program organization level is effective and engages students more deeply with, and facilitates their understanding of, research and learning by research within not only single course modules, but across their degree program and into post-graduate pursuits.

For example, the core of the McMaster first year learning is through interdisciplinary, group research projects. These projects are based upon current topics or big questions that are relevant to society. With this framing, a context for direct application is provided for the students. They learn introductory, and some more advanced, material, knowing where it applies and how understanding of elementary concepts helps to understand such big topics. Situating this in the model proposed in Figure 2, the first-year research projects start in the research-briefed and research-based quadrants, with the intention of transitioning students to research-oriented by the end of first year and then towards research-apprenticed models in upper levels.

With this perspective, we provide examples of how each of the two programs uses each facet of the nexus to integrate and prepare students for success in programs designed upon the research-apprenticed pedagogical approach (Figure 3).

Research-briefed

To reiterate, the point of research-briefed pedagogies is to provide, primarily, one-way delivery of research findings to students. This is effective in exposing students to current research (particularly within the local faculty), but at the same time, demonstrates where fundamental concepts are relevant and necessary to understand current research.

In McMaster's iSci, research-briefed pedagogies are primarily used in the first and second year of the program, but at a distinctly lower rate compared to more traditional lecture-based courses. The first year starts with almost all of the courses being more research-briefed, yet by the end of the first year, research-briefed content is closer to 25%. The standard, research-briefed lecture is used to present students with background content or, occasionally, topics perceived by an instructor to be more challenging. Students are also mandated to attend weekly seminars given by invited, expert researchers from fields that are relevant to the particular research projects students are pursuing at the time. These invited seminars start in the students' first year and continue to the end of their fourth year. Similar primary research talks have also been used to facilitate reviews of topics. By having a course instructor provide a discipline research talk (at the conference or seminar level) to students, they can evaluate student understanding with a debrief session, consider whether students are able to ask informed questions, identify underlying discipline concepts, and extrapolate and apply interdisciplinary concepts to make connections associated with the presented research.

In the Leicester Natural Sciences program, students are research-briefed throughout the first three years of the program as part of the scaffolding of the interdisciplinary problem-based learning modules (Gretton et al., 2013). In addition to researching each module problem using literature sources, the students encounter a number of academics whose research areas fall within the problem topics. These researchers take part in "expert sessions" with the students, which are informal and interactive lectures where experts disseminate research knowledge relevant to responding to the set problem.

Figure 3
Program examples utilising the quadrants

Level	In the Nexus	Natural Sciences	In the Nexus	Integrated Science
I	Br	• Expert content sessions	Br Ba O A	• Invited Speaker Seminars • Research-based Projects • Science Literacy • Final Project Research proposals
II	Br Ba	• Expert content sessions • Research-based Projects	Br Ba O A	• Invited Speaker Seminars • Research-based Projects • Paper Discussions • Enrichment Study Research
III	Br Ba O A	• Expert content sessions • Research-based projects • Journal Club • JIST publication	Ba O A	• Student-created and led tutorials • Paper Discussions • Independent Study Research
IV	Ba A	• Research-based project • Thesis Research	O A	• Thesis Peer Review • Thesis Research

Examples of how the Natural Sciences program at Leicester, and Integrated Science program at McMaster, employ the four quadrants of the nexus across levels (I-IV) to engage and integrate students in their learning while reinforcing their understanding and ability in scientific skills and concepts. **Br** – Research Briefed Learning, **Ba** – Research Based Learning, **O** – Research Oriented Learning, and **A** – Research Apprenticed Learning.

Additionally, Leicester students are also research-briefed in a more traditional lecture format via the bi-annual Interdisciplinary Guest Research Lecture. This co-curricular activity provides a platform for invited speakers from various scientific backgrounds to present their most recent research developments. In addition to engaging students with current research themes in interdisciplinary science, the lectures provide an opportunity to interact with researchers in formal and in informal settings outside the module curriculum context.

Research-based

At McMaster, the core modules in the first term are research projects which are primarily research-based. Students investigate complex, interdisciplinary topics (e.g., Exoplanetary Exploration; Drugs, Doses, and Biodistribution, or the way drugs interact across biological and environmental systems) by exploring existing literature and engaging in non-recipe-based labs. For example, in their first research project, Exoplanetary Exploration, students learn and apply introductory concepts from calculus and Newtonian physics to investigate gravity and planetary motion; thermodynamics and chemical energy for rocket propulsion; planetary geology and geochemistry to map and plan landing sites; simple metabolism, redox chemistry, and biogeochemical cycles to search for signs of potential life; and social psychology in planned space missions. Student groups are also challenged to demonstrate application and comprehension by designing an informative and engaging undergraduate laboratory protocol, complete with learning objectives, as an educational companion to a simulated planetary space mission. Moving away from textbook-centred learning, from the first project in their first term through to the end of the program, students are asked to interact with primary literature to create review papers and use meta-analysis in a variety of fields, some directed, and some student selected.

At Leicester, delivery of the key scientific concepts is achieved using interdisciplinary problem-based learning modules (Gretton et al., 2013). Each module is introduced with interdisciplinary problems to provide a "hook" to engage the students, each of which requires a response in the form of one or more summatively assessed artifacts ("deliverables"). Students are assigned to groups to research and produce the deliverable. The module starts with a problem-planning session which requires students to identify previous learning and areas they need to research in order to address the problem posed. The remainder of each module consists of "facilitation sessions" and "expert sessions" (as described previously in the research-briefed section). Facilitation sessions are led by a teaching instructor from the Natural Sciences teaching team and designed to support the students in researching and tackling the problem. These sessions have evolved to a more scaffolded implementation of the PBL approach, where students are provided with reading materials and electronic resources to assist them in preparing for the sessions. Students are also given suggested discussion questions to aid them when considering the key issues behind the problem. This research-based approach puts the student at the centre of the learning process, treating them as a "researcher" in terms of gathering and synthesising knowledge. It is designed to embed key research skills such as information gathering, teamwork, critical thinking, and problem-solving.

A typical example of a problem that students encounter in their first year of studies is in the module Biophysics, Physiology, and Metabolism. In this module, students are posed the open-ended problem hook: "what limits the speed at which a human can run?". Facilitation sessions and expert sessions in the module focus on how energy is transferred and utilized in human metabolism (from chemical and biological perspectives) and functions of human physiology (from a biological, but also mathematical/physical perspective). The deliverable for this module is a group presentation to members of the UK Sports Council on strategies for preparing athletes with lower limb reduction or loss to compete in the Para-Olympic games. The open-ended nature of the problem allows students to consider limits in different scenarios (i.e., differing artificial limb scenarios, varying running distances, etc.) and requires them to synthesize and apply knowledge.

Research-oriented

This quadrant provides the opportunity for students to critique research content and process. Primary literature is often seen as a challenging medium for undergraduate students. The perceived challenges associated with primary literature can, we have found, be used as an effective teaching tool when structure is provided to help students how to navigate and digest the format to better understand the information. This structured approach has allowed them to take more responsibility for how they learn, gain an appreciation for the communication of science, improve their skills in critically evaluating scientific writing, and expand their ability to glean pertinent information from this source. Further, students practise leading others in the understanding and evaluation of sources of information.

Students first try formal peer review in their second term at McMaster by reviewing short research briefs produced by their peers. In the second and third year, their skills are developed further via organized paper discussion seminars, where students are given pre-defined roles or sections of papers to critique. By breaking primary research papers down, students learn to concentrate and express their review comments at an appropriate and useful level. By level four, the students peer review each other's thesis work regularly, and many are also involved in voluntary peer review through student journals and symposia.

At Leicester, this is achieved through our "journal club sessions" that occur in the students' third year, preparing them for research-apprenticed activity: the undergraduate journal *Journal for Interdisciplinary Science Topics* (see below). All students are allocated two or three papers to read each week, with students taking turns to present papers. Staff work in interdisciplinary teams to select papers which demonstrate the intersection of disciplines at the research frontiers. This is designed to be an authentic activity mirroring the process of a research group, encouraging peer discussion.

Research-apprenticed

Research-apprenticed activities can take a variety of forms, dependent particularly on the degree discipline, but they all share the common aim of allowing students to generate new knowledge. Generally, research-apprenticed activities constitute the final summative assessment or capstone project within a degree program. Students experience and learn about the entire research process by undertaking research themselves, albeit under the firsthand guidance of a supervisor: akin to an apprenticeship model.

Both programs contain "traditional" research thesis/project components. All McMaster iSci students complete an undergraduate thesis in their fourth year. A shorter "independent research project" in their third year serves as a precursor to this thesis, but in total, all of the iSci research projects have progressively prepared the students for this realistic research mode (Symons, Colgoni, & Harvey, 2017). The progression towards research-apprenticed learning is the central design of the iSci program. Indeed, by their third year, students are expected to behave as research colleagues to one another and to instructors. The final project for BSc students at Leicester is the culmination of the undergraduate program and constitutes a quarter of the third year (MSci students undertake a half-year project in their final year). Students work individually with a research academic on an experimental, computational, or analytical project, where they are expected to plan and carry out their own research and analysis in a range of scientific disciplines.

In addition to thesis work, two main channels have emerged within the iSci structure for students to communicate their work: the student-organized *Synthesis* symposium and the student-run journal, *The iScientist*. Both activities not only provide showcases and models for science communication, but also gives the students experience in how science communication structures work in real professional networks as part of the research process. *Synthesis* is an annual event lasting around ten days in April which all students (across the four years) attend, contribute to, and support. It provides a capstone to each year and allows first-year students to perceive their potential development and identity as researchers.

The Leicester Natural Sciences program has an additional novel research-apprenticed activity: the undergraduate journal (*Journal for Interdisciplinary Science Topics*). *The Journal for Interdisciplinary Science Topics* is a compulsory module for Leicester students and is also available as an optional credit activity for McMaster students. The module gives undergraduates first-hand experience in the process by which research output reaches the public domain by acting as authors, referees, and editors of the undergraduate journal. This is more than an "opt-in" undergraduate journal. As a mandatory activity, it can be used as a novel pedagogic tool to develop key research skills. Students are split into small research groups where they devise original ideas for research, which are then written as short scientific papers. They peer-review the work of other groups in a process overseen by a student editorial board who, based on the referees' reports of their peers, have the final say on whether or not a paper is published. Some of the more creative published papers (e.g., "How much of the Amazon would it take to print the internet" and "Is it possible to cry a river?") have been reported in news and media outlets as far and wide as France, Italy, Australia, China, and Russia (Hurkett, 2018).

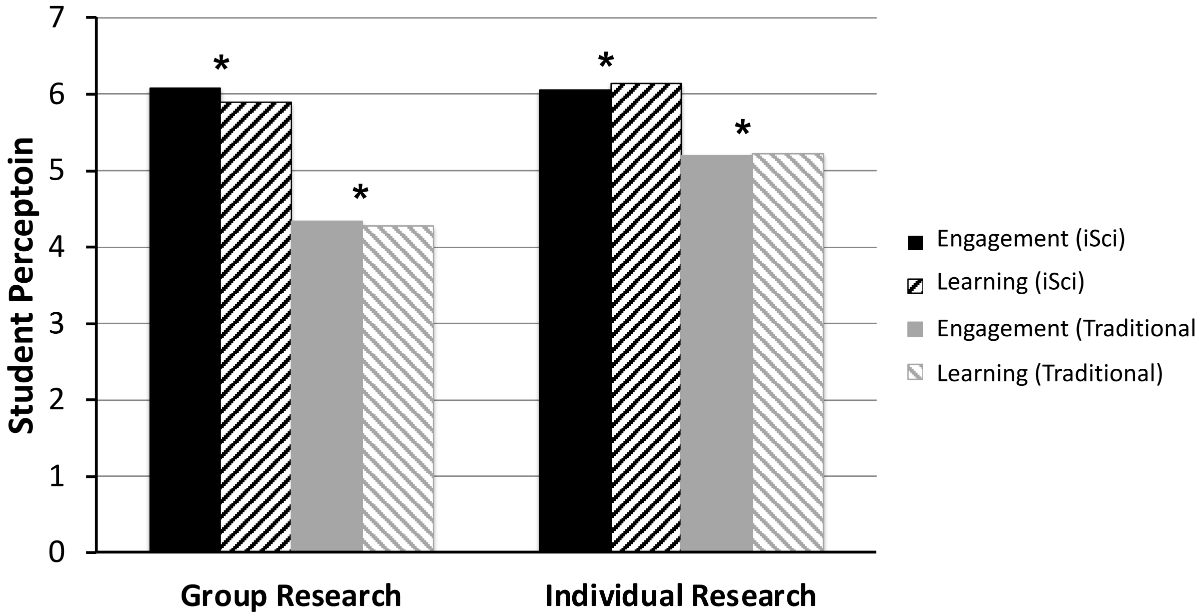
Evaluation

Both programs have successfully incorporated this research-teaching framework for a number of years (Figure 3). However, we were also interested in whether the effectiveness of these teaching approaches could be identified. We therefore engaged in survey-based research. Our data indicate this approach has been successful: the positive effects of this approach have been identified in both the current student and graduate populations. We discuss some of this in the following paragraphs.

Students in both programs are able to identify and elucidate the benefits of following a clearly embedded research pathway during their degrees. Surveys of Leicester students found that all final year students identified independent learning, research skills, and problem-solving as attributes they considered to be important to learn and develop in the program. The use of research-based learning in the Leicester program was further discussed as part of a focus group. Students' comments illustrate their recognition of this pedagogy in honing research skills:

Figure 4

Student perceptions of learning and engagement



Perceived (mean ± 1 SE) level of engagement (solid bars) and level of learning facilitation (hashed bars) for students from the Integrated Science Program (N= 124) compared to students from more traditionally taught programs in the Faculty of Science (N= 324) at McMaster University for group-based and individual research. Asterisks denote significance at $p<0.0001$, assessed with two-sample t-tests (R v. 2.13.1), between perceived level of engagement or learning, respectively.

Participant 1:

> [research-based learning] is hard and it is really different, but if you get through it then you've got so much more going for you than just the knowledge… not only can you prove you know this stuff but you can also utilize it rather than just being able to write it in an exam

Participant 2:

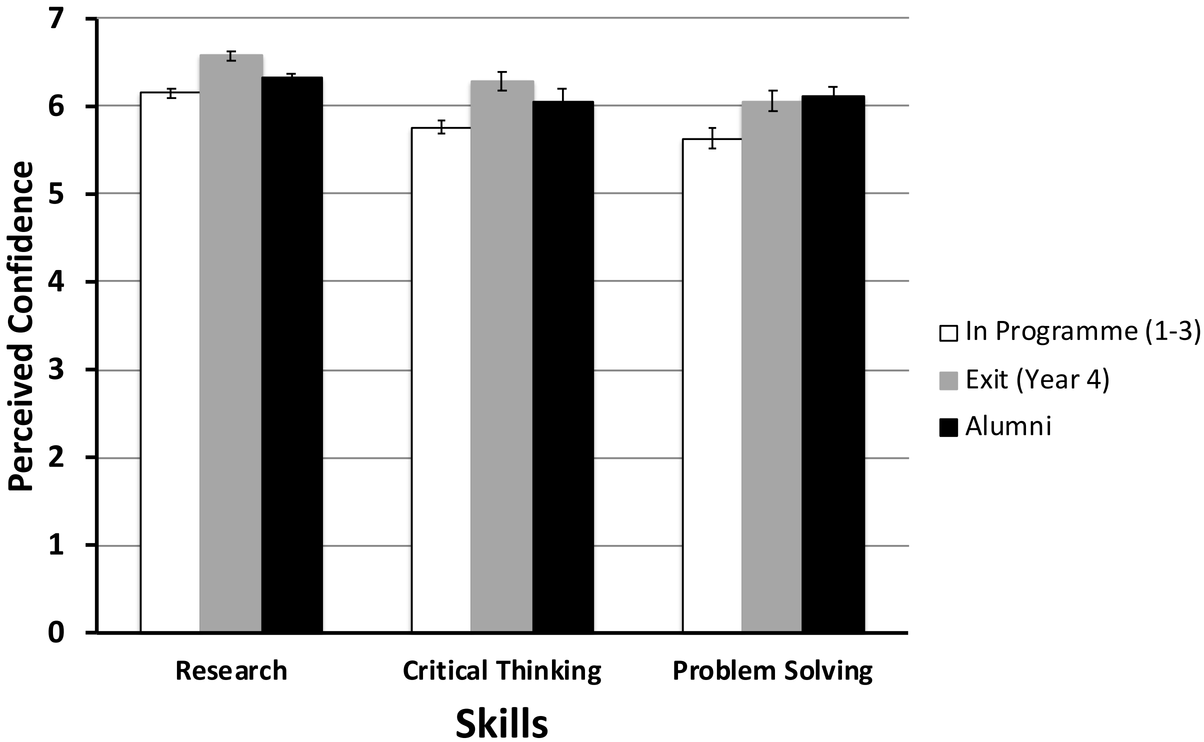
> If I was applying for a job, I wouldn't have the same knowledge as a biologist or someone in a certain field, but I'd know where to get it from, that's the thing; I know how to go and learn this certain thing and I'll come back tomorrow and I'll be fine.

Through a longitudinal pedagogical research survey, McMaster has undertaken a more detailed analysis. Starting in 2012, all students entering the iSci program, as well as at the end of each year of study, at graduation, and as alumni (at least one year after graduation) have been asked to participate in this research. Through a multitude of Likert scale questions, students are asked to rank their perception of research, critical thinking, and problem-solving skills, as well as resources and pedagogies (e.g., group-based or independent learning). In 2013, a comparative study was also performed to directly compare perceptions between students in the iSci program and students enrolled in more traditional programs across the Faculty of Science. In line with findings by Healey (2015), both sets of students entering University attach a high level of importance to learning research, critical thinking, and problem-solving skills (e.g., Figure 1), further indicating pedagogies that centre upon these skills as motivation for applying to the iSci program. Using a program design that cyclically exposes students to all quadrants of our research-teaching nexus greatly increases their perceived engagement and level of learning, from both group-based and individual research, compared to students in more traditional, science programs (Figure 4). This results in a high level of overall student perceived confidence in research, critical thinking, and problem-solving skills during their education as well as after graduation (Figure 5).

Conclusion

Integrating learning and research is challenging and requires new reflective approaches and initiatives

Figure 5
Perceived skills confidence of current students and alumni



Perceived confidence (mean ± 1 SE) in research, critical thinking, and problem solving skills, for current (Years 1-3; N= 562, 2012-2017), graduating (Year 4; N=54, 2016 & 2017) students, and alumni (N=68, 2014, 2015, 2017) based on a 7-point Likert scale from the Integrated Science Program at McMaster University.

to link teaching (Brew, 2010). This is a challenge that institutions are increasingly prepared to embrace though, with initiatives such as the Connected Curriculum at University College London, UK aiming to "close the divide between teaching and research…. [and] integrate research into every stage of an undergraduate degree, moving from research-led to research-based teaching" (Arthur, 2014).

What we describe in this paper is the theory and implementation of a program-level framework, supporting a developmental journey from resource consumers to research generators. We provide examples of two similar but distinct programs which have used this framework to successfully implement a degree curriculum; these two programs scaffold the development of research skills and thereby allow students to get more value from research-apprenticed tasks by having previously experienced the research-based and research-oriented quadrants. Although much has been reported on how to integrate teaching and research at an institutional level, little has been reported on how this can be achieved in a holistic way at the program level. The aim of this iteration of the research-teaching nexus is to provide a framework that can be used to facilitate the design or review of a program level curriculum.

Although both programs teach science via interdisciplinary modules, which we believe enhances the understanding of the research process, and provides relevance as well as applications, and identifies a sense of meaning and purpose, we also believe that this framework could easily be used within a single discipline context and in non-science disciplines, such as social sciences and humanities.

How does our nexus compare with others presented in the literature? Our framework may not fit with views of all academics on how research should be embedded within the curriculum. It contrasts with the views of some academics as reported by Zamorski (2002) where many academics followed a linear model of knowledge acquisition before introducing research. However, it is interesting to note this did not always fit with student expectations of how they should interact with research at University; some students appeared to be advocating an apprenticeship model of teaching (Zamorski, 2002). In contrast to Griffiths (2004), we do not include research informed teaching. In our generation of the research-teaching nexus, teaching and curriculum design are actually "research-informed" itself as specified by Griffiths (2004). Both our programs are somewhat unique in using teaching-focused staff to design and deliver much (but not all) of the curriculum. Interestingly, a number of papers identify that students value delivery by researchers (Marsh & Hattie, 2002), but others note that some students felt research staff prioritized research over teaching activities (Healey et al., 2010; Jenkins et al., 1998). It would be interesting to investigate whether embedding the teaching-research nexus framework actually benefits more if instructors are engaged with Scholarship of Teaching and Learning than from being a cutting-edge discipline-based researcher.

In summary, we present a research-teaching framework which draws on previous literature but places the student journey at the heart of its design and helps to streamline previously loosely defined terminology. Following students from two programs that utilize this scaffolded pathway has provided data which suggest this approach has many merits compared to more traditional models: the students' perceived confidence in research, critical thinking, and problem-solving skills are significantly higher than that of their more traditionally taught peers.

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