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Teaching and Learning Science in the 21st Century: Challenging Critical Assumptions in Post-Secondary Science

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Abstract: It is widely agreed upon that the goal of science education is building a scientifically literate society. Although there are a range of definitions for science literacy, most involve an ability to problem solve, make evidence-based decisions, and evaluate information in a manner that is logical. Unfortunately, science literacy appears to be an area where we struggle across levels of study, including with students who are majoring in the sciences in university settings. One reason for this problem is that we have opted to continue to approach teaching science in a way that fails to consider the critical assumptions that faculties in the sciences bring into the classroom. These assumptions include expectations of what students should know before entering given courses, whose responsibility it is to ensure that students entering courses understand basic scientific concepts, the roles of researchers and teachers, and approaches to teaching at the university level. Acknowledging these assumptions and the potential for action to shift our teaching and thinking about post-secondary education represents a transformative area in science literacy and preparation for the future of science as a field.

Keywords: evolution; misconceptions; nature of science; science education; science literacy; undergraduate

1. Introduction

Science literacy is a concept that is simple in theory yet has been a challenge to describe in terms of practice. As scientists and educators, we want all students, regardless of level, to leave their science courses with the critical skills needed to make decisions based on logic and to understand the processes that underlie the science they come across in the news and in daily life. We expect those leaving our programs in post-secondary education to be exemplary of science literacy in both thinking and practice. The need for science literacy is especially apparent when framed in the context of modern public controversy surrounding issues such as climate change and evolution in the United States, where the battle for science literacy plays out in the media, state governments, churches, and school systems. As a result of known shortcomings of the traditional approaches to science teaching and negative perceptions of science and scientists, society struggles in reaching this high level of literacy. Furthermore, there are students entering—and leaving—undergraduate programs of study with inadequate, or absent, comprehension of science as a way of knowing—how it is conducted, the philosophical and historical frameworks of our modern understandings, and science as a self-correcting set of process skills. It is a shared responsibility of secondary and post-secondary faculties to ensure that science literacy is a priority and that approaches to teaching across levels strive to meet that goal.

The definitions of scientific literacy set forth by Bybee (1997) and Shamos (1995) suggest several implications for faculties of science [1,2]. Not only is it reasonable to expect that faculties at all levels

can support students in achievement of higher levels of scientific literacy, but that achieving those higher levels should be our goal for instruction [3]. While these were set forth for K–12, they extend upward to higher education as well. Research in science education across levels identifies gaps in foundational understandings of science among students and the public. Collectively referred to as the ‘nature of science’ (NOS), there are fundamental elements of scientific epistemology that exemplify scientific thinking, processes, and practices. At the same time, many of these misunderstandings and misconceptions are the very ammunition used to attack scientific knowledge and discovery in the public sphere. Unfortunately, a barrier to correcting these problems lies not with the public but in the approaches faculties take regarding address of what students should know and understand, both entering and leaving our courses/programs, as well as faculty and student roles and expectations in higher education. We must remember that it is the role of faculties of science not only to teach our content but to “provide students with the necessary background knowledge and skills for this pursuit” and to “help motivate students to value scientific knowledge and skills” [3]. To reach that end, it is imperative that we take what we have learned from science education and continue to revisit how we represent and approach science and scientific literacy in higher education.

2. Background

2.1. Defining Scientific Literacy

“Science literacy has a complex and dynamic nature that is not easily defined or mastered. . . . It is a lifelong pursuit not achievable just by completing science requirements for graduation or pursuing a degree in science” [3]. The definition of science literacy has taken shape over the last 70 years and represents a massive body of literature and syntheses of the literature [4–9]. Examination of seminal articles addressing the concept shows that definitions can generally be grouped into three major themes: states of knowing, capacities to be developed, and personal traits to be acquired [10]. According to the NSES, scientific literacy is “the knowledge and understanding of scientific concepts and processes required for personal decision making, participation in civic and cultural affairs, and economic productivity” [11].

The modern conceptualization of science literacy shifts the focus away from concepts themselves and moves toward greater understandings of the context and nature of science [12]. To highlight the fact that scientific literacy represents a continuum of experience, Robert Bybee described levels of literacy in terms of the depth and scope of understanding and connection, from illiteracy to multidimensional understanding and connection with the latter being the pinnacle of understanding and ability to connect beyond the content [2]. In furtherance of the continuum model, there are also dimensions of literacy that must be considered. Science literacy exists in three dimensions that include (1) Bybee’s levels of literacy from illiteracy to multidimensional literacy; (2) domains of literacy, including the different fields of study that are possible; and (3) the value that is attached to the pursuit of scientific literacy at the individual and community levels [1].

2.2. Changing the Landscape of Undergraduate Sciences

For nearly a decade, the American Association for the Advancement of Science has advocated for a shift in the approach taken to teaching in undergraduate science courses [13]. The landscape and technologies of science are rapidly evolving and, for many, the scientific practices, tools, and thinking around which they were trained bears little resemblance to the interactive and dynamically enhanced practices of modern science. Along that same line, it is not uncommon for science faculties to have little or no training in teaching methods and practices, relying on traditional approaches with which they are familiar, such as direct instruction by lecture, rather than the diverse non-traditional approaches to teaching that are advocated by current research [13]. Conversely, those trained as bench scientists often represent the higher academic ranks and are not intimately familiar with the struggles many students face in academic performance. By failing to consider and evaluate the critical assumptions

made by faculties regarding students of higher education, among science majors and in science courses for non-majors, understandings of science are hindered, often to the detriment of scientific literacy.

The learning environment common in university settings has changed little over generations in comparison to the changes that have occurred in K–12 science education. If one examines the halls of any university, they are likely to continue to find lecture halls and lecterns filled to capacity with students. It is not uncommon for introductory life science classes to have student numbers in the hundreds, and most often one finds that instruction consists of little more than the lecture and examination format that has been in place throughout university history. In more advanced coursework, we may or may not find students in traditional classroom settings, characterized by neat rows of desks in which students are diligently making notes from a presentation or lecture at the front of the room. The shared space for student engagement is often relegated to the laboratory, where they often work with a partner or team to complete tasks and procedures that are set forth in a manual or given through instruction of a professor or teaching assistant, often a graduate student. What is noticeably missing is the spirit of scientific enterprise and the motivation and stimulation of interest that is needed to advance scientific literacy, and science, as a community and individual value.

Research in science education is telling us that lecture is not as effective as other means of teaching, that active learning is the only way to engage students on a level beyond knowledge and understanding, and that, to reach higher orders of scientific literacy, we must engage students not only in explorations of the history and theory that represents science, but the processes, context, and practices as well. This can be a difficult endeavor in undergraduate courses with large numbers of students, but it is not one that is impossible. Technology gives us a wide range of options to activate student learning and interest while changes to our approaches and thinking about our teaching can lead to the creation and implementation of more active learning in undergraduate science courses.

2.3. 'Controversial' Topics as a Lens for Change in Undergraduate Instruction

For many, if not most, students in the United States, introductory biology courses are the pathway chosen to meet core requirements for science in undergraduate degree programs. Therefore, one area of focus that highlights the struggle for scientific literacy is that of evolution, a concept that is viewed among United States society as controversial yet unanimously accepted in the scientific community as valid, well supported, and logical. In comparison to other first tier nations, the United States has the second lowest rate of acceptance of evolution among the public, second only to Turkey [14]. While it is noted that the trends surrounding evolutionary acceptance and rejection in the United States do not necessarily transfer to other nations around the world, it provides a venue by which other conflicts of beliefs and science, misconceptions about science, and misuse of scientific knowledge in politics and policy can be explored. Efforts undertaken and underway in the United States, in fact, highlight some universal considerations and approaches to bridging conflict that can be applied to a wide range of situations and circumstances.

It is often assumed that, by choosing science as their field of study, science majors enter their programs of study with interest and basic knowledge of scientific concepts and leave with a well-rounded understanding of the history and concepts of evolution, accept that it is widely supported by the scientific community, and are similarly situated in their acceptance. These assumptions, based on evidence from existing and preliminary studies, simply do not hold true. Studies in science education in the last decade reveal patterns in the teaching and learning of evolution and science in higher education settings including low levels of acceptance of evolution in the general public and among science students, lacking content knowledge even in biology majors, struggles to understand how scientific knowledge is generated, and surprising absence of knowledge to acceptance correlations [15–17]. One element identified as a key predictor of acceptance of evolution among these students is an increased understanding of the NOS, including the fundamental epistemology of science as a practice [16].

Nature of science (NOS) refers to a collection of premises that explain what science is, how scientific knowledge is generated, and characteristics of scientific thinking [18]. Concepts such as the difference between laws, which describe events that occur, and theories, the collections of data and evidence that explain how those events occur are included, along with the concept of science as an uncertain and thus self-correcting field. In addition, NOS explores the concept of the scientific method, not a single set of steps but rather a process of observations and revisions that may or may not include formal experimentation [19]. As to the role and thinking of scientists, understanding of the nature of science involves understanding that culture and other factors inherently bias all science, that it is the role of the researcher not to claim absence of bias, but to identify and seek to balance that which is present. Research calls for greater explicit inclusion of the NOS in science coursework and goes further to state that a combination of NOS infused in inquiry lessons represents the most meaningful means to that end, as students become active participants in the same processes of discovery undertaken in the original research [19].

3. Summary

A variety of factors come into play when it comes to development of scientific literacy. Two of those factors are the perceptions of individuals and society, of both science and scientists, and the understandings and experiences had by individuals during formal and informal education. Scientific literacy involves not only the ability to recall and apply concepts of science in the classroom, but a deeper understanding of how scientific knowledge is generated, the processes that take place, and the cultural and social context of scientific discovery and exploration. In addition to controllable factors, such as teaching approaches and exposure to authentic experiences, there are factors such as interest and community support that also impact scientific literacy and how it translates outside of classroom experiences. For our part, university teachers of science have the opportunity to change how we approach science teaching in an effort to positively impact both the content elements and the perceptions, as professors are often the only practicing scientists students will encounter.

4. Discussion

Discussions regarding adequacy of preparation of students in higher education are not a new occurrence in academia. Rose (2009) drew examples of professors from the 1800s, demonstrating concern for the level of preparation they perceived their students as having coming into their courses [20]. This is especially true in introductory level and general courses, where lack of clarity regarding where secondary ends and post-secondary begins, at least content and rigor-wise, often leads to a blame game regarding exactly whose job it is to bridge those gaps [20]. In higher education, we enter our courses with high expectations of student background and fundamental knowledge, and some are quick to place the burden on secondary education science teachers to ensure that our students are up to par, rather than taking the needed steps to ensure that the gaps are filled. Furthermore, we bundle students into single-track introductory courses and expect science majors and non-majors to both have their needs for understanding met in a meaningful manner. The idea that students have additional needs for understanding of the content or that their background is less than our expectations is categorized in some minds as remedial instruction, a concept which is in and of itself controversial in academic conversation. Consequently, those students with gaps in understanding or who lack sufficient background are deemed by some as being unworthy among their peers or not ready to perform in a higher education environment.

However, if we are acting in such a way as to fill gaps in our students' knowledge and skills, we are not merely correcting the mistakes of others but are ensuring future success and strength in our fields [20]. As Tierney (2011) pointed out, there is a stark difference between remedial teaching and developmental teaching [21]. The primary difference being that remedial teaching is focused on true deficiencies, whereas developmental teaching is an approach to teaching that involves learning student areas of strength and weakness and structuring a learning foundation that will fill those

knowledge gaps to help our students better understand the depth and connections in our field. Research demonstrates that programs and courses that take these developmental approaches enable students to better persist in their college studies [22]. Designing instruction and classroom experiences based on an understanding of our students' needs, preconceptions, and misunderstandings ensure that the time spent in introductory post-secondary work is structured in a way that gives university students, major and non-major alike, the richest possible foundations for their future studies.

An intersecting area of focus in undergraduate education is shifting the approach from traditional passive learning modes to more active learning approaches that are advocated in K–12 education [23]. Active learning, or interactive engagement (IE), shifts the focus from delivery of knowledge in lecture to more authentic learning experiences that model scientific thinking, application of process skills, problem solving, and modelling of the behaviors of science in tandem with scientific concepts [24]. This includes the use of discussions, group engagement, scenarios, and other hands on and “minds on” exercises that increase both student attitudes and content knowledge in undergraduate science classes [25,26]. Shifting to this approach in any classroom requires a deeper understanding of learning and learners as well as time and dedication to a more intensive and less controlled mode of facilitation student learning in science. However, many faculty members in teaching positions have little to no formal training in pedagogical approaches to teaching and limited time to devote to improving or changing their approach; relying instead on familiar practices despite having a desire to change their mode of teaching [13,27].

Assumptions about teaching and learning not only paint our personal viewpoints but have a far-reaching impact on our student learning that goes well beyond each student and classroom. Among the assumptions that we tend to harbor is that science majors, because they have chosen science as their field of study, have at least a basic understanding of what science is, origins of scientific knowledge, and the practices of scientific inquiry. In their secondary experiences, many students receive little-to-no background on how the scientific process actually works in practice, the history that has defined the practices we use, or the wide range of fields and approaches that make up our research. Biology majors often harbor the same fixed misconceptions that are seen in the general public—conflating law, theory, and hypothesis; maintaining inaccurate conceptualizations about science as proving rather than best interpretations of evidence; and misunderstanding of the uncertainty and self-correcting nature of science—that, if not addressed, persist throughout their training. If these persist throughout the academic careers of our major students then they are even more so among our non-majors, who have fewer opportunities to explore, discuss, and test their preconceptions against practice.

As post-secondary researchers and professors of various levels, we expect students to enter our courses with a background of basics from their secondary experiences upon which we can build their theoretical and practical application. What we find, in fact, is that controversial topics, such as evolution, are taught in ways that are incomplete, taught side-by-side with non-scientific alternatives, or avoided all together. That is not to say that no student comes in with a rich background, but the odds, based on preliminary results of a national study on evolutionary understanding among undergraduate students [28], point to a higher likelihood than one would expect for college-level students when it comes to the absence of understanding of the nature and process of science.

Awareness of the critical assumptions that interfere with learning and conceptual integrity in science is the first step to combating misconceptions and misinformation in the next generation of scientists and science educators. If we fail to identify and address these issues in our time with these students, whether by laying the burden on past teachers or future professors, we are risking the possibility that students are leaving our programs without a true understanding of the practices, processes, and mindsets that provide the theoretical and practical underpinning of science. As such, a new generation of educators could propagate the same misconceptions and misunderstandings of science for many generations to come. We know that understanding scientific processes of thought and behavior, as well as how science itself is conducted (nature of science) has a positive impact on student learning and understanding, even in controversial topics; therefore, addressing our assumptions and

using ever resources at our disposal to better understand our students and adjust our instruction to meet them at their levels of understanding might also have a lasting positive impact on the coming generations of scientists and science educators [15]. Finally, we are tasked with promoting the valuation of science through our teaching and representation of respective fields and motivating students, and thereby the community, toward the lifelong pursuit of greater scientific literacy [1].

5. Conclusions

Long standing conceptions of teaching and learning in higher education are reflected in the continued focus on classical learning and traditional approaches that have been in place for generations. The classical approach to higher education has long focused on lecture as the delivery mode in classrooms, with the premise that understanding and acceptance are increased with extended exposure to knowledge. Such ideas and misconceptions about students and learning in the sciences are proving as dangerous to the education of the next generation as the misconceptions students bring into the classroom [15]. When viewing areas of controversy where students across levels struggle with scientific content knowledge and acceptance, such as evolution, we can highlight two areas of approach that have been proven to impact student understandings and even acceptance levels with reasonable adjustments to our approach.

While there is no one-size-fits-all approach to improving scientific literacy and active engagement in the undergraduate classroom, there are approaches that can be explored to begin changing the way we think about teaching and learning in higher education science. The first suggestion is to find ways to get students to engage in the content. This can be daunting in large lecture sections, but technology provides a means by which students at the undergraduate level can become more engaged in the learning process. There are available many existing resources, from interactive websites to faculty blogs that can help instructors begin the process of shifting the burden of learning from passive to active. Additional opportunities for training in active learning and engagement would further benefit members of faculty who are interested in shifting their approach in their classrooms.

The second suggestion is to rethink laboratory exercise structures to allow for more inquiry and discovery over procedures with fixed results. Research tells us that prescriptive exercises do not encourage thinking or engage higher literacies in students. Therefore, adjusting the structure to more closely align to actual practices would give more opportunities for students to experience failures, apply their understanding, and troubleshoot issues in ways that mimic that which is done in research settings. The third recommendation is to increase our focus at the post-secondary level on addressing misconceptions about science and scientists through intentional engagement in courses. Often instruction in higher education is focused on addressing facts and sharing knowledge while operating on the assumption that the students in the class enter with an appreciation for—or at least a general background in—basic science. Incorporation of foundational elements such as nature of science, philosophy of science, and history of science, in tandem with the content in courses and/or as stand-alone courses, would provide additional opportunities to address both deficiencies and common misconceptions that obstruct scientific literacy.

If we do not take action to strengthen our programs and expectations of students, we take the risk that the gaps between science and public will expand further. Without higher literacy, graduates of programs in science will continue to leave programs with incomplete and inaccurate understandings of the fields they represent. For those who are in non-science fields, the limited experiences they have in undergraduate study are even more important, as they represent the last opportunity to positively impact perceptions about science as well as their understanding of content. We are no strangers to bias and assumptions in our fields, but we can agree that seeking to identify and address shortcomings enables us to take steps to counter them. This is as true in the classroom as it is in research, where our critical assumptions can grossly alter the outcomes of our study. Students who leave natural science and science education programs should be adequately prepared for scientific practice, teaching, research, and mentorship, representing the highest levels of literacy, at least in their given domain.

Students outside of science programs should at least see connections between science and life and the value added to society by scientific understanding and pursuit. To reach this end, members of faculty must be provided support and options to increase their pedagogical understanding, be encouraged to apply more active approaches in the classroom, and have opportunities to share with one another their successes for sustained growth.

Conflicts of Interest: The author declares no conflict of interest.

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