1 Introduction

> Everybody says I should be incorporating research in my undergraduate courses, and it would sure help my Broader Impacts section on my next NSF proposal. But I don't know how to do it! And even if I did know, how would I find the time? I'm too busy DOING research to spend time redesigning my courses to incorporate research! HELP! – *Anonymous Paleontologist*

Sound familiar? Perhaps you have heard – or made, or at least thought – such a comment. Let's examine the statements made by Anonymous Paleontologist (henceforth AP) more closely.

Is AP correct that paleontologists should be incorporating research in their undergraduate teaching? Traditionally teaching and research have been viewed as competing interests (Lopatto, 2010; Carleton University, 2017) or at best disconnected activities (Jenkins, 2001). This viewpoint is echoed by AP, who feels pressured by the various demands inherent in the academic profession. AP's viewpoint reflects the fact that academic units often treat research and teaching as unrelated activities (and evaluate faculty separately in each category; Brew, 2010), with one or the other valued more highly depending on the institution (Jenkins and Healey, 2012).

In recent years, however, there has been a push to integrate research and teaching. At the U.S. National Science Foundation (NSF), this push is reflected in the NSF strategic objective to "integrate education and research to support development of a diverse STEM workforce with cutting-edge capabilities" (National Science Foundation, 2014, p. 8). Activities that support this objective fall under the domain of "Broader Impacts" mentioned by AP; all NSF research proposals must address the broader impacts of the research to society and particular desired societal outcomes. One criterion initially proposed for merit review of broader impacts was "How well does the activity advance discovery and understanding while promoting teaching, training, and learning?" (National Science Board, 2011, p. 4). Such integration continues to contribute positively to a proposal's review score in the broader impacts category (personal observation, based on participation in the 2017 NSF Division of Earth Sciences Committee of Visitors; National Science Foundation, 2017).

But why this emphasis on integrating research and teaching? The 2014–2018 NSF Strategic Plan (National Science Foundation, 2014, p. 8) states:

> One of NSF's most enduring contributions to the national innovation ecosystem is the integration of education and research in the activities we support. When students participate in cutting-edge research activities under

> the guidance of the Nation's most creative scientists and engineers, the students can gain the up-to-date knowledge and practical, hands-on experience needed to develop into creative contributors who can engage in innovative activities throughout all sectors of society.

Other benefits accrue as well from incorporating research into teaching (Jenkins, 2001; Brew, 2010; Lopatto, 2010; Science Education Resource Center, 2016). Students become more engaged in learning and more motivated to pursue science. They understand scientific reasoning better and are poised to be better citizens (Carleton University, 2017) who are prepared to evaluate the validity of competing claims and make evidence-based decisions (in daily life and in the voting booth!) – a benefit of vital importance to the United States, where much of the population is scientifically illiterate (Lopatto, 2010) and even downright hostile to science. In a world in which factual knowledge (as well as misinformation) can be accessed on smart phones (see Brew, 2010), a premium is placed not on delivering facts but on promoting students' abilities to "create and find and synthesize new knowledge" (Jenkins, 2001, p. 18). Development of critical thinking and problem-solving skills, which are fostered by integration of research and teaching (Lopatto, 2010), will be essential for success in what has been referred to as the "knowledge economy." Brew (2010, p. 141) concluded:

> Students are going to need to be able to critically evaluate knowledge; to make rational judgments in the light of good evidence, evidence that they perhaps gather, and to reflect on what they are doing and why. These are the skills of critical inquiry, which are central to a super-complex society. Today's society demands creativity. It demands the ability to deal with complexity and uncertainty. We need new kinds of teaching, new spaces, new ideas about knowledge, new ways to engage students. I believe that the integration of research and teaching provides exciting ways to meet this agenda.

But will it help students learn paleontology? If "learning paleontology" means knowing the stratigraphic ranges of strophomenid brachiopods, perhaps not, unless students are specifically involved in research that includes strophomenids. But if "learning paleontology" means being able to apply paleontological concepts discussed in class, my experience indicates that incorporation of research into teaching does lead to improved learning of paleontology (see student reflections below). After all, students can look up information about strophomenid brachiopods on their smart phones, but using that information to answer research questions or test hypotheses about evolutionary or ecological processes requires a deeper understanding of paleontology, which can be derived from research involvement.

2 How Do We Do It? Three Approaches to Incorporation

AP worries about not knowing how to incorporate research in teaching, despite being motivated to do so by the "Broader Impacts" NSF research proposal review criterion. But to some extent AP probably already includes research in teaching. Whether AP's attempts provide convincing fodder to make an impact on "Broader Impacts" likely depends on how, and how strongly, research is embedded in teaching.

Griffiths (2004; see also Jenkins and Healey, 2012; Healey and Jenkins, 2017) distinguished research-led, research-oriented, and research-based teaching. In research-led teaching (which I will refer to as RLT), students learn about current research findings, including those of the instructor, typically in the lecture mode; I consider it content focused. Research-oriented teaching (memorable acronym ROT) is more focused on the research process, including students' knowledge of it and their ability to use the research methods of the discipline, although they may not conduct actual research; I characterize it as technique focused. In contrast, research-based teaching (RBT) actively involves students in inquiry and research; I see it as experience focused. The three pedagogies need not be mutually exclusive, and a single course may include more than one approach. In particular, research-based teaching almost always includes RLT and ROT.

2.1 Research-Led Teaching

Unless AP is a long-term teacher who is still lecturing from class notes that have not been updated in decades, AP's pedagogical approach probably already includes RLT. Even at institutions with minimal research expectations, faculty are expected to present information consistent with the current state of knowledge in the discipline, including questions currently being investigated, new methods and technologies for addressing them, and/or the results of such research. With the instant access to information noted by Brew (2010), new research discoveries can be incorporated into PowerPoint presentations the same day they are announced. For instance, online science news subscriptions, e.g. to Sigma Xi Smart Brief (released every week day by Sigma Xi, the Scientific Research Honor Society) or LiveScience, often feature paleontological discoveries. I regularly incorporated such research news into my 100-student general education Prehistoric Life class, which helped reinforce the point to these mostly non-science majors that science is not a static set of facts; in science, our ideas are constantly open to testing and modification by new discoveries.

Incorporating new discoveries in our lectures is not the same as incorporating our own research (unless we happen to be the ones discovering the oldest/largest/coolest fossil eurypterid/dinosaur/mosasaur/hominid – those "sexy" organisms likely to be featured in news releases). But unless there is a real disconnect between their research area and teaching assignments, faculty should be able to find a way to relate their research to a topic about which they are teaching (and I have read many "Broader Impact" statements in NSF proposals, in which the researchers promise to transmit information gained from their research to their introductory classes). In my case, classes on evolution in historical geology and invertebrate paleontology have been venues to discuss my research on tempo and mode in evolution (e.g., Kelley 1979, 1984). Faculty may think that their research is too complex to be talked about with undergraduates, or that undergraduates would not be interested in it. However, I found that students were interested in, and that they benefited from, knowing about my research. Such RLT humanizes the scientific process and makes it less threatening to those suspicious of science – and students loved seeing field shots of me taken across the decades. And all research should be translatable in some way to language understandable to a non-scientist. An approach I have found useful is to think about what I would tell a class of kindergarteners – or my grandmother – about my research.

Most often such transmission of information about current research – even our own – occurs in lecture mode, which has been criticized for being the least effective pedagogy (Deslauriers et al., 2011; Hackathorn et al., 2011, Budd et al., 2013). Hackathorn et al. (2011) compared student learning of concepts taught by lecture, demonstrations, discussion, and in-class activities. Overall learning, as measured by quizzes and exams that emphasized different aspects of learning (knowledge, comprehension, and application; Bloom et al., 1956), increased as more active techniques were used. Similarly, in a comparison of two high-enrollment physics courses, Deslauriers et al. (2011) found that use of small-group problem-solving tasks with instructor feedback but no formal lecturing led to a 20 percent increase in attendance, a doubling of engagement as assessed by trained observers, and an improvement in examination scores compared to lecture-based sections. Student satisfaction with the mode of instruction also increased. I found similar outcomes in teaching my general education Prehistoric Life class; scores on my teaching evaluations by students increased as I incorporated more active learning techniques, and daily attendance averaged 80 to 90 percent of the 100 students enrolled (Kelley 2012). Budd et al. (2013) also reported that increased learning in physical geology courses occurred when students were expected to construct their own understanding of content through in-class activities and interactions with one another.

In keeping with best practices, RLT need not be restricted to transmission of research results via lecture (which Griffiths, 2004, referred to as research "weakly embedded" in teaching). In contrast, "strongly integrated" research is "used deliberately to shape the learning activities carried out by students" (Griffiths 2004, p. 721). Various activities that more strongly integrate research and teaching are available, e.g., assigning journal articles for reading and class discussion (Darden, 2003). Robinson (1987) advocated this approach in introductory geology classes, noting that success depends on the topic chosen and the preparation students receive for each assignment. To help introductory students handle complex topics, Klemm (2013) used Adapted Published Research Reports, re-writes of published articles to make them more accessible to first-year students; students worked independently and then in teams to answer a series of questions resembling those asked of reviewers of journal submissions. He reported that, in addition to learning content, students gained understanding of the research process, including scientific reasoning and argumentation, and developed critical thinking and analytical skills in this "minds-on" approach. Activities in which students conduct literature searches, develop annotated bibliographies, and write or critique research proposals (Peterson et al., 1996; Darden, 2003; Science Education Resource Center, 2016) may develop similar skills. Such approaches are usable by faculty who are research active as well as those not currently engaged in research projects. And faculty may benefit from these activities as well, e.g., if students discover articles relevant to their instructor's research (Darden, 2003) – mitigating AP's "I'm so busy doing research that I don't have time for this" complaint.

Research-led teaching, beyond simple conveyance of information, may also include laboratory or other exercises using real data to provide a "minds-on" approach that also includes aspects of ROT. For example, I have provided students in historical geology and invertebrate paleontology with data I collected to test punctuated equilibrium (Kelley, 1979, 1984). Students graphed and analyzed the data and interpreted what mode of evolution occurred – and realized that interpretations are not always straightforward. The online availability of real datasets has increased the ease of incorporating such an approach (Wei and Woodin, 2011). For example, Gutiérrez and Baker (2013) described a class exercise in which students analyzed online soil data using methods found in the literature; different students selected different methods to use and collaborated to compare their results. Use of real data in RLT helps students realize that science is messy (Gutiérrez and Baker, 2013), in contrast to "cookbook" experiments that always turn out "right" if students follow the instructions. Ellwein et al. (2014) found similar results from surveying students who used long-term climate science data sets. Working with authentic data serves to engage students (although not as much as hands-on data collection; Gold et al., 2015). Students develop higher-order thinking skills and understand the scientific process better.

2.2 Research-Oriented Teaching

Research-oriented teaching, as defined by Griffiths (2004), focuses on how knowledge is produced in the discipline, rather than on learning that knowledge itself. ROT is exemplified by methods courses, which are designed to train students in the techniques of the discipline. Such courses may provide instruction and experience in field methods, use of instrumentation and analytical methods, geospatial and quantitative methods, and use of programming languages and software environments such as R and MATLAB. Methods courses are common within geoscience curricula. For instance, at University of North Carolina Wilmington (UNCW) the “Field Methods in Geosciences” course is described as “Introduction to methods and techniques used in the geosciences including field measurement, sample retrieval and data analysis” (University of North Carolina Wilmington, 2017). For BS Geology students, this course is followed by “Techniques in Applied Geology” and ultimately the “Field Course in Geology,” a traditional field camp-style course. Our department also offers techniques-based courses in quantitative methods, oceanography, Geographic Information Systems, remote sensing, and cartography, as well as special topics methods courses (e.g., petrographic techniques).

Although research methods courses need not engage students in actual research (National Academies, 2017), in some ROT students may be working with existing data sets or collecting real data in a manner similar to RBT. For instance, Hopper et al. (2013) described a 1-credit-hour research course in which students experienced authentic research tasks of collecting and analyzing Doppler radar data. Koretsky et al. (2012) described a field-based environmental geochemistry course in which students learned field and laboratory research skills to investigate water quality in a local lake, a project they characterized as “authentic inquiry.” Such inquiry shares some of the characteristics of research (Healey and Jenkins, 2017) and yields a variety of benefits. Inquiry-based teaching improves learning of content, develops student skills in problem solving and critical thinking, and allows students to “practice the activities involved in science” (Apedoe et al., 2006, p. 414; see recommendations in Apedoe et al., 2006 for how to implement inquiry in undergraduate geoscience courses).

2.3 Research-Based Teaching

In inquiry, the results of an investigation are unknown to the student but are not new to the scientific community (and probably not to the instructor); in contrast, research yields information new to the scientific community (Lopatto, 2010; Auchincloss et al., 2014). Therefore research-based teaching goes beyond the approach of inquiry to involve students in research experiences that generate new knowledge, i.e., “an original intellectual or creative contribution to the discipline” (Wenzel, 1997, p. 163). Much has been written about the benefits of research experiences for undergraduates (see summaries in, e.g., Lopatto 2010; Kelley and Visaggi, 2012; Koretsky et al., 2012; Corwin et al., 2015; Kortz and Kraft, 2016; National Academies, 2017). Benefits extend beyond enhancement of scientific skills (reading literature, developing and testing hypotheses, analyzing data) and life skills (problem solving, critical thinking, communication) to personal development (self-confidence, ability to work independently and in teams).

At many institutions, these benefits are reserved for a select group of students (Jenkins, 2001), determined by such criteria as grade point average or acceptance into Honors programs. Typically, such experiences follow an apprenticeship model: members of this privileged group work one-on-one with a faculty mentor on a research project or thesis, or they enroll in a research internship or co-op experience. These capstone experiences involve a significant investment by the research supervisor, who likely also has research deadlines and goals to meet (per AP’s concern). Consequently, the faculty mentor may not wish to expend effort on less promising or less motivated students (Jenkins, 2001; see also Kortz and Kraft, 2016). Thus there has been a tendency to resist offering research opportunities to the entire student body. But if RBT yields such benefits, shouldn’t all students have the opportunity to participate? I agree with Healey and Jenkins (2009, p. 3; see also Healey and Jenkins, 2017) that “*all* undergraduate students in *all* higher education institutions should experience learning through, and about, research and inquiry.”

An effective avenue for broadening the participation of students in research is through research-embedded courses, referred to in some cases as CUREs (Course-based Undergraduate Research Experiences; Auchincloss et al., 2014). Such courses provide research opportunities for a wider range of students (e.g., students with less experience or less stellar academic records) and confer benefits comparable to those of the apprenticeship model (Lopatto, 2010; Kelley and Visaggi, 2012; Auchincloss et al., 2014; Corwin et al., 2015; National Academies, 2017). According to Auchincloss et al. (2014), CUREs involve students in the activities of science (hypothesis development, study design, data collection and analysis, interpretation, dissemination); result in discovery of new knowledge that is relevant to the discipline; and are iterative (see also American Library Association, 2015), building on previous knowledge (e.g., findings of previous students in the course). CUREs also involve collaboration among participants, an advantage not usually offered by the apprenticeship model (see Burke, 2011, for a discussion of benefits and best practice in employing group work). Research-embedded courses are becoming more common in the sciences (National Academies, 2017), with good examples from the geosciences provided by Foos (1997; geochemistry lab course), Mayborn and Lesher (2000; advanced igneous petrology course), Gonzales and Semken (2006; field-based igneous petrology course), Davies-Vollum (2006; sedimentology course), and Montgomery and Donaldson (2014; introductory honors paleontology course). At some institutions, the curriculum is structured to include a sequence of CUREs that provide students with a multi-year sustained research experience (e.g., Allen et al., 2017).

In the next section of the Element I focus on a semester-long research-embedded course in invertebrate paleontology (IP) I taught for a dozen years at UNCW. This course provides an opportunity to illustrate best practices in experiential learning and the incorporation of research in undergraduate teaching. The structure of the course is described briefly here, with more details presented by Kelley and Visaggi (2012). Figure 1 provides a general schedule for student activities and deliverables, as well as a timeline for instructor implementation of best practices in experiential learning.

IP is a four-credit-hour elective course with three hours of lecture and three hours of laboratory each week. As I taught it, the content combined paleontological principles with discussion of taxonomic groups. The laboratory provided hands-on work each week in a traditional format (observing, sketching, and answering questions about specimens from the teaching collection) related to the lecture topics, after which students spent approximately two hours working on a team research project worth 20 percent of the entire course grade. Two or three teams (depending on class size, which usually ranged from 10 to 14 and averaged 11 students) were each assigned a bulk sample from a Cenozoic site in the region, often one they collected themselves on a field trip early in the semester (Figure 2) but in some cases an archived but unprocessed sample. Students wet-sieved the samples to remove the specimens from their matrix, sorted them into species, identified them at least to genus level, developed hypotheses, and collected data on abundance, predation traces, life modes, and/or morphology depending on the focus of the project that semester. Each student produced a paper coauthored with team members in professional

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COURSE TIMELINE								
	Pre-class	**Week 1**	**Weeks 2 - 3**	**Weeks 4 - 10**	**Week 11**	**Week 12**	**Week 13**	**Week 14**
STUDENT RESPONSIBILITIES								
Tasks		Project intro	Collect, sieve, reflect	Pick, sort, ID, count	Enter data	Analyze data	Write	Revise
Products			Inten-tion papers		Data spread sheets	Results to team	Rough drafts	
INSTRUCTOR TASKS								
Intent	Determine intent, goals, approach							
Prepare and plan	Develop and distribute plan		Refer to frequently with class, modify as needed, adjust syllabus if necessa					
Make authentic		Project intro	Stress protocols and standards of the discipline in student work, connectio research program					
Reflect			Unstructured reflection on own and with students					
Orient and train		Provide context	"On the job" training for each task; workshops on reference searches and technical writing					
Monitor			Ongoing monitoring of progress relative to intentions and goals for studen and for research experience					
Assess			Formative					
Acknow-ledge			Informal acknowledgment of student work as tasks are completed successf					

Figure 1 General timeline for the Invertebrate Paleontology course, showing weekly student re
the timeline of instructor implementation of eight principles of best practices in

Figure 2 Invertebrate paleontology students wet sieving samples in the field collected at Kirby Pond, Timmonsville, South Carolina, for use in the 2015 team research project. Photo by Chetara Davis King.

journal format, with individually written sections and contributions from other group members. Finally, we submitted abstracts synthesizing the results produced by the different teams to a Geological Society of America (GSA) meeting. Because abstracts were due after the semester ended, and all student data required vetting prior to abstract submission, students usually did not participate in writing the formal GSA abstracts. However, I urged all IP students to present at GSA the following semester; students who were interested (and who could balance work, family, or other commitments in order to attend) applied for and received travel grants from UNCW's Center for Support of Undergraduate Research and Fellowships. Typically, several students from each class attended the GSA meeting and presented the posters.

3 A Tale of 23,276 *Mulinia*

Let's listen in on the IP laboratory on a typical Tuesday afternoon in spring 2013. The students and I were pouring over a vast array of mollusc fossils from the Plio-Pleistocene Waccamaw Formation of Horry County, South Carolina. Note that I have substituted names of family members to preserve students' anonymity.

"I hate *Mulinia*!" Katherine declared.

McKenzie commiserated. "I know – I've counted over a thousand *Mulinia* this afternoon!"