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Many Paths Toward Discovery: A Module for Teaching How Science Works

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Improving students' understanding of how science works requires explicit instruction. Here, we test the efficacy of a module based on two previously published activities (the Cube Puzzle *and the case study* Asteroids and Dinosaurs*) that teach how science works to college science majors. Students also use the* How Science Works Flowchart *from Understanding Science (http://undsci.berkeley.edu/) to reflect on these activities. To assess the efficacy of this module, we asked students to illustrate the process of science before and after the intervention. After the intervention, students' diagrams were significantly more complex and nonlinear. Students also incorporated more social aspects of science, such as discussing results with colleagues. However, few of the pre- or postdiagrams mentioned the way science benefits society. We conclude that our intervention is an easy-to-implement strategy for improving some aspects of scientific literacy in college students.*

Implicit instruction on how science works, such as conducting a laboratory experiment, does not convey to students the depth and richness of how science works (Lederman, Lederman, & Antink, 2013). Therefore, to improve scientific literacy, science courses must include explicit instruction on the way science works (Brewer & Smith, 2011; Lederman et al., 2013; NGSS Lead States, 2013). Much of the recent research on how science majors learn about how science works has focused on course-based research experiences (e.g., Brownell & Kloser, 2015), which "enculturate" students into the process of doing science (Linn, Palmer, Baranger, Gerard, & Stone, 2015, p. 628). These experiences often ask students to reflect on how to improve their experiments (Brownell & Kloser, 2015), and these reflections are part of scientific practice that tend not to be apparent from a linear, step-by-step recipe. However, course-based research is both resource and time intensive. If our objective is to improve student's understanding of how science works in a wide variety of course settings, it would be helpful to have an effective intervention with less investment of resources and time. We designed our intervention to help students understand that research involves many components, including ways to explore a topic, design an experiment, and impact the scientific community and society at large (Figure 1).

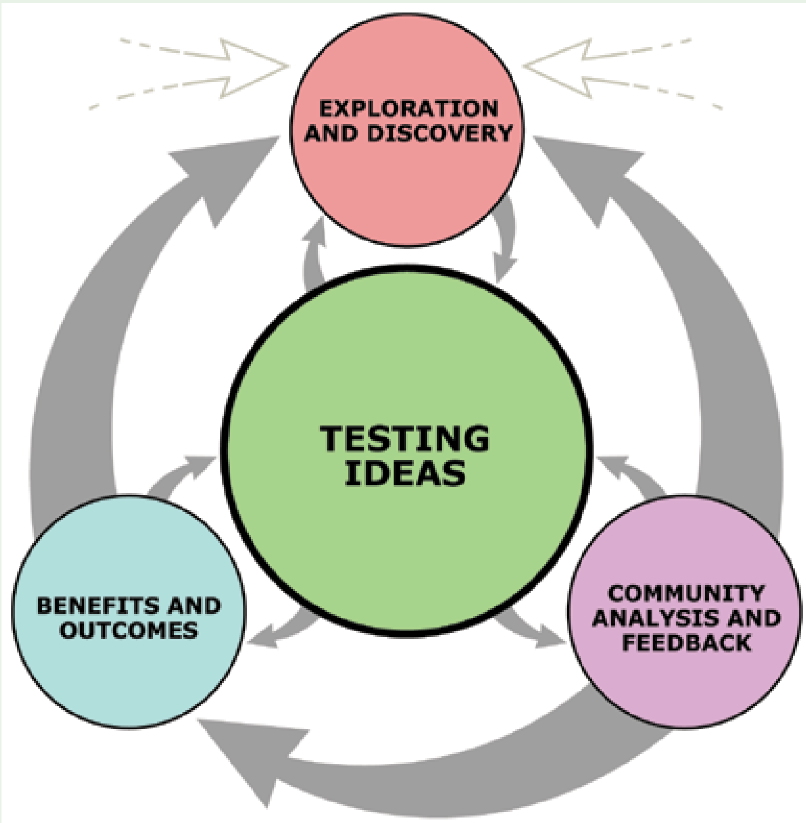
Before going further, it is worth noting that the research literature uses many phrases to describe how science works, including *scientific practices* (NGSS Lead States, 2013), *science as a way of knowing* (Aikenhead, 1979), *thinking like scientists* (Brewer & Smith, 2011), *nature of science* (e.g., Lederman, 1992), *nature of scientific inquiry* (e.g., Schwartz, Lederman, & Abd-El-Khalik, 2012), *nature and process of science* (Understanding Science, 2016b), and *whole science* (Allchin, 2011). Philosophers recognize distinctions among these terms, but our intent is to focus on their similarities. We want students to understand how scientists conduct research, but also how those discoveries impact larger communities and vice versa. Here we use the phrase that the Understanding Science team advocates, *how science works* (Understanding Science, 2016b, Figure 1), a phrase that incorporates community impact into research.

The many decisions that scientists make as they conduct research are described as four categories in the *How Science Works Flowchart* (hereafter referred to as *Flowchart*) by Understanding Science (Figure 1, Understanding Science, 2016b; http://undsci.berkeley.edu/). Understanding Science is a comprehensive, practical resource for teaching how science works published by the University of California Museum of Paleontology (Thanukos, Scotchmoor, Caldwell, & Lindberg, 2010). *Testing ideas* is the central category on the *Flowchart*, and three other categories inform—and are informed by—those tests. At the top of the diagram is a category that emphasizes inspiration for discovery (Exploration and Discovery); also included is the social component of science including both the engagement of the scientific community in how a scientific investigation unfolds (Community Analysis and Feedback) and the societal and personal benefits of the outcome of answering a scientific question (Benefits and Outcomes).

Our module consists of three activities (Table 1). The first is the *Cube Puzzle*, a simple activity that illustrates a metaphor for the scientific process (Working Group on Teaching Evolution, 1998). The second is the *Asteroids and Dinosaurs* case study (Understanding Science, 2016a), which uses the *Flowchart* to uncover the asteroid impact that led to the extinction of the dinosaurs. The original descriptions of these first two activities are available free, and although we briefly summarize them in Table 1, we refer readers to the original text for more details. In the third activity, students integrate the previous activities by illustrating the steps they used to solve the *Cube Puzzle* on the *Flowchart* (Figure 2).

FIGURE 1

The *How Science Works Flowchart* by The University of California Museum of Paleontology, Berkeley, and the Regents of the University of California (Understanding Science, 2016b; http://undsci.berkeley.edu/lessons/pdfs/complex_flow_handout.pdf). The version of the *Flowchart* on the Understanding Evolution website shows how each of these categories is composed of many subcategories. The subcategories for Exploration and Discovery are reprinted in Figure 6A. Used with permission.



Research question

We asked whether this module (Table 1) that takes two class periods is effective at explicitly teaching how science works (Table 2). We wanted students to better understand that scientific research is circuitous instead of linear and that it relies on interconnections among many different steps (Allchin, 2011; Understanding Science, 2016b). Science is more than conducting an experiment, for example by involving primary literature, communicating with colleagues, explaining the reasons for asking particular questions, and working to benefit society (subcategories of the Benefits and Outcomes and Community Analysis and Feedback categories from Figure 1).

Data collection

Our sample consists of 42 students: 25 students at a master's university on the West Coast enrolled in a third-year course on the scientific methods intended for environmental science majors, and 17 students from a moderate research university in the Southwest enrolled in a third-year course on science communication with an emphasis on biology. Students in this sample agreed to participate in the study and completed all of the steps in the study design (Table 1). Data were collected with the approval of our Institutional Review Boards (University of Washington: 42505; University of Texas Rio Grande Valley: 2014-089-09). Because we wanted to observe the whole population of students, rather than individual performance, we did not collect demographic data or data about students' experience with research.

To measure the effect of the module (Table 2), we asked students to "Draw a diagram that illustrates the scientific process. Label the steps in the diagram so it is clear to a reader how someone can go about doing science." They constructed these drawings before and after the intervention. The module was taught over two class meetings (2–5 days apart) for a total of 75 to 120 minutes, depending on the instructor.

We used the *Flowchart* (Understanding Science, 2016b) to develop a novel coding scheme to characterize students' diagrams. We counted the number of steps, the number of times a step splits into two or more steps, and the number of steps that were repeated. Each repeated step increased the number of total steps by one point; because some diagrams included cycles, this limit avoided counting to infinity. This approach also meant that if a diagram included several arrows to a box called "test hypothesis," then the test-hypothesis step would contribute to the total number of steps twice: once for the first time and once because it is repeated. In general, we interpreted lines connecting two points on a chart to be arrows, showing progress from one step to another. To compare how nonlinear the diagrams were, we defined nonlinearity as

$$\frac{\textit{Number of repeated steps} + \textit{number of split steps}}{\textit{Total number of steps}}$$

We also compared students' diagrams to the *Flowchart* by coding whether the students represented the four categories of Testing Ideas, Exploration and Discovery, Community Analysis and Feedback, and Benefits and Outcomes (Figures 1, 2) into their diagrams. Within Exploration and Discovery, we recorded whether diagrams referred to "making an observation," "asking a question," "exploring the literature," and/or another form of "finding inspiration," all of which are subcategories of Exploration and Discovery (Figure 6A). We used finer subcategories within Exploration and Discovery because they were commonly used in students' work. In some cases,

TABLE 1

Description of the instructional intervention.

Step	Description
Activity 1: *Cube Puzzle*	Students use five sides of a cube to predict what is on the sixth, covered side. They begin with an easy puzzle, move onto a more advanced one, and then create puzzles for their classmates to solve. Then the instructor facilitates a whole-class discussion about how this activity compares with how science works (Working Group on Teaching Evolution, 1998).
Activity 2: *Asteroids and Dinosaurs*	Students explore the *How Science Works Flowchart* (Figure 1) with a short interactive lecture of *Asteroids and Dinosaurs*, a module on the Understanding Science website (2016a). This case study introduces the discovery of the asteroid impact that led to the Cretaceous-Tertiary Extinction, with slides highlighting the unpredictability of scientific exploration. Animations map each step of the research onto the *Flowchart* and emphasizes interactions among the categories (Understanding Science, 2016b). The *Flowchart* was formulated to counter the misleading idea that science is a simple, linear process, allowing students to realize that the steps scientists take can change unpredictability and are informed by interactions among the scientific and public communities.
Reflection	Students map their process for completing the *Cube Puzzle* onto the *Flowchart*. By constructing this map, students recognize when they engage with different categories of how science works (Figure 1).

it was obvious that students were trying to recreate the *Flowchart* in their postdiagrams. These diagrams may reflect memorization rather than deep thinking, but they still represent a shift away from thinking of science as linear. Thus, we retained these in our analysis.

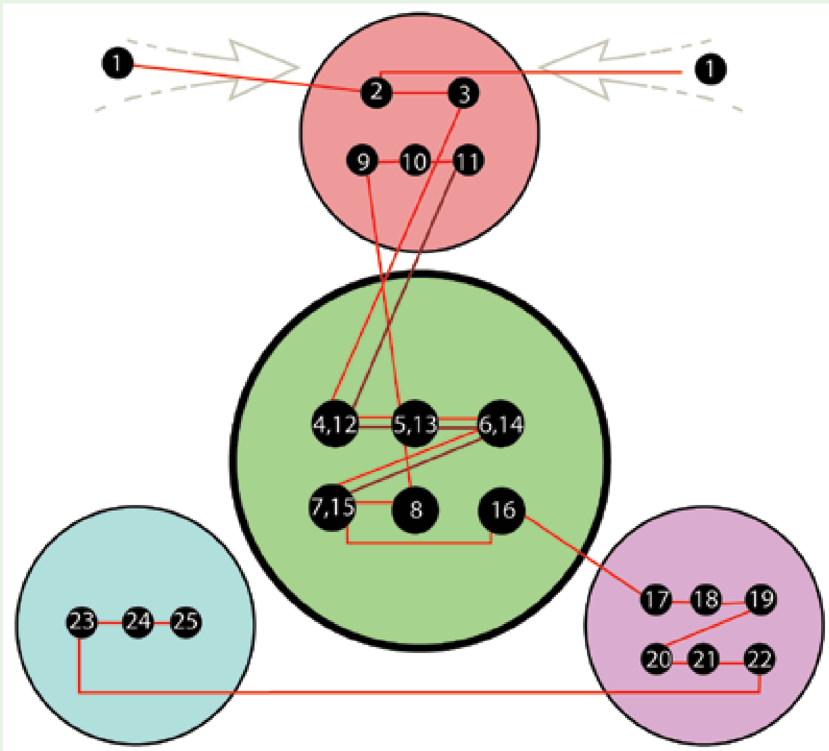
Finally, we examined the diagrams to determine how they reflected an understanding of target concepts in Table 2, rating each as 0 = *poor representation*, 1 = *mixed representation*, or 2 = *adequate representation*. We describe the system we used to determine these scores in Table A1 (available at http://www.nsta.org/college/connections.aspx).

Evidence of students' learning

As we will describe, most (5 of 7) of our predictions were supported (see Table A2, available at http://www.nsta.org/college/connections.aspx). In one way, students' diagrams were more sophisticated than we anticipated when the study began: 100% of pre- and postdiagrams included Testing Ideas. However, we did not see an increase in the mention of Benefits and Outcomes or an adequate understanding of the nature of discovery. We discuss possible ways to improve this below.

FIGURE 2

After students completed the activities, we asked them to reflect on the scientific approach that they used to complete the *Cube Puzzle* (Table 1: Activity 1; Working Group on Teaching Evolution, 1998) onto the *How Science Works Flowchart*, following the style illustrated with *Asteroids and Dinosaurs* case study (Table 2: Activity 2; Understanding Science, 2016a). We illustrate this reflection step (Table 1: Reflection) with a drawing of one student's map; darker lines point to steps that are repeated. The students' original diagrams can be difficult to read, so we have redrawn this example to communicate clearly the connections one student made.



Complexity: Repeated steps and linearity

The intervention shifted students toward a more complex understanding of how science works. When we compared the diagrams that students drew to depict their concept of science before and after instruction, we found that the postdiagrams contained 30% more steps, on average, than the prediagrams, a significant improvement with a large effect (paired t test, $p << .01$; Cohen's $d = 0.75$; Middlemis Maher, Markey, & Ebert-May, 2013; Figure 3A). The postdiagrams were also significantly less linear, with a medium effect ($p << .01$, $d = 0.51$, Figure 3B). These encouraging results indicate that the module leads to large, positive changes in several aspects of student understanding of how science works, and they are consistent with what Wilson and Rigakos (2016) found in a study using a similar assessment.

Testing Ideas

The central category of the *Flowchart* is Testing Ideas (Figure 1), and students' diagrams demonstrated that they understood these concepts before instruction (Figures 4 and 5). Subcategories of Testing

Ideas, including the practice of basing conclusions on observations and experiments, were found in 100% of pre- and postdiagrams (Figures 4 and 5: Concept 1, Table A2, available at http://www.nsta.org/college/connections.aspx). This success indicates that because students enter our classrooms understanding the basics of how to test ideas, their understanding about how science works will improve most dramatically when our instruction emphasizes other categories of the *Flowchart* (see also Thanukos et al., 2010).

Exploration and Discovery

The Exploration and Discovery category of the *Flowchart* encompasses the processes that inspire scientific investigations (see subcategories in Figure 6A). Even before instruction, the students consistently referenced asking questions and making observations in their diagrams (Figures 4, 5, and 6), and they continued to do so after instruction. However, postdiagrams included significantly more references to finding inspiration and working from the primary literature (χ^2 test, $p << .001$ in both cases, Figure 6B). Finding inspiration and using the literature to ask new questions are both aspects of science that are heavily emphasized in *Asteroids and Dinosaurs* (Understanding Science, 2016a).

Community Analysis and Feedback

Students' postdiagrams included significantly greater mention of Community Analysis and Feedback (Figure 4; χ^2 test, $p << .001$). However, the number of students mentioning the Benefits and Outcomes of science

TABLE 2

Predictions and the measurements evaluated to test the effectiveness of this module.

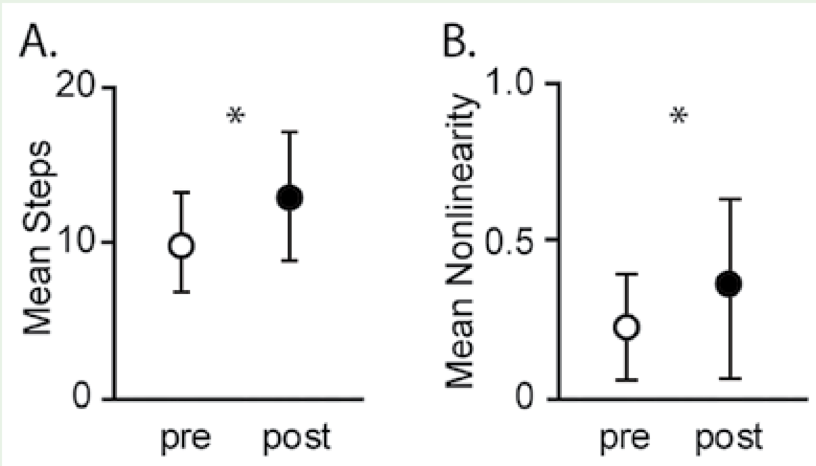
After the module, more of the diagrams would . . .	We will measure this by evaluating the . . .
be complex.	total number of steps. nonlinearity: $\frac{N\ repeated\ steps + N\ steps}{Total\ N\ steps}$
reference Testing Ideas.	number of diagrams referencing subcategories of the Testing Ideas category.
illustrate multiple ways of generating testable ideas, as explained in the Exploration and Discovery category of the *Flowchart*.	number of diagrams mentioning observations, asking questions, finding inspiration, and reading the literature.
reference the subcategories from Benefits and Outcomes and Community Analysis and Feedback categories of the *Flowchart*.	number of diagrams referencing subcategories of Benefits and Outcomes. number of diagrams referencing subcategories of Community Analysis and Feedback.
emphasize the concepts that[a] 1. scientific conclusions are based on data that have been observed, modeled, and/or derived from experiments. 2. current scientific research depends on previous scientific investigations and influences future ones. 3. scientific discovery creates knowledge that is new and unpredictable.	scores for each concept (0 = *not depicted*; 1 = *incomplete*; 2 = *reaches target*; see Table A1, available at http://www.nsta.org/college/connections.aspx).

Note: Testing Ideas, Exploration and Discovery, Benefits and Outcomes, and Community Analysis and Feedback are categories of the *How Science Works Flowchart* (Figure 1). Subcategories within each of these can be found at http://undsci.berkeley.edu/lessons/pdfs/complex_flow_handout.pdf
[a]The language of these objectives is modified from published description of the cube activity (Working Group on Teaching Evolution, 1998).

did not change significantly (Figure 4, χ^2 test, $p = .41$; see also Wilson & Rigakos, 2016: Figure 6D). These results are simultaneously encouraging and frustrating. Students learned more about the collaborative aspects of how science works, but did not recognize the impact science has on society or their own lives. Allchin argued that effective science instructions must develop "culturally functional knowledge" (2011, p. 519) of science, an understanding and appreciation for how science is integrated into students' lives. Community Analysis and Feedback models the way research is integrated into the scientific community; Benefits and Outcomes explains how research is integrated into society. As interesting as dinosaurs are, the instructional approach in this study seems to have failed to change the way students incorporate Benefits and Outcomes into their diagrams, perhaps because dinosaurs do not affect people's lives. The case studies that Allchin (2011) proposed (e.g., Climategate, vaccine controversy, and disease) may do this better because of their immediacy. Alternatively, instructors can highlight more explicitly the Benefits and Outcomes within the *Asteroids and Dinosaurs* case study (Understanding Science, 2016a).

FIGURE 3

A. The number of steps that students used to describe how science works (paired *t* test, *p* << .01, Cohen's *d* = 0.75). B. The nonlinearity of students' diagrams (paired *t* test, *p* << .01, *d* = 0.51); we graphed nonlinearity instead of linearity because it is easier to discuss a positive change as evidence of learning. Error bars are standard deviation. Both comparisons show a statistically significant increase after the intervention.



Target concepts in diagrams

As discussed previously (see Testing Ideas), 100% of the pre- and postdiagrams included elements of Concept 1: Scientific conclusions are based on data that have been observed, modeled, and/or derived from experiments (Figures 4 and 5). Concept 1 essentially summarizes the Testing Ideas category of the *Flowchart*. However, the other concepts proved more challenging for students.

Few diagrams incorporated a complete picture of how current scientific knowledge relies on previous scientific investigations (Concept 2 in Table 2, Figure 5). We found a statistically significant increase in understanding of this learning goal (Mann Whitney U test, $p << .001$), but students usually recognized either that their research was informed by previous scientists' work or that it would inform future scientists' work (score of 1 in Figure 5: Concept 2). Few diagrams incorporated both past and future impact, and recognizing both directions of impact was necessary for the highest score in our scheme (Figure 5: Concept 2; Table A1, available at http://www.nsta.org/college/connections.aspx).

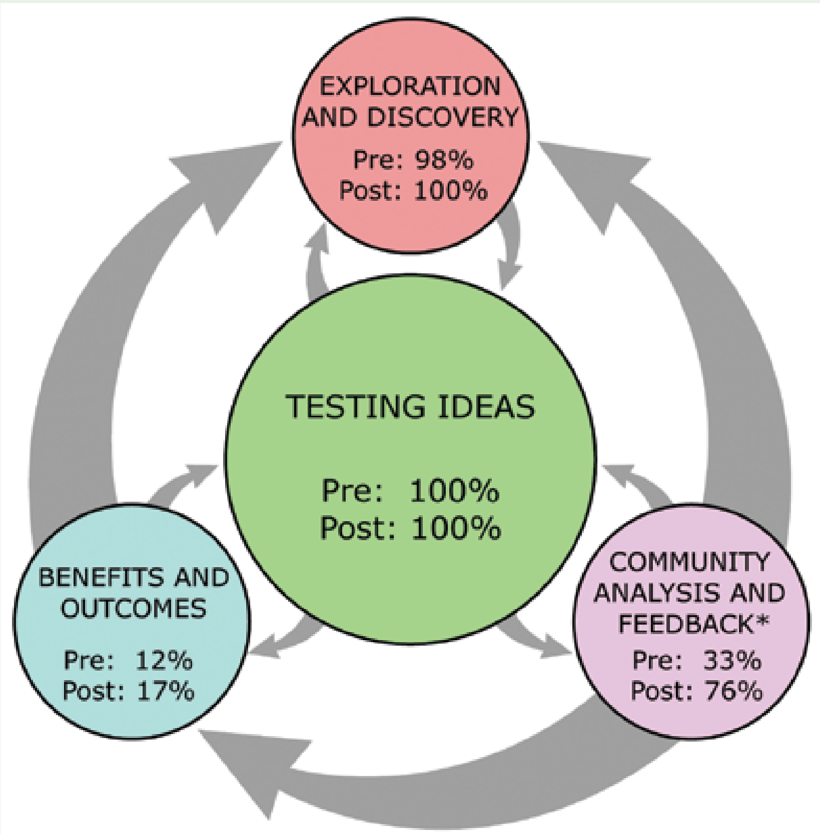
We expected that the *Asteroid and Dinosaurs* case study (Understanding Science, 2016a) would improve students' understanding that science leads to new and unpredictable knowledge (Concept 3 in Table 2, Figure 5). However, we found no significant difference in students' representation of discovery before and after instruction (one-tailed Mann-Whitney U test, $p = .23$). This result may be due to the inaccurate idea displayed by students that science confirms hypotheses. As one student wrote, "repeat steps 5 & 6 until your evidence supports your hypothesis." A number of students wrote that experiments "failed" when the results were not consistent with their hypothesis. In other words, students struggle to connect discovery with rejecting a hypothesis.

Summary with a student example

One student's pre- and postdiagrams

FIGURE 4

All of the students' diagrams included aspects of Testing Ideas (green, center) and most included Exploration and Discovery (red, top) before and after instruction; * indicates that a significantly greater number of students mentioned Community Analysis and Feedback in the postdiagrams (purple, lower right; χ^2 test, $p << .001$). Although more students mentioned the Benefits and Outcomes of science in the postdiagrams, this increase was not significant (blue, lower left, χ^2 test, $p = .41$).



summarize our results (Figure 7). These diagrams illustrate learning, because the postdiagram includes more steps and incorporated more of the iterative aspect of science than the prediagram. The central component of both the pre- and postdiagrams is Testing Ideas, with a hypothesis and experiment. The process of experimentation begins with Exploration and Discovery by making observations and asking questions. The postdiagram also indicates that scientists find inspiration for asking questions through curiosity and the desire to solve problems. The category Community Analysis and Feedback is represented in the postdiagram by the need to talk to others.

On the other hand, this example also shows that this student still carries some naïve ideas about how science works. The diagram does not include any explicit reference to the Benefits and Outcomes of science, and it depicts the inaccurate ideas that experiments are conducted to verify, rather than test, hypotheses and that experiments only need to be repeated when their results are surprising. These misunderstandings are difficult to shift. It is challenging for students to think critically about when and why to participate in the steps in the Testing Ideas category of the *Flowchart* (e.g., Allchin, 2011; Brownell et al., 2014).

Conclusion

Much of the research on teaching the way science works has focused on courses intended for preservice teachers (e.g., Allchin, 2011; Lederman, 1992; Lederman et al., 2013; Seung, Bryan, & Butler, 2009). Here, we present strategies that work for college science majors and that we believe can be adopted for nonscientists (as was done by Wilson & Rigakos, 2016). We have demonstrated that our module improves how junior-level science majors understand critical aspects of how science works, including the fact that science is iterative and unpredictable, encompassing many paths. After instruction, more students began incorporating aspects of Community Analysis and Feedback into their diagrams.

In our study, this module was taught in courses emphasizing skills more than content. However, it can be modified to be included in introductory science courses and upper division specialty courses. For example, students can use the *How Science Works Flowchart* (Understanding Science, 2016b) to analyze the history of any scientific experiment. We predict that using the *Flowchart* in courses that use primary literature to teach how a research program unfolds (e.g., Hoskins, Stevens, & Nehm, 2007) would be particularly effective. In conclusion, the module we present is an effective tool for improving students' understanding about how science works. ■

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FIGURE 5

What diagrams conveyed about the concepts specified in Table 2 before and after instruction; * indicates significant change. All of the students understood Concept 1 (Scientific conclusions are based on data that have been observed, modeled, and/or derived from experiments) in the prediagrams and the postdiagrams. Diagrams illustrated a significantly greater understanding of Concept 2 (Current scientific knowledge relies on previous scientific investigations) in the postdiagrams; one-tailed Mann-Whitney U test, $p << .001$), although few students reach the target level of understanding. There was no change in understanding of Concept 3 (Scientific discovery creates knowledge that is new and unpredictable) over time (one-tailed Mann-Whitney U test, $p = .23$). See sections on *Testing Ideas* and *Target concepts in diagrams*.

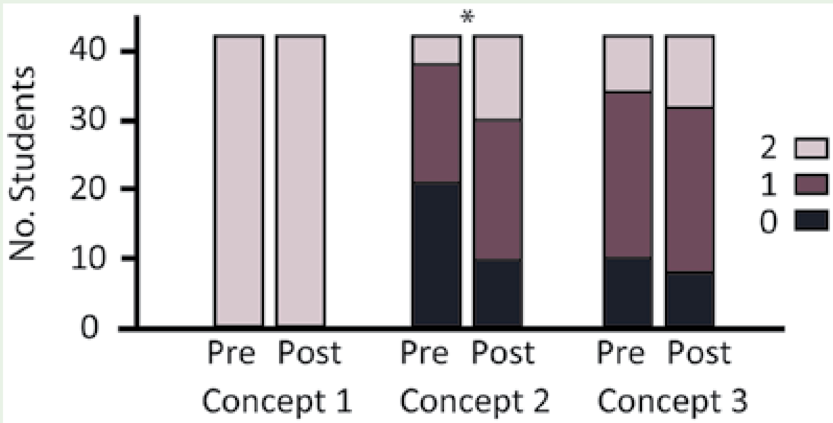

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FIGURE 6

A. Exploration and Discovery in the *How Science Works Flowchart* by The University of California Museum of Paleontology, Berkeley, and the Regents of the University of California (Understanding Science, 2016b; http://undsci.berkeley.edu/lessons/pdfs/complex_flow_handout.pdf). Used with permission. B. The way students expressed Exploration and Discovery in their diagrams; *indicates statistically significant increase in postdiagrams. Most pre- and postdiagrams included making observations and questions, and the slight increases observed in the postdiagrams are not significant (χ^2, p = .05 and p = .43, respectively). However, significantly more students included a response that we categorized as "finding inspiration" (χ^2, p << .001) and mentioned using the literature to inspire their research question (χ^2 test, p << .001).

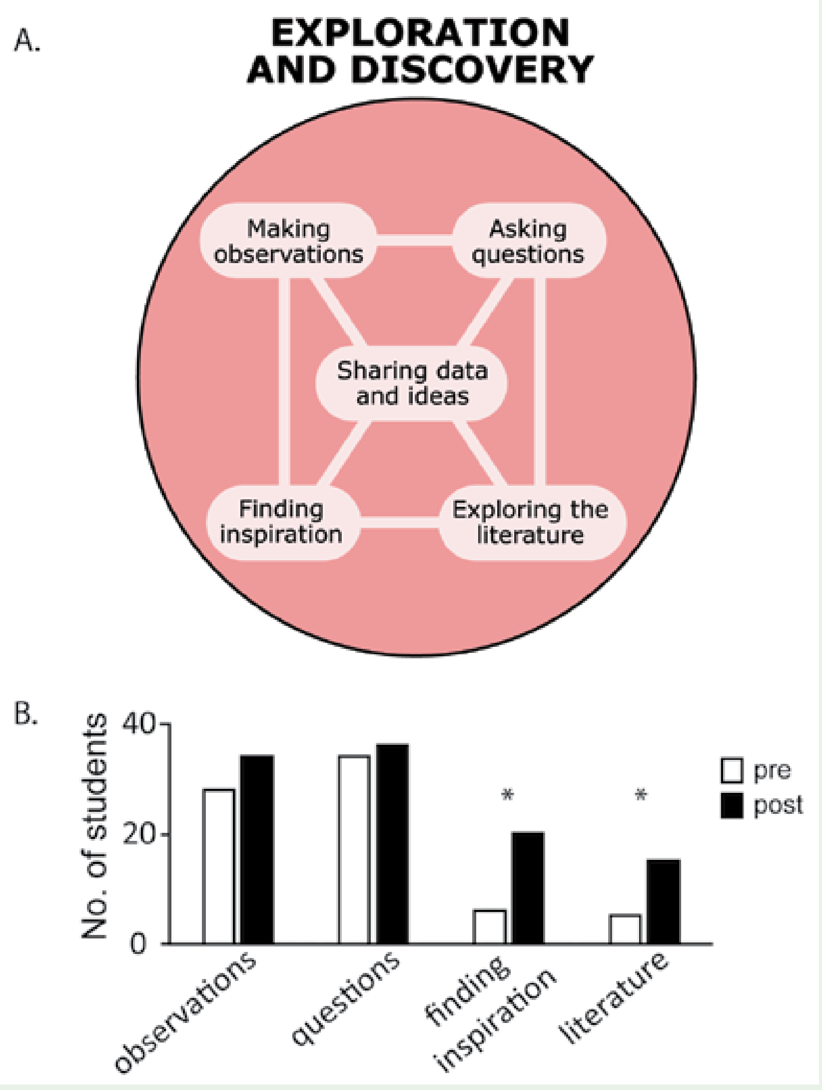

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FIGURE 7

One student's pre (A) and post (B) diagrams illustrating the scientific process. Most students drew their diagrams in pencil or light-colored pens; we redrew this diagram to show the work clearly.