

Patterns vs. Causes and Surveys vs. Experiments: Teaching Scientific Thinking

RUSSELL C. WYETH, MARJORIE J. WONHAM

ABSTRACT

The scientific method is a core element of all science. Yet, its different implementations are remarkably diverse, based on the varied concepts and protocols required in each specific instance of science. For experienced scientists, coping with this diversity is second nature: they readily and continually ask tractable questions even outside their expertise, and find the process of forming hypotheses, designing tests, and interpreting results fairly transparent. At the secondary school stage, the scientific method is often introduced as a series of clear steps in a pre-planned lab activity. In between these two stages comes the essential step of abandoning the supports of a step-by-step approach, and instead learning how to work through the scientific method to generate and answer one's own questions. In our experience, this process is rarely taught explicitly. Yet, undergraduate students (even strong students) can have difficulty translating their initial questions into testable hypotheses, and designing and interpreting appropriate corresponding tests. To combat this difficulty, we have developed a conceptual framework that distinguishes the fundamental concepts of pattern and cause. This framework guides undergraduates directly to posing tractable questions, formulating testable hypotheses (descriptive or mechanistic), and designing clear tests (surveys or experiments). Anecdotal evidence, including our in-course assessments and student feedback, suggests this approach leads to improvement of students' scientific abilities. The benefits are noticeable when students apply the scientific method to their own questions and also while interpreting science reported in biological literature.

Key Words: scientific method; science education; nature of science; descriptive hypothesis; mechanistic hypothesis; experimental design; hypothetico-deductivism; NGSS.

○ Introduction

Scientific literacy, as a central goal of science education, encompasses an understanding of the nature of science and of the practice of scientific inquiry (Lawson, 2009; Campanile et al., 2015; McComas, 2015a; Johnson, 2016; Kampourakis, 2016). A central approach

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to scientific inquiry is the scientific method. Both the method, and the very idea of there being a method, have long been subjects of thought, discussion, and critique (e.g., Sanford, 1899; Gower, 1996; Woodcock, 2014). Nevertheless, most contemporary views of the scientific method agree that at its core is the hypothetico-deductive approach. This approach entails formulating hypotheses that can be tested through falsifiable observation or experimentation, and can guide the logical and critical investigation of empirical problems (Gauch, 2012). Our goal here is to present a conceptual framework to help teach students to successfully understand and apply hypothetico-deductivism while learning the scientific method as it is conducted in the life sciences.

For students in biology, learning to work through the scientific method poses a variety of challenges (reviewed in Deng et al., 2011; see also Allen & Duch, 1998; McComas, 2015b; Pelaez et al., 2015; Strode, 2015). The specifics of experimental design can be especially problematic, including distinguishing types of variables (discrete versus continuous; independent versus dependent), understanding and interpreting treatments (particularly controls), coping with variability (replication and randomization), and drawing appropriate conclusions (reviewed in Dasgupta et al., 2014; see also Brownell et al., 2014; Coleman et al., 2015). In our own teaching experience, students make several key mistakes at all stages of applying the scientific method.

We suggest that these mistakes tend to arise from a central difficulty in distinguishing patterns from underlying causes. By “patterns,” we mean the many variations seen in the natural world: spatial, temporal, phylogenetic, morphological, and so on. By “causes,” we mean the many mechanisms that produce these patterns, both abiotic and biotic processes, spanning all levels of organization, from environmental to organismal to molecular scales. In a test of a pattern-and-cause relationship, the pattern is the dependent variable and the cause the independent one. The underlying difficulty of discerning pattern from mechanism can lead to a morass of muddled thinking by students.

Problems can arise as students interpret their observations, develop hypotheses, design their studies, or interpret their predicted or actual results—in other words, throughout their application of the scientific method. We find that we can confront this difficulty by making explicit the crucial distinction between pattern and cause from the outset.

Here we introduce a Question-Hypothesis-Test (QHT) framework for teaching and learning the scientific method. The framework explicitly distinguishes pattern from cause at all stages. We find that this framework helps our students—and us—more clearly think through the process of an empirical investigation. This is particularly useful to students at the outset of an assignment or project, before they invest time and energy collecting and interpreting their data. It also helps us build the nature of science (NOS) directly into our science courses (McComas, 2015a)—not by having students study it as an abstract concept, but by having them do it. We find that when students use this framework they are better equipped to apply the scientific method as they develop their own independent work.

Because the QHT framework is an approach, and not a content-specific activity, it can be customized to many different subject areas. The context in which we initially developed it was field-station biology courses, which have a decades-long tradition of fostering independent, individualized, inquiry-driven research projects. We have since refined the framework over more than a decade of teaching over forty classroom- and field-based courses to groups of 10–30 undergraduates (primarily in third- and fourth-year biological sciences courses at Bamfield Marine Sciences Centre, St. Francis Xavier University, and Quest University Canada).

We anticipate the QHT framework can be integrated into other approaches to teaching science and the scientific method. Although we have not formally pursued such integration ourselves, our focus on ensuring accurate logical links among questions, hypotheses, and tests could provide added value alongside other specialized systems for teaching science. For example, the QHT framework fits easily with the student and teacher templates in the scientific writing heuristic (Keys et al., 1999). The heuristic has broader goals that go beyond what we teach with the QHT system. However, teachers could incorporate the QHT framework both to help students generate good questions and matching tests (components 1 and 2 of the student template) and to make the logical links between observations, claims, and evidence (components 3, 4, and 5). Other possibilities would be to incorporate the QHT framework into course-based undergraduate research experiences (CURE; Pelaez et al., 2015, Shortlidge et al., 2016) and literature analyses (e.g., CREATE; Hoskins et al., 2007).

Our disciplinary focus is zoology and ecology, but the QHT framework applies readily across the empirical life sciences. We apply it at the undergraduate level, but at least certain aspects (particularly with regard to questions and hypotheses) could be taught to secondary students, and the full set of skills we teach are further honed in graduate school. Comparing our goals to more formal recommendations for teaching science, the QHT framework is tightly aligned with the Next Generation Science Standards (NGSS; NGSS Lead States, 2013) for secondary students (the first two cross-cutting concepts in the NGSS are “Pattern” and “Cause and effect: Mechanism and explanation”). Similarly, our ideas directly address students’ abilities to apply the process of science, the first of the core

competencies under the *Vision and Change* recommendations for undergraduate biology education (AAAS, 2011).

Our emphasis is always on helping students apply the scientific method to their own empirical observations arising in a relatively free context, rather than to those arising during a planned lab. We find that a student’s ownership of the starting point gives them more impetus to engage in the hard work of thinking critically as they pursue their questions. Although we have not formally tested the efficacy of this framework, we find it helpful, and we continue to use and refine it based on positive feedback from students and colleagues.

We begin by characterizing each stage of the scientific method in the QHT framework, and then outline our approaches—and common pitfalls—in teaching each stage. We illustrate the framework with a selection of biological examples drawn from our courses, and provide sample assignments.

○ Characterizing the QHT framework for the Scientific Method

For our purposes, we think of the scientific method as a cycle of a logical thinking with four main stages: observations, questions, hypotheses, and tests—where the tests in turn generate new observations (Figure 1). This is a deliberately simplified version of the scientific method stages that can be found in many other sources (e.g., Sanford, 1899; Reiff et al., 2002; Lawson, 2009; Gauch, 2012; Understanding Science, 2016). In this section, we outline how the central concepts of pattern and cause are integral to clear understanding of each stage.

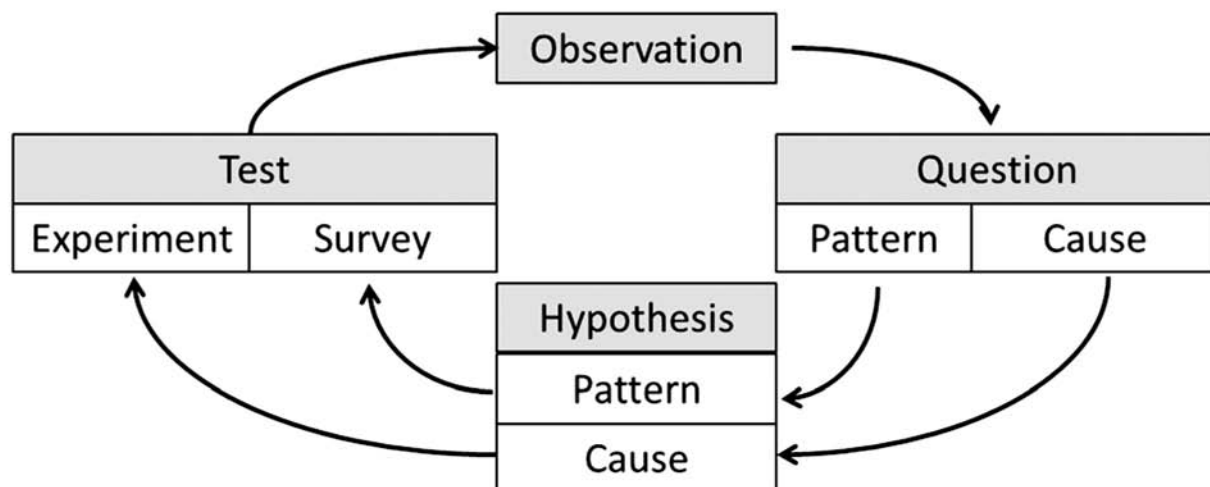
Observations

In the observation stage, students’ scientific inquiry is prompted by their own empirical observations (Figure 1). More broadly, the initiation of scientific inquiry could stem from a number of sources (Gauch, 2012): from results of previous work, from data, models, or theories encountered in the published literature, from news (or even social) media—in other words, from anything that prompts students to wonder. To streamline this overview, we use students’ personal empirical observations as our starting point here.

Questions

We classify questions generated from observations into two groups: descriptive and mechanistic (Figure 1). Descriptive questions ask what patterns can be observed: What is the value of x ? What is the shape of the relationship between x and y ? What is the difference in the value of x between y and z ? Here, x , y , and z may be any characteristic (e.g., identity, abundance, size, speed, temperature, color, etc.) of any biological entity (e.g., molecule, organism, population, ecosystem, etc.) Mechanistic questions, in contrast, ask how or why the pattern arises (e.g., How does x cause y ? Why does x do y ?). These are rich questions for sustained inquiry as they can lead to investigations of proximate and ultimate mechanisms at multiple scales. For example, questions about a predator-prey behavioral interaction could scale out to consider population dynamic, landscape, ecosystem, and climate mechanisms that caused the evolution of the behavioral patterns. Alternately, the questions could scale in, to consider biomechanical, sensory, and metabolic mechanisms that produce the behaviors.

(a)



(b)

SM Stage	Testing the Pattern	Testing the Cause
Question	Descriptive: Does the pattern exist? (often phrased initially as who/what/when/where)	Mechanistic: Does the mechanism cause the pattern? (often phrased initially as how/why a pattern exists)
Hypothesis	Descriptive: Pattern exists	Mechanistic: Mechanism causes pattern
Test Design	Survey	Manipulative experiment
Anticipated Results	Support/refutation of pattern	Support/refutation of causation
Conclusion	Pattern does (or does not) exist	Mechanism does (or does not) cause pattern

Figure 1. Question-Hypothesis-Test (QHT) framework for applying the scientific method (SM), highlighting the difference between a pattern and the mechanism that causes it. **(a)** Cyclical nature of the SM, illustrating how descriptive questions about patterns lead to surveys, and mechanistic questions about causes lead to experiments. **(b)** Comparison of the scientific method stages for investigating a pattern vs. its cause. To describe a pattern requires a descriptive hypothesis and survey test. To understand what causes the pattern requires a mechanistic hypothesis and an experimental test. The anticipated results should consider all possibilities; the actual results will demonstrate the effect size, which will determine whether the hypothesis is considered supported or refuted.

Hypotheses

We identify hypotheses as single, testable propositions that, when tested, can help answer the questions (Figure 1). For descriptive questions, the simplest hypothesis wording is: *The pattern exists*. For mechanistic questions, the simplest hypothesis wording is: *The mechanism causes the pattern*. Our distinction between descriptive and mechanistic hypotheses corresponds to that between generalizing and explanatory hypotheses outlined by McComas (2015b) and Strode (2015).

Tests

Under tests, we include study design, anticipated or observed results, and conclusions (Figure 1). For a descriptive hypothesis, the appropriate test design is an observational survey. By “survey,”

we mean measuring or estimating variables to test whether a pattern exists, under conditions unchanged by the investigator (as for “generalizing hypotheses,” McComas, 2015b). This could include, for example, counting moths in traps (to make a point estimate of abundance), measuring plant growth rates over a range of elevations (to test a correlation between continuous variables), or measuring gene expression frequencies between infected and uninfected populations (to compare between groups of a categorical variable). For a mechanistic hypothesis, the appropriate test design is a manipulative experiment, in which the investigator alters the proposed cause and measures the response of the pattern, relative to appropriate controls (as for “explanatory hypotheses,” McComas, 2015b).

The test results constitute new observations that are more informed and detailed than the initial observations. These spur further inquiry through the scientific method cycle. Support for a descriptive

hypothesis can serve as the impetus for subsequent mechanistic questions, while results from a test of a mechanistic hypothesis can serve as patterns for the next level of descriptive inquiry. When students internalize the key distinction between these two types of test, they navigate this cycle with greater success.

○ Teaching the Scientific Method using QHT

As students begin to apply the scientific method to their own research, they readily understand the idea of each stage (observations, questions, hypotheses, and tests). In implementing them, however, they encounter a slew of reasoning difficulties. To make the process more manageable, we find it useful to teach the QHT cycle incrementally, beginning with students' observations and then adding questions, hypotheses, and tests one step at a time (see Appendix). At each stage, we emphasize the distinction between pattern and mechanism to help students slow down, clarify their thinking, and build more logical chains of reasoning throughout the cycle. In teaching, we often begin with questions (because they generate more engaged note-taking and discussion, and emphasize the importance of inquiry over knowledge in this initial context). We then backtrack to observations, and then return to refine the questions before proceeding with hypotheses and tests. Here we outline key approaches and common pitfalls at each stage.

Questions

We begin by asking students to prolifically record their questions while they are observing organisms in the lab or field (or from images or videos). The only potential pitfall here is that many students seem initially tentative. They appear to mistrust their ability to ask their own questions, or to fear appearing ignorant. Repeatedly asking students for their questions helps them cultivate the valuable scientific habit of documenting curiosity, and generates material for them to select from in the later stages.

We cannot overstate the motivating value of working with students' own observations in this process. These observations provide an accessible entry point to scientific inquiry regardless of a student's past experience; they require no prior knowledge. When students can invest in pursuing questions piqued by their own experience and interest, they are much readier to engage in the hard work of reasoning through the scientific method (and to find it fun). Admittedly this freedom is to some extent a luxury of small class sizes, as it can take longer for an instructor to provide feedback and grades on highly individual work. We nevertheless consider it an essential step in students' development of scientific autonomy.

Observations

In examining their initial questions, we ask students to discuss or report the observations that prompted them. Here a common pitfall is that students leap directly to what they assumed or inferred or interpreted from their observations. Thus, we focus on isolating *only* what was observed, which sometimes can take several iterations to clarify (Table 1, Figure 2). The reason we start by asking students to record their questions and then backtrack to observations is that this route seems to prompt more curiosity and creativity in their thinking than simply asking them to record and discuss their observations.

Questions Reformulated

After zeroing in on the underlying observations, we return to questions and ask students to select some that are amenable to further investigation with the scientific method. Students then reformulate their questions as descriptive questions about pattern ("What do I see?") or mechanistic questions about causation ("How/why does it happen?"). One of the greatest pitfalls for students at this stage is not recognizing the difference between a singular event and a broader pattern (Table 1). In articulating descriptive questions, students confront this important difference directly. In articulating mechanistic questions, they begin to appreciate the difference between an observed pattern and its underlying cause. Thus, it is at this revised question stage that we first directly engage with students' central pattern vs. mechanism difficulty. When students reword their questions following a simple pattern or mechanism template, they find it easier to subsequently generate matching hypotheses and tests (Figure 2).

Hypotheses

Converting questions to hypotheses is straightforward, provided the questions are clearly descriptive or mechanistic (Figure 2). Following the simple declarative QHT template can help avoid many logical and syntactical difficulties (Table 1) and generate simple hypothesis statements: "The pattern exists" or "The mechanism causes the pattern." These then lead more readily to appropriate tests (Figure 2).

Tests

With clearly stated hypotheses, students can use similarly precise terminology to articulate their test designs (Figure 2). For a pattern hypothesis, students focus on a survey designed to measure and test for the pattern, without getting distracted by attempts to eliminate confounding variables or establish causation. When students spend time considering a survey, they come to appreciate the value of gathering measurable evidence for a broader pattern. This also helps to avoid premature leaps to test a hypothesized mechanism on the basis of a one-time observation that may or may not have broader relevance. Moreover, the explicit emphasis on simply surveying patterns, or correlations among multiple patterns for some complicated descriptive hypotheses, makes it easy for students to understand the limits of inference regarding causation. Just because two patterns are measured together does not mean one causes the other.

For a mechanistic hypothesis, students focus directly on a manipulative experiment that isolates and alters individual variables. Identifying the correct variable to manipulate is particularly vexing for many students, and getting it wrong can lead to testing an unintended or illogical hypothesis (Table 2). This difficulty is eliminated if students have stated their hypotheses as "the mechanism causes the pattern." Then the manipulated variable is (always and only) the mechanism. Thus, the challenge in designing the experiment is reduced to the problem of controlling all possible confounding variables.

When students develop complementary surveys and experiments, they come to appreciate the combined value of both approaches: an experiment provides explanatory power, and a survey provides a real-world reality check. Together, they deepen our understanding of how organisms work.

For both surveys and experiments, having students illustrate their anticipated results as a mock graph helps them articulate and refine their arguments. It is particularly useful for them to graph different

Table 1. Challenges and solutions under the Question-Hypothesis-Test (QHT) framework for issues that students commonly encounter when developing questions and hypotheses. Examples are based on the scenario of students exploring the seashore and noticing that the two dominant sessile organisms are mussels and barnacles (see article header image). The mussels are attached directly to the rock, and the barnacles are attached either to the rock or to mussels. The students know that both species are suspension feeders that eat plankton when the tide is in, and a variety of questions ensue. Similar examples could be developed, for example, around an epiphytic plant growing on a tree, both of which need access to light.

Problem	Preliminary Q or H	Revised Q or H	Instructor Prompt
<i>Common issues students encounter developing hypotheses</i>	<i>Student questions (Q) or hypotheses (H) whose wording leads to difficulties with hypotheses and tests.</i>	<i>Revised versions with wording that can help students more successfully launch an investigation.</i>	<i>Optional prompt from the instructor if necessary to help guide students' revision of their preliminary Q or H.</i>
Problems developing descriptive hypotheses to test patterns			
Event vs. pattern: Assumption that a singular observation of an event represents a broader pattern	Q: Why do mussels live only on rocks? (Observation: The only mussels I saw were on a rock.)	Q1: Do mussels live only on rocks?	Great question! But do all mussels only live on rocks? Are you sure that's a pattern?
Ill-defined pattern(s): Unclear what student is asking	Q: Can mussels eat zooplankton while barnacles eat planktonic algae?	Q1: Do mussels consume zooplankton? Q2: Do barnacles consume planktonic algae? Q3: Do mussels and barnacles feed simultaneously?	Interesting question! What exactly is the pattern you are interested in describing? Or are you thinking about multiple patterns?
Mechanism included prematurely: For a pattern question, omit mechanism	Q: Do barnacles reduce growth of mussels because of competition?	Q: What is the pattern of the relationship between mussel size and barnacle presence?	Cool question! Do you know if mussels are smaller when barnacles are present? Does that pattern exist?
Problems developing mechanistic hypotheses to test causes (note: existence of the pattern is known or assumed)			
Undefined mechanism	Q: How do barnacles attach to mussels?	Q: Does a secreted glue cause barnacle attachment to mussels?	Fantastic question! How might mussels attach to rocks? Propose a mechanism.
Ill-defined mechanism	Q: Do barnacles affect the growth of mussel shells?	Q1: Does the <i>presence</i> of barnacles cause reduced mussel growth? Q2: Does the <i>glue</i> secreted by barnacles cause reduced mussel growth? Q3: Does <i>food competition</i> from barnacles cause reduced mussel growth? Q4: Does <i>drag</i> from barnacles cause reduced mussel growth?	Superb question! But what do you mean by "affect"? Can you propose some specific mechanisms?
One mechanism, multiple patterns	Q: Do barnacles reduce food for mussels and stimulate them to close their shells more often?	Q1: Do barnacles cause reduced food availability for mussels? Q2: Do barnacles cause more frequent mussel shell closures?	Intriguing question! How many patterns are you asking about? Are you actually asking two questions? Can you simplify by separating the ideas?

(continued)

Table 1. Continued

Problem	Preliminary Q or H	Revised Q or H	Instructor Prompt
Multiple mechanisms, one pattern	Q: Do barnacles and tubeworms reduce food for mussels?	Q1: Do barnacles cause reduced food availability for mussels? Q2: Do tubeworms cause reduced food availability for mussels?	Fabulous question! How many mechanisms are you proposing? Does it make sense to test both in the same experiment? Can you simplify by separating the ideas?
Swapped pattern and mechanism (when converting Q to H)	Q: Does flow rate generated by mussels affect the amount of food they capture? H: Changing food availability will cause a change in flow rate generated by mussels.	Q: Does a decreased flow rate generated by mussels cause decreased food capture? H: Decreased flow rate generated by mussels causes decreased food capture.	Scintillating question! What are the pattern and mechanism in your question? Say your hypothesis again; are the pattern and mechanism the same as in the question?
Unaddressable pattern and mechanism	Unanswerable Q: Does greater food capture lead to barnacle growth on mussels? Untestable H: Greater food capture causes barnacles to settle and grow on mussels. <i>This H is not practical to test since it tests the evolution of the adaptation.</i>	Answerable Q: Does barnacle growth on mussels cause greater food capture by barnacles? Testable H: Barnacle growth on mussels causes greater food capture by barnacles. <i>This H is testable since it measures the potential benefit of the adaptation.</i>	Brilliant question! How long would it take you to test if improved food capture caused evolution of an adaptive preference for barnacles to grow on mussels? Instead, could you test whether the proposed adaptation causes a benefit? What are your mechanism and pattern then?
Unclear mechanism (<i>The Q cannot be answered, but leads to testable Hs about natural selection if it is adjusted with clearer ideas about mechanisms.</i>)	Unanswerable Q: Did barnacles evolve to settle on mussels?	H1: Settlement on mussels causes higher fitness/greater growth/longer survival for barnacles. H2: Heritable genes cause differences in settlement choices by barnacles.	Awesome idea! Could you ever answer that question for sure? What benefit might settlement on mussels cause? What then would your mechanism and pattern be?
Test method included prematurely, so prediction presented in lieu of hypothesis	Q: Does feeding by barnacles reduce the feeding rate of mussels? H: Gluing the barnacles shut will allow the mussels to feed faster.	Q: Does feeding by barnacles cause a reduction in the feeding rate of mussels? H: Barnacle feeding causes a reduction in the feeding rate of mussels.	Marvelous question! Can you focus your hypothesis on the biology, rather than on predicting an experimental outcome? Can you identify the mechanism in your question?

scenarios showing data that would either support or refute their hypothesis. Sketching these graphs helps them detect and correct errors in study design. (It also provides a valuable opportunity to hone graphing skills and practice additional relevant vocabulary, e.g., quantitative/qualitative, control/experimental, dependent/independent, continuous/discrete, nominal/ordinal, correlation/causation.)

○ Assignments & Assessment

We have used the QHT framework to help guide scientific inquiry in a variety of formats. Two sample assignments (see Appendix) illustrate student progression from the initial stages of asking questions

to more advanced stages of designing pattern and mechanism tests. In practice, we have adapted the core outline of the framework for use in a variety of assignments, depending on the goals of the course:

1. As a small-group and class discussion based on field or lab observations;
2. As a regular weekly written assignment, usually incrementally progressing, based on field or lab observations;
3. As the basis for student research proposals:
 - a. To outline and choose among potential projects;
 - b. Before they begin their projects;
 - c. After they complete their projects, to propose next steps;

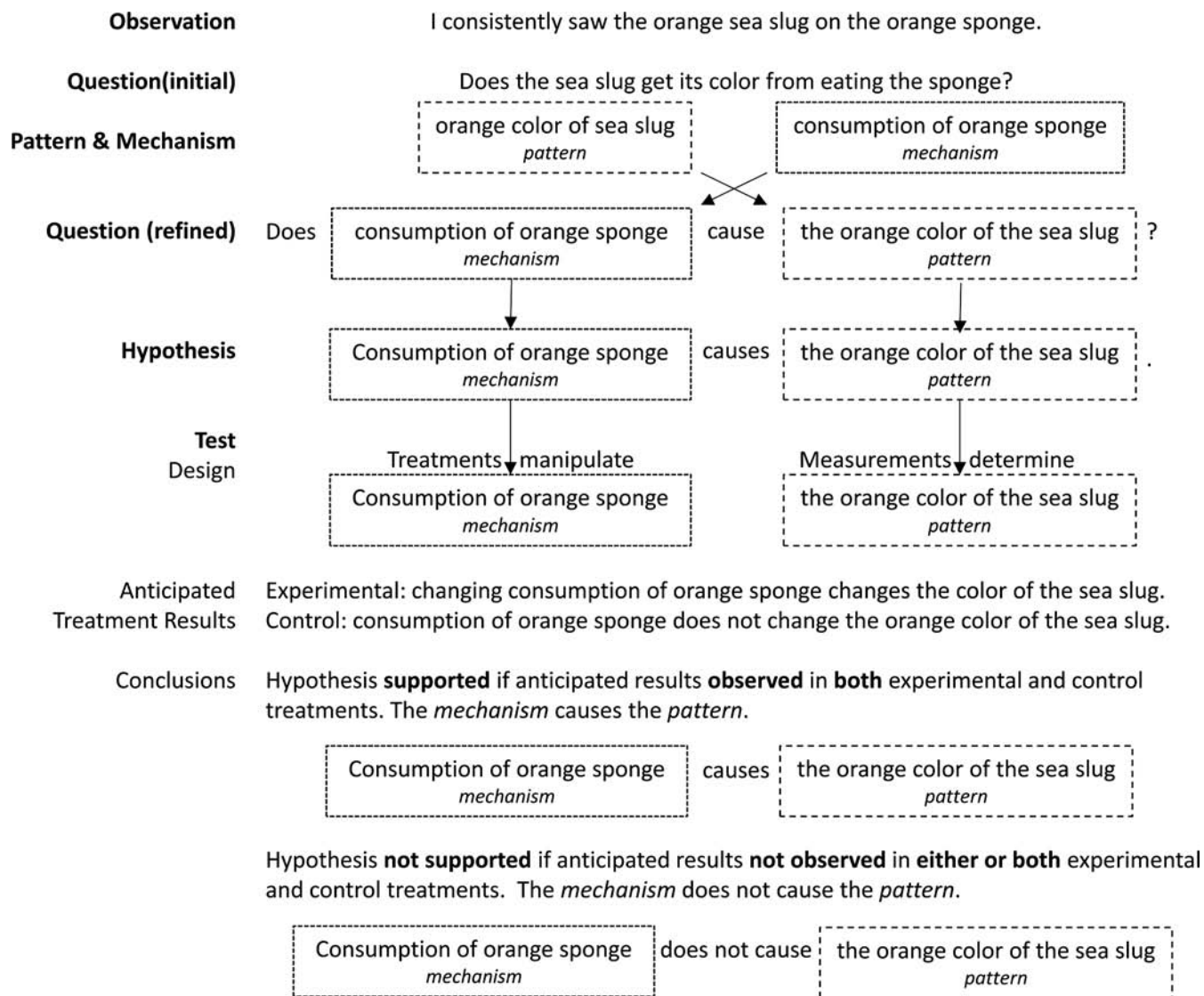


Figure 2. Example of how a student could apply the QHT framework to the scientific method investigating a field observation. A key pedagogical benefit is that once the pattern and mechanism are identified in the question, the same two concepts are used at each stage of the scientific method, helping to avoid deviations in logic. This example is based on the scenario of a student exploring the seashore and finding the tiny bright orange sea slug, *Rostanga pulchra*, that indeed gets its color from eating a bright orange sponge, *Ophlitaspongia*. It's a find that always generates excitement. Similar examples could be developed, for example, around a visually camouflaged caterpillar on a leaf.

4. As the complement to a class lab or field project (e.g., designing experiments to complement a class survey, or vice-versa);
5. To unpack a scientific paper (married, for example, with approaches borrowed from CREATE; Hoskins et al., 2007).

Regardless of the format, we recommend setting students up for success by taking an iterative and interactive approach. Questions should be examined and refined before developing hypotheses, and hypotheses likewise before designing tests. We also recommend having students generate far more questions than hypotheses or tests, because not all questions are amenable to a hypothesis-testing approach. It takes time for students to learn to recognize those that are. More advanced students may be challenged beyond the basics. They can design studies, for example, (1) that test not only whether

an independent variable has an effect but also the shape of the dependent variable response, (2) that involve more complex arrays of independent and dependent variables, (3) that compare multiple alternate hypotheses, or (4) that use suites of complementary surveys and experiments.

The assessment of a QHT assignment depends on the pedagogical goals of the course and the activity. The most important decision is whether the instructor wishes to evaluate only the internal logic of the assignment, or also its biological sophistication and realism. We consider the former essential and the latter optional. A question or hypothesis we might consider trivial in today's field may have been ground-breaking when it was first posed, and may be exciting to a beginning student. Study designs that are

Table 2. Common problems when students propose tests of hypotheses, and corresponding solutions using the Question-Hypothesis-Test (QHT) framework. In all cases, the teaching goal is clear distinction between pattern and mechanism, and the understanding that surveys always test the hypothesis that a pattern exists, whereas experiments always test the hypothesis that a mechanism causes a pattern.

Example Problems	Solutions Using Pattern & Mechanism
Proposing a survey to test a mechanistic hypothesis. E.g., Testing the hypothesis that temperature determines a plant's abundance by measuring both across the species' range.	This conflation is the most common problem that we encounter. A survey tests the pattern's existence in the real world, which neither supports nor refutes the mechanistic hypothesis. When the hypothesis is <i>mechanistic</i> , an <i>experiment</i> is called for.
Proposing an experiment to test a descriptive hypothesis. E.g., Testing the hypothesis that fish eat more insects than snails, with an "experiment" to examine gut contents involving a vaguely defined "control."	This kind of semantic confusion usually reflects the misuse of "experiment" for something that is not, and may include a mistaken attempt to force an unnecessary "control" into the design. The confusion evaporates when the hypothesis is recognized as <i>descriptive</i> , requiring a <i>survey</i> to measure a <i>pattern</i> .
Swapping pattern and mechanism in an experimental design (same problem as reversing dependent and independent variables). E.g., Testing the hypothesis that a predator affects prey abundance by altering the abundance of prey and measuring the predator's response.	This reversal of causation can often be revealed to a student by asking for graphs of anticipated results. The revised test will ensure the proposed mechanism (independent) is manipulated to test for a change in pattern (dependent).
Omitting or ignoring controls from an experiment. E.g., Injecting a drug without a sham injection control, or excluding a competitor in the field without an exclusion control.	This logical gap becomes more clear to students as they become familiar with the methods of the field. The revised experiment will include and illustrate anticipated results from sufficient controls to isolate the hypothesized mechanism alone. Graphing is again helpful here.
Designing a test that addresses a different question or hypothesis than originally stated. E.g., Testing the hypothesis that oxygen level affects snail egg development, while also manipulating temperature and UV.	This mismatch often follows a complex or convoluted question or hypothesis. The revised test may require several sets of reworded and streamlined questions and hypotheses to cleanly separate multiple ideas.

wildly unrealistic may nevertheless be logical. Thus, when our goal is solely to encourage inquiry through creative and critical thinking, we focus on the internal logic alone. We allow studies of (living) dinosaurs, aliens, or zombies to develop, and we do not worry if a hypothesis or test is based on a false premise unknown to the student. When our goal is to develop feasible hands-on research projects, we work toward biological realism. The relative importance of the logical vs. biological can only be determined in a course-dependent context.

○ Anecdotal Benefits & Student Feedback

We have not formally tested the learning benefits of teaching the scientific method with the help of the QHT framework. However, in every course in which we have implemented it, our assessments show the same progression in the students. Initially, when we ask students to pose questions, convert them to hypotheses, and outline how they might test their hypotheses, we see the problems noted above

(Table 1) in all but a few exceptional students. For most of the remaining students, these issues progressively disappear as we use the framework to help them fearlessly pose questions, and learn to recognize flawed logic. By the end of the course, we find that students demonstrate more ease and sophistication in asking and answering their own questions via the scientific method. We also find they are better able to understand examples of real biological science (presented in class or in primary literature articles read by the students). They are more willing to dive into the details of the experimental design, and once any technicalities of the measurement methods are dealt with, they emerge with a better grasp of how the evidence presented leads to conclusions. Finally, we also see improvements in recognizing the difference between conclusions and speculation, and the appropriateness of each given evidence available. Grasping this distinction helps student come to grips with the larger progress of science, beyond the bounds of any one question, hypothesis, or test.

Our qualitative student feedback on teaching the QHT framework includes two clear themes. The first is more immediate and more critical: they note the extra effort required or express frustration

at the difficulty they experience as they wrestle with these concepts. We believe this feedback reflects the valuable challenge of the assignment, and is a necessary consequence of the teaching goal (to have good scientific reasoning, the challenge must be met sometime). This is why we teach the framework in stages, balancing the difficulty of the entire process with relatively small steps as we progress toward full test designs. The second feedback theme is longer term and very positive: students note the benefits of the framework for understanding the scientific method. They highlight how it has helped them in subsequent courses or after graduation, how it helps them to think like a biologist, and how it is different from what they are taught in other courses. Many students express both themes in their feedback, and make it clear they feel the effort is worth surmounting the challenge.

○ Conclusion

The hypothetico-deductive scientific method is a core component of scientific inquiry and of the nature of science (Lawson, 2009; Campanile et al., 2015; McComas, 2015a; Kampourakis, 2016; Johnson, 2016). It is not infallible, particularly when implemented in isolated contexts by beginning scientists. Results can be consistent with a hypothesis that is nevertheless untrue (illustrating the fallacy of affirming the consequent, and highlighting the importance of multiple alternate hypotheses). Alternatively, a hypothesis can be correct even when results appear to falsify it, if the study is in some way flawed. In addition, some interesting questions cannot be tested in an experimental way, and some logical hypothesis tests cannot be conducted for ethical or logistical reasons. Nevertheless, it provides a fundamental approach to the logical analysis of observations and understanding of biological patterns and their causes. By focusing on these two key concepts throughout the question, hypothesis, and testing stages, the QHT framework provides a useful tool for helping students learn to creatively and critically apply the scientific method.

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RUSSELL C. WYETH (rwyeth@stfx.ca) is an Associate Professor in the Department of Biology at St. Francis Xavier University, Antigonish, Nova Scotia, B2G 2W5, Canada. MARJORIE J. WONHAM (marjorie.wonham@questu.ca) is a Life Sciences Professor at Quest University Canada, 3200 University Blvd., Squamish, British Columbia, Canada, V8B 0N8. Both authors also work at Bamfield Marine Sciences Centre, 100 Pachena Rd., Bamfield, British Columbia, Canada, V0R 1B0.

Appendix. Sample Assignments and Activities

Introductory Written Assignment

During the field trip, make notes of biological questions that occur to you. Then:

1. List 4 of your most biologically interesting questions.
2. Briefly (in 1 sentence) explain the observation that led to each question.
3. Convert one of your questions into a testable hypothesis.

In this version, students are encouraged to take ownership of the assignment by deciding (individually) what questions are interesting, with the sole constraint that questions be about some aspect of life (i.e., biological). Subsequently asking students for their observations helps them isolate what they noticed from what they assumed or inferred, and helps the instructor understand what prompted the question. Asking for a testable hypothesis often generates some poorly matched questions and hypotheses, which can be used to highlight the value of the Question-Hypothesis-Test (QHT) framework in clarifying their thinking and wording.

Advanced Written Assignment

During the field trip, make notes of biological questions that occur to you. Then:

1. List 4 of your most biologically interesting questions that are amenable to investigation of both pattern and mechanism through the scientific method.
2. For each initial question, provide the following analysis.
 - a. Observations:
 - i. Briefly explain the observation that led to the question.
 - b. Questions:
 - i. Ask a question about the existence or shape of a biological *pattern* prompted by your initial observation.
 - ii. Imagine a possible *cause* of this pattern, and express this possibility as a question.
 - c. Hypotheses:
 - i. Convert the question about the *pattern* into a testable *descriptive* hypothesis.
 - ii. Convert the question about the *cause* into a testable *mechanistic* hypothesis.
 - d. Tests:
 - i. Design a *survey* to test the *descriptive* hypothesis.
 - ii. Design a manipulative *experiment* to test the *mechanistic* hypothesis.
 - iii. Sketch graphs to illustrate the different potential results that would support and disprove each hypothesis, and explain.

In this version, which ideally follows after several intermediate assignments of increasing complexity, students are asked to develop their own initial field observations and questions into a rigorous question amenable to analysis through both description and experimentation. The level of detail required for the survey and experiment designs depends on the context of the course.

Introductory Discussion to Build QHT Framework

1. Small group:
 - a. Each person shares a few questions recorded during a field trip.

- b. Group considers the *kinds* of questions being asked (disregarding the biological content, and focusing on similarities and differences between types of questions).
 - c. Group develops a simple classification system for the questions.
2. Full group:
- a. Small groups briefly present question classifications.
 - b. Instructor elicits useful distinctions (pattern vs. mechanism; survey vs. experiment; observation vs. inference; question vs. hypothesis; hypothesis vs. prediction) and builds the QHT framework of the scientific method.

In this approach, students are guided through the development of the QHT framework. Alternatively, it can simply be provided to them.

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