

Surveying Science Literacy Among Undergraduates: Insights From Open-Ended Responses

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This paper presents the qualitative analysis of data from a 20-year project analyzing the knowledge and attitudes toward science of undergraduate students enrolled in introductory astronomy courses. The data were collected from nearly 10,000 students between 1989 and 2009 via a written survey that included four open-ended questions, inquiring into students' knowledge of scientific inquiry, DNA, computer software, and radiation. Trends in students' responses were arranged into concept maps that depict patterns in student thinking. Students' responses were also compared with criteria established by a sample of scientists. Students were familiar with empiricism in science and understood that science tries to explain the world but were not as attuned to the need to support arguments with evidence as scientists would expect. Students had a narrower conception of DNA, yet often related a blend of accurate and inaccurate ideas. The accuracy of students' descriptions of software increased over time, though they were more likely to approach software from a consumer rather than computer science perspective. Students attended overly much to the dangers of radiation, and the accuracy of responses decreased over time. This research demonstrates that students' ideas about science are less focused than scientists would like.

Instructors who take constructivist, learner-centered approaches to teaching know that students come to the classroom with their own histories of learning that influence the way they respond to and process new information. It is important to acknowledge and engage these learning histories so that students can connect their prior knowledge with the new knowledge presented to them. Often, the topics covered in science courses are not entirely new to students; they have had perhaps nearly 20 years of experience the world and construct their own notions of how it works. The question is: What *do* students think about these topics when they come into the classroom? Are their ideas similar to the ideas presented in class, or are they radically different from the understandings the instructor hopes to engender?

This paper presents the qualitative analysis of data from a large long-term project, which aims to analyze the science knowledge and attitudes toward science of undergraduate students who were enrolled in introductory astronomy courses at the University of Arizona (Impey, Buxner, Antonellis, Johnson, & King, 2011). The students were predominantly freshman and sophomore nonscience majors taking a science class as part of a general education requirement. The data described in this paper were col-

lected via a written survey from nearly 10,000 students in the first week of introductory astronomy courses at the University of Arizona over the course of 20 years, from 1989 to 2009. The survey was adapted from the science literacy questions analyzed by the National Science Foundation as part of its biannual report to Congress (National Science Board, 1988, 2010). The qualitative data are derived from four open-ended questions designed to delve deeper into respondents' understandings of concepts than the forced-response questions.

In addition to the student data, in 2009 we collected data from 170 University of Arizona science faculty members, postdocs, and graduate students; three questions from this online survey inquired into the scientists' criteria for assessing students' responses to three of the questions from the student survey. The first of these questions posed to students is the quintessential question for assessing scientific literacy: What does it mean to study something scientifically? We also inquired into students' knowledge and scientists' assessments for two content-knowledge questions: (a) What is DNA? and (b) Briefly, define computer software. Students were also asked: What is radiation? Although this question was not included on the scientists' survey, we had a substantial literature base on the topic from which to draw.

Our analysis of trends in students' responses allowed us to create a picture of student thinking relative to these four topics. Thus, we can assess both the range and the incidence of these different ideas, which provides us with a wealth of information about what conceptions students may have constructed prior to entering the classroom and assess them in comparison with the scientists' criteria for success.

Methods

For the purposes of understanding how this group of students conceptualized the subjects represented by the four questions, we developed methods that went beyond classifying responses as more or less "correct" and provide a more fine-grained picture of students' thinking. With the large number of responses (ranging from 5,700 responses for the radiation item to 7,800 responses for the DNA item), the method captured both the complexity of the variation in students' responses and systematically distilled the data into a manageable form for analysis. Each coding scheme (a) documented the frequency of common themes, (b) brought to the forefront the more unusual ideas that were nevertheless elucidating patterns in student thinking, and (c) noted the scarcity of other ideas that were less prevalent than anticipated or hoped for. The rich and varied landscape of responses to the open-ended questions, and the challenge of comparing students' and scientists' responses, meant that we decided early on to develop a coding scheme, driven by the data, so that we could draw inferences quantitatively. This approach was also necessary to track changes in responses over time, a core goal of the survey. The responses were coded iteratively by monitoring the responses for

common ideas and classifying and sorting the ideas that appeared to be related, making adjustments as the schemes continued to develop, until the entire data set had been analyzed. This technique allowed for analysis that was informed by the richness of the data, rather than prejudging what we might find. The final number of codes included 63 for science, 41 for DNA, 18 for software, and 87 for radiation. Taken together, these bodies of codes represent an extensive map of collective student thinking about these topic areas, with some elements arising more frequently than others. To allow for the visualization of the realms of student thought on the topics and the frequencies with which different elements arise, we created color-coded concept maps arranging the codes into meaningful categories. Dashed lines around the code represent misconceptions, and colors represent frequencies of the codes in the dataset, according to the following scheme:

Black:	0
Red:	1 to 99
Orange:	100 to 499
Yellow:	500 to 999
Green:	1,000 to 1,499
Blue:	1,500 to 1,999
Purple:	2,000 or more

Overarching categories were color-coded as well and the n sizes reported, though it is important to note that the category n sizes often differ from the sums of the codes that fall under them because the codes are not mutually exclusive and because often the category totals include less-frequent codes that are not included in the concept maps.

In order to seek out any changes over time, the data were grouped into four time periods with roughly

similar n sizes and number of years. The group of the earliest years—1989, 1990, 1991, and 1993—has 2,587 total participants; 1996–1999 has 1,851 participants; 2001–2005 has 2,273 participants; and 2006–2009 has 3,041 participants. The trends over time indicate changes in the population, not changes in the individuals, as new students were surveyed each year.

The scientists' data, all of which were gathered through an online survey tool in 2009, were analyzed in a similar manner, as the schema created to capture the ideas of the students also applied to the vast majority of ideas represented by the scientists. The results from the scientists drove our assessment of the comparison between what students reported for the three shared questions and what professionals in the field would hope and expect for them. The following sections describe the results of these analyses of the four open-ended questions.

Results and discussion

What does it mean to study something scientifically?

The coding scheme for this question was informed by the Views of the Nature of Science (VNOS) literature (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002). The VNOS is an instrument designed to assess views about the values and philosophies underlying the scientific enterprise and identifies five characteristics of the nature of science chosen for their relevance to students' learning about science. They are that science is (a) tentative, (b) empirically based, and (c) subjective (theory laden); that it (d) involves inference, imagination, and creativity on the part of the scientist; and that it is (e) socially and culturally embedded. The characteristics of science

presented in the VNOS literature and refined by the research team were placed into a coding scheme that categorized students' responses in three main ways. The first was by how they described what science is and what it does; the second was by the activities they identified as being part of scientific study; and the third was by their perceptions of the underlying philosophies of the scientific enterprise. Individual codes were developed from this framework and further refined on the basis of patterns that arose out of the student data. As with the other coding schemes, the codes are not mutually exclusive, and individual student responses were often coded with a variety of different codes to capture all the meanings present.

Figure 1 shows a piece of the cod-

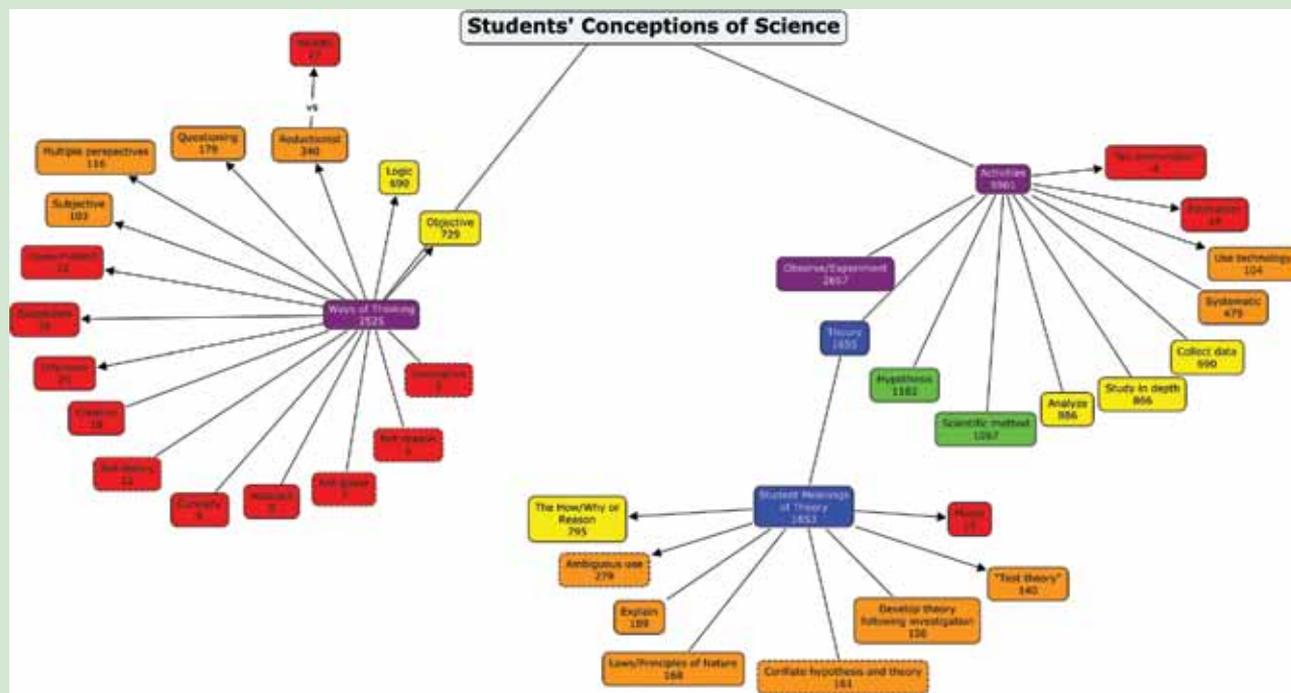
ing scheme representing our investigation of responses ($n = 7,523$) to this question, grouped thematically by ways of thinking, activities related to science (including a disaggregation of student uses of "theory"), science as knowledge building, science as evidence based, and science as a human endeavor. The full image can be viewed online at <http://www.nsta.org/college/connections.aspx>. The numbers of respondents in the sample whose answers fit each code are also included. The categories of scientific activities and ways of thinking are especially prominent. Students were more than twice as likely to discuss science on the basis of its activities ($n = 5,961$) than on ways of thinking associated with science ($n = 2,525$). That is, students were much more likely to talk about

what scientists do rather than why or how they do it. They were also more preoccupied with analyzing activities (analyze, reductionism, in-depth; $n = 1,900$) than synthesizing activities (inference, develop theory, explain, model, holistic, relationships; $n = 686$).

Students were more familiar with the empirical element of science ($n = 2,657$) than virtually any other characteristic. This idea was categorized under Activities because it was commonly only referred to indirectly as observation and/or experimentation. Though students may not have been very well-informed about the details of doing science, many recognized that it is a way of building knowledge about the world (knowledge building; $n = 1,802$). Nevertheless, it was much more likely for students

FIGURE 1

Partial map of codes related to students' concepts of science. The full image can be viewed online at <http://www.nsta.org/college/connections.aspx>.



to only implicitly refer to theory as determining the “how” and “why” for phenomena (total $n = 999$) than to use the word accurately ($n = 448$); they were about half as likely to use the word inaccurately or vaguely ($n = 408$). Not surprisingly, students sometimes conflated scientific theory with the common-language use of the word (total $n = 154$).

Also unsurprising, the most popularly referenced terms are those associated with “school” science, that is, the ones that are typically covered in textbooks when covering the scientific method ($n = 1,057$): observe/experiment ($n = 2,657$), hypothesis ($n = 1,182$), theory ($n = 1,855$). Concepts associated with more sophisticated understandings of science were more rare (e.g., supporting ideas with

FIGURE 2

Frequencies of scientist-defined criteria for “study scientifically” in the scientist and student data sets.

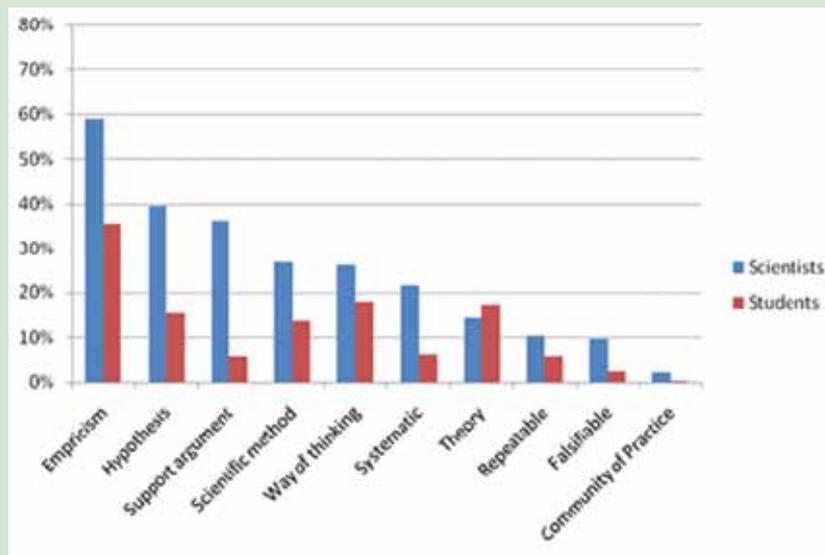


FIGURE 3

Map of codes related to students’ concepts of DNA.

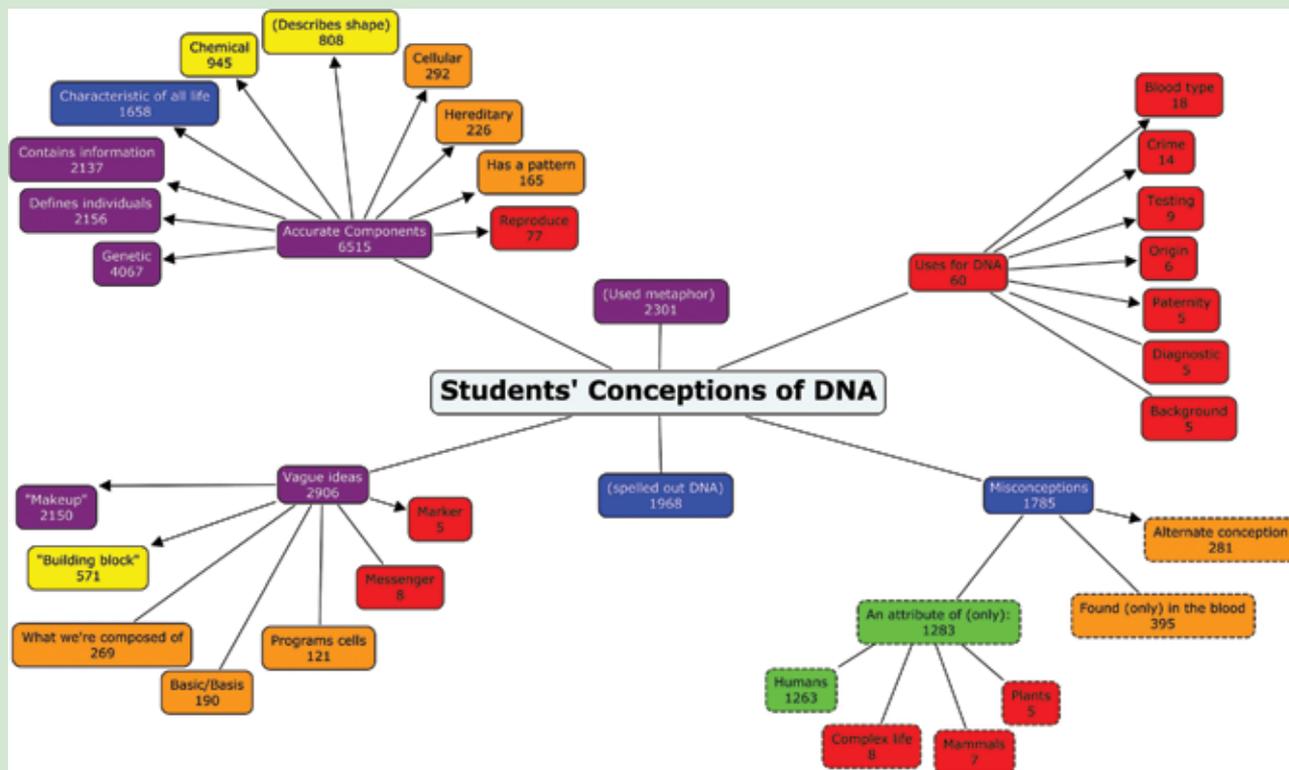
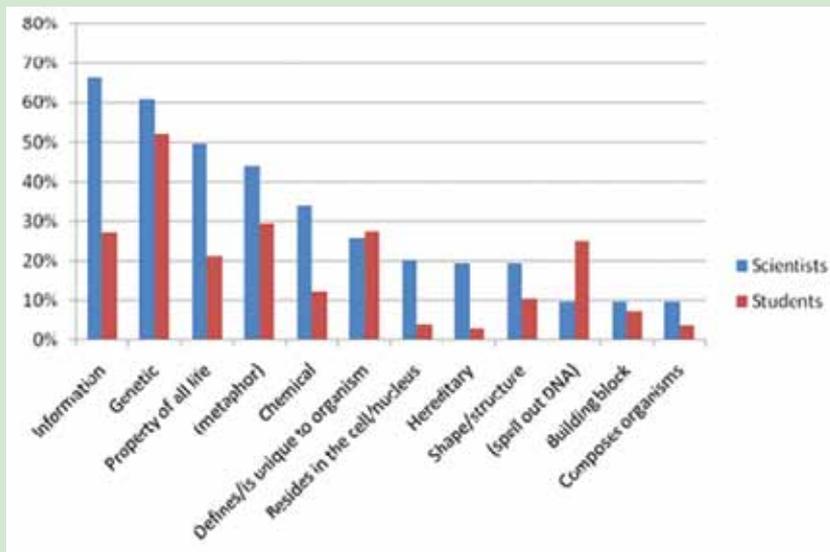


FIGURE 4

Frequencies of scientist-defined criteria for “What is DNA” in the scientist and student data sets.



evidence, $n = 452$; questioning, $n = 179$; inference, $n = 29$). Nevertheless, though the notion of science “proving” ideas was prevalent ($n = 383$), so too were using evidence ($n = 196$), building support for and validating ideas (total $n = 527$), disproving hypotheses ($n = 180$), and scientific ideas as tentative ($n = 425$). Unfortunately, however, it was rare for students to make any reference to science as a human endeavor (total $n = 40$).

The science responses over time showed no significant changes: Discussion of activities related to science arose in 75%–81% of responses consistently, with no trends by year; knowledge building arose between 34% and 38%; empiricism (observation and experimentation) in 30%–39%; and scientific method between 12% and 15%. It appears that the general understanding of science of this population as a whole is not changing discernibly over time.

The themes from the scientists’ expectations for “study scientifically” ($n = 144$) were examined for their overlap with, as well as dissimilarities from, students’ responses. Because students and scientists associate science with similar concepts, yet conceive of these concepts in different ways, there was a good but not perfect correspondence between the two coding schemes. Figure 2 is a comparison of the most prominent criteria for students’ responses that arose from the scientists and the frequency with which students addressed those criteria. The scientists and students were similar in their emphasis on empiricism as well as theory and ways of thinking (in this analysis we compiled only the student responses related to ways of thinking that reflected those identified by scientists: objectivity, logic, and skepticism). However, students fall short in the areas of supporting an argument and being systematic.

With their emphasis on theory building, students seem to understand that science is meant to explain the natural world but not to understand that such explanations need to be supported by evidence. This notion is not getting through to students, despite their ease in repeating the scientific method and their recognition that science involves certain ways of thinking.

What is DNA?

Unlike the coding for students’ responses about science, the scheme for DNA was not framed by previous literature. The codes for this question arose purely from trends in students’ responses, similar to the methodology used by Lewis, Leach, and Wood-Robinson (2000) in their study of students’ ideas related to genes. The codes were organized into three main categories: accurate descriptions, trivial or uninformative descriptions, and misconceptions. An additional category for metaphors used by students was added because of the frequency with which these metaphors appeared, in nearly 30% of responses ($n = 2,301$).

Figure 3 depicts the codes used to characterize students’ understandings of DNA. A greater proportion of students responded to the DNA question than any other question ($n = 7,806$). Nevertheless, the overall number of responses that contained trivial, vague, or inaccurate information is fairly high (total $n = 5,353$) compared with the number containing accurate elements (total $n = 6,515$). Considering the total n size is under 8,000, this indicates that for the most part, students’ responses were a blend of both on-target and off-target conceptions of DNA. For instance, students commonly identified DNA as genetic ($n = 4,067$), as representing informa-

tion ($n = 2,137$), and as that which defines organisms and/or is unique to each organism ($n = 2,156$), but they frequently merely spelled out “deoxyribonucleic acid” ($n = 1,968$) or erroneously suggested that DNA is solely a property of humans ($n = 1,263$).

We hypothesized that with the greater visibility of genetics in the media in the past 20 years, students would show an increase in accurate ideas and a decrease in inaccurate ideas over time, but this was not the case. In fact, the most recent group of students, from 2006–2009, were on par with the earliest group of students from 1989–1993. Mystifyingly, students in the groups from 1996–1999 and 2001–2005 showed an almost 30% increase in inaccurate and trivial ideas compared with students from the other two eras, though the frequency of accurate ideas in all four groups was similar.

Although our previous hypothesis did not stand up, our hypothesis that more students would be willing to tackle this question over time did.

Our rationale was again that with increased visibility of the topic, more students would be familiar with it and would be willing to put their knowledge on the line. The difference from the early years to the later years was more dramatic than anticipated, however; 71% of students from the 1989–1993 group responded to the question, whereas percentage response rates were in the low to mid-80s for the 1996–1999, 2001–2005, and 2006–2009 groups.

Although the number of codes arising from the student data was fairly small, the trends in the scientists’ criteria were strikingly similar, though in distinctly different proportions. Figure 4 shows the comparison; students and scientists ($n = 143$) are on par in terms of characterizing DNA as genetic, but students were far less likely to mention that DNA is information, a property of all life, and hereditary, among other attributes. Interestingly, although students’ use of metaphors was high, scientists anticipated more; a greater proportion of scientists

cited examples of metaphors in their expectations of students’ responses (44%) than the students actually used (29%).

Briefly, define computer software.

Students’ responses for software were categorized into 18 codes, divided into four categories: primary components of a definition of software (that it is programming, or more specifically code, that directs the computer to perform a function), which were the most frequent codes (total $n = 4,803$); additional but secondary elements, such as that software is an interface between the computer and user and that it must be installed (total $n = 2,510$); vague or trivial elements, such as software as “technology” (total $n = 899$); and misconceptions (total $n = 1,283$). The most common misconception in this data set involved students’ conflating the media containing the programs with the programs themselves ($n = 724$).

The results for this topic area are

FIGURE 5

Map of codes related to students’ concepts of computer software.

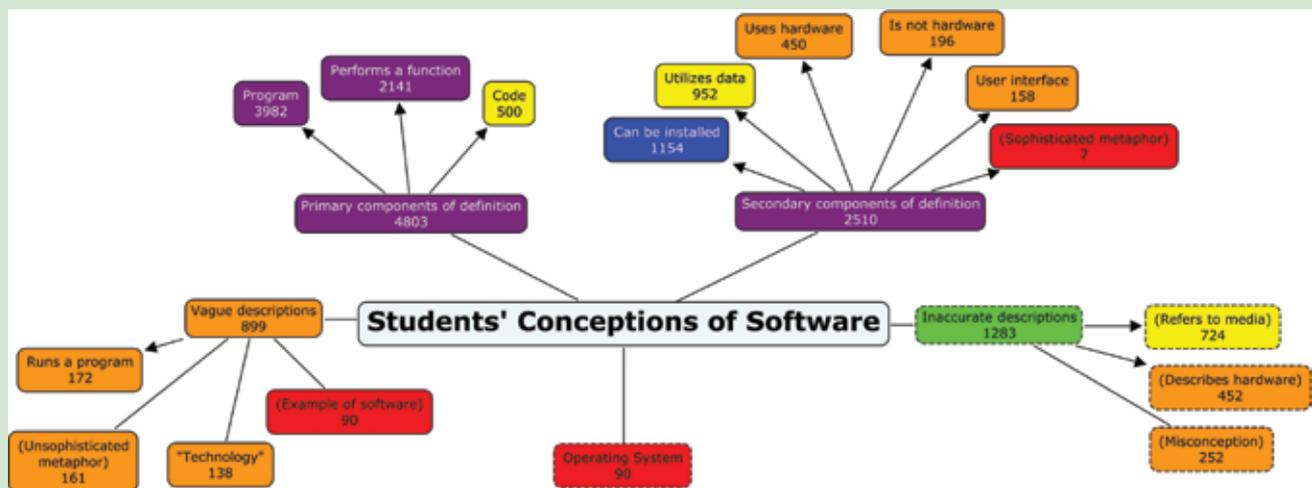
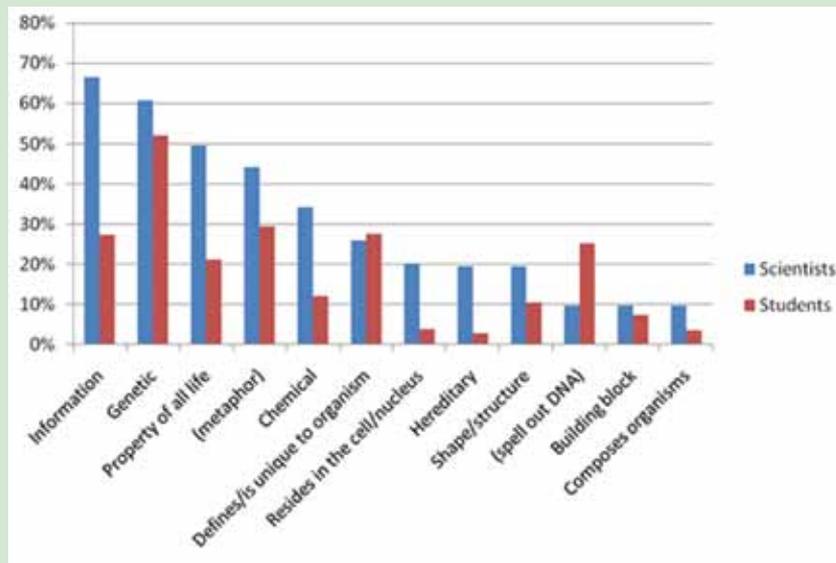


FIGURE 6

Frequencies of scientist-defined criteria for “Briefly, define computer software” in the scientist and student data sets.



displayed in Figure 5. Accurate responses outnumbered inaccurate or vague responses almost three to one ($n = 5,675$ and $2,179$, respectively). However, the total number of respondents was low overall ($n = 6,743$), so a self-selection effect likely influenced this outcome. Nevertheless, the increase in the prominence of computer technology in students' lives over the two decades of the data collection appears to have had a significant effect on their responses. The percentage of the sample citing accurate ideas increased from 82% in both the 1989–1993 and 1996–1999 samples to 87% in 2001–2005 and 86% in 2006–2009. Even more noteworthy, the prevalence of vague and inaccurate responses decreased from 40% in 1989–1993 to 20% in 1996–1999 and less than 10% in the latter two groups (9% and 7%, respectively).

The comparison between the students' responses and the scientists'

expectations in Figure 6 reveals that, although the frequencies are different because of the discrepancy in n sizes (scientist, $n = 138$), the shape of the distributions among the different concepts are similar. There are two main disconnects: (a) students were more likely to reference that software is added to the machine, and (b) students were far less likely to speak of software as a code or as the interface between the user and the hardware. Both of these trends suggest that although scientists would like students to understand software from the perspective of computer science, students are more likely to identify with the consumer perspective.

What is radiation?

The scheme for coding students' responses about radiation ($n = 5,782$) was based on research literature pertaining to students' understanding of radiation and radioactivity and on trends arising from the data

(Boyes & Stanistreet, 1994; Henriksen, 1996; Klaasen, Eijkelhof, & Lijnse, 1990; Lijnse, Eijkelhof, Klaasen, & Scholte, 1990; Prather, 2005; Prather & Harrington, 2001; Rego & Peralta, 2006). The categories were designed to be inclusive enough to compare our results with the frequencies of trends cited in the literature as well as the frequencies of other trends in these data. Although certain codes are used very infrequently, we were able to document the relative absence of certain ideas in the data set, as well as the relative abundance of other ideas. Hence, this is the only coding scheme in which codes with zero respondents are found.

Figure 7 depicts a selection of students' conceptions about radiation. The full image can be viewed online at <http://www.nsta.org/college/connections.aspx>. Students were overly attentive to the perceived dangers of radiation, focusing much more on the high-energy (total $n = 455$) than low-energy (total $n = 142$) wavelengths of light and on its dangers (total $n = 2,635$) than its uses (total $n = 325$). The association with environmental danger is important because it helps explain why students' responses include so many references to other, unrelated phenomena that are also associated with environmental danger, such as “by-products” and the atmosphere. It seems that students have learned to be afraid of radiation but have not been so successful at learning why they should be afraid, so they have associated it with other frightening things they have learned about.

Although students expressed a range of inaccurate beliefs about the nature of radiation (e.g., that it is sound, gas, magnetism, a by-product, or an effect; total $n = 1,499$), many more students correctly

characterized it as energy, light, electromagnetism, or radioactivity (total $n = 3,220$). However, among the different wavelengths of light, the one most commonly referenced ($n = 233$) was some distinct part of the electromagnetic spectrum that, in these students' minds, is the only part that counts as radiation. This could be a half-step between "all radiation is bad" and "there are different types of radiation, some harmful and some harmless" and may be an accommodation of, on the one hand, what students "know" from media and common-sense understandings of radiation as "dangerous" and, on the other hand, what they have been taught in school—that radiation is the transmission of energy.

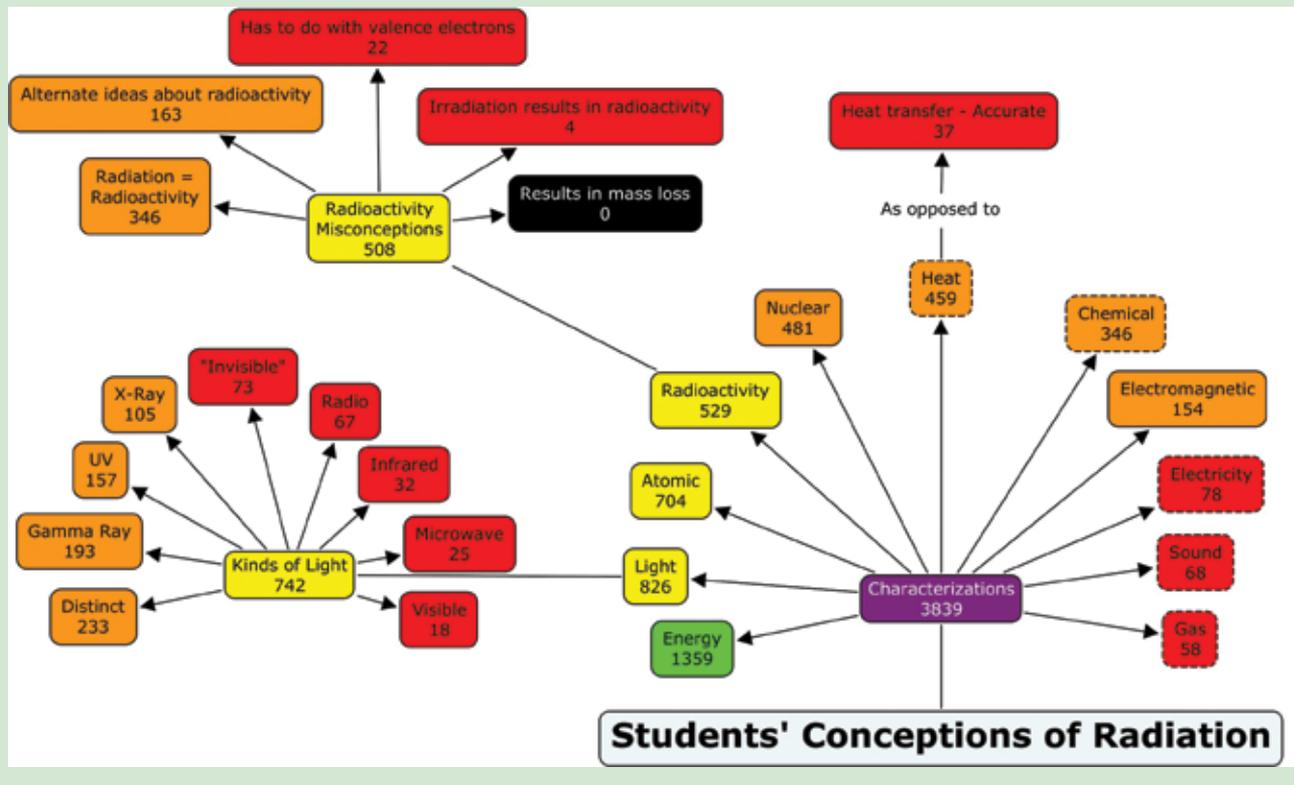
Students have myriad ideas about where radiation comes from, most of them vague. Many students referred to the Sun as a source ($n = 464$) but most frequently referred to radiation coming from nebulously defined substances ($n = 813$). The majority of other student-defined sources are misconceptions (total $n = 713$). However, if students identified a source of radiation ($n = 1,827$), they were far more likely to identify natural sources ($n = 1,401$) than human-made sources ($n = 603$). As well, when students identified natural sources, they were far more likely to be accurate ($n = 1,324$) than to have a misconception ($n = 99$). In contrast, when students identified a human-made source, they were far more

likely to have a misconception ($n = 532$) than to be accurate ($n = 103$).

Surprisingly, students seemed to become less informed about radiation over time. Although this question was consistently the least likely to be answered (62% response rate and lower throughout), there was a slight increase in the prevalence of inaccurate ideas over time, from 24% in the 1989–1993 group up to 28% in the 2006–2009 group. Even starker is the steady decrease in accurate ideas, from 66% in the 1989–1993 group to 49% in the latest group. Whatever the reason, these students' conceptions of radiation have become more nebulous and less correct over time. The radiation question is the only one for which we do not have a scientist data

FIGURE 7

Partial map of codes related to students' concepts of radiation. The full image can be viewed online at <http://www.nsta.org/college/connections.aspx>.



set to which to compare and so we cannot speculate on the gap between the ideas of scientists and students.

Conclusions

Patterns in undergraduate students' responses to four open-ended questions about science and science topics were derived from a sample of nearly 10,000 students spanning 20 years. Rather than making knowledge models or coding according to prior expectations, the coding categories were driven by the data. Few significant trends with time are seen. On the core issue of their understanding of how science works, students tend to emphasize empiricism over theory, and they seem generally unaware of how the two relate. Responses for the other open-ended items also favor specific examples over broader conceptual frameworks.

This research demonstrates that students are able to communicate a wealth of ideas about the scientific endeavor and three areas of its content. However, if the incidence of misconceptions and trivial or shallow characterizations is taken as a sign of insufficient depth of knowledge for true understanding, then science literacy is a continuing concern for educators of undergraduate students; students do not have as solid a grasp of the fundamental core of these subject areas as scientists and science educators would like. The data are consistent with the supposition that knowledge of facts or terminology in a scientific subject does not connote a general understanding of either the content or the process of science or the ways that new knowledge is gained by scientists.

This investigation also begs the question of whether students' responses to these questions are indica-

tive of their overall scientific literacy and, if so, how our qualitative coding capturing the many intricacies of student thinking can be used to assess that literacy. Our preliminary inquiries into these questions, to be presented elsewhere, have found that students' open-ended responses are not tied to their scores on the forced-choice component of the survey, calling into question existing assessments of public science literacy. We welcome collaboration to extend our findings to other populations in order to delve further into unraveling this mystery. ■

References

- Boyes, E., & Stanisstreet, M. (1994). Children's ideas about radioactivity and radiation: Sources, modes of travel, uses and dangers. *Research in Science and Technological Education, 12*, 145–160.
- Henriksen, E. K. (1996). Laypeople's understanding of radioactivity and radiation. *Radiation Protection Dosimetry, 68*, 191–196.
- Impey, C., Buxner, S., Antonellis, J., Johnson, E., & King, C. (2011). A twenty-year survey of science literacy among college undergraduates. *Journal of College Science Teaching, 40*(4), 31–37.
- Klaasen, C. W. J. M., Eijkelhof, H. M. C., & Lijnse, P. L. (1990). Considering an alternative approach to teaching radioactivity. In P. L. Lijnse, C. W. J. M. Klaasen, & H. M. C. Eijkelhof (Eds.), *Relating macroscopic phenomena to microscopic particles: A central problem in secondary science education* (pp. 304–315). Utrecht, the Netherlands: CDB Press.
- Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching, 39*, 497–521.
- Lewis, J., Leach, J., & Wood-Robinson, C. (2000). All in the genes? Young people's understanding of the nature of genes. *Journal of Biological Education, 34*, 74–79.
- Lijnse, P. L., Eijkelhof, H. M. C., Klaasen, C. W. J. M., & Scholte, R.L.T. (1990). Pupils and mass media ideas about radioactivity. *International Journal of Science Education, 12*, 67–78.
- National Science Board. (1988). *Science and engineering indicators 1988*. Arlington, VA: National Science Foundation.
- National Science Board. (2010). *Science and engineering indicators 2010*. Arlington, VA: National Science Foundation.
- Prather, E. (2005). Students' beliefs about the role of atoms in radioactive decay and half-life. *Journal of Geoscience Education, 53*, 345–354.
- Prather, E. E., & Harrington, R. R. (2001). Student understanding of ionizing radiation and radioactivity: Recognizing the differences between irradiation and contamination. *Journal of College Science Teaching, 31*(2), 89–93.
- Rego, F., & Peralta, L. (2006). Portuguese students' knowledge of radiation physics. *Physics Education, 41*, 259–262.

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