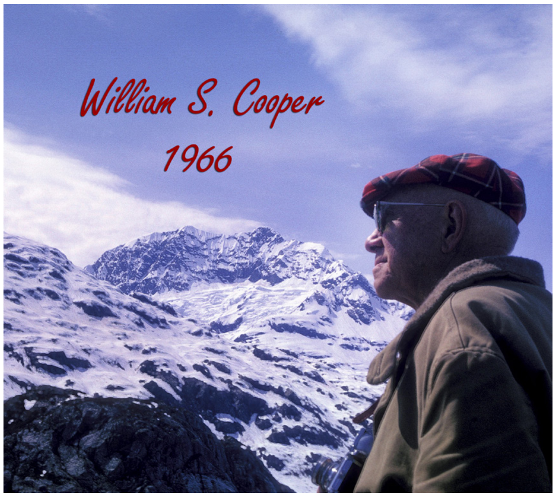

ECO 101

Note: Charlene D'Avanzo is the editor of **Ecology 101**. Anyone wishing to contribute articles or reviews to this section should contact her at the School of Natural Sciences, Hampshire College, 893 West Street, Amherst, MA 01002. E-mail: cdavanzo@hampshire.edu

A Practical Guide for Mentoring Scientific Inquiry

L. B. Symes,[1,2] N. Serrell,[3] and M. P. Ayres[1]

[1]Department of Biological Sciences, Dartmouth College, 78 College St., Hanover, New Hampshire 03755 U.S.A (Corresponding Author E-mail: laurel.symes@dartmouth.edu)

[2]Biological Sciences, University of Wisconsin, 2200 E. Kenwood Blvd., Milwaukee, Wisconsin 53201 USA

[3]Dartmouth Center for the Advancement of Learning, Dartmouth College, 102 Baker-Berry, Hanover, New Hampshire 03755 USA

Abstract

Science is a process of acquiring understanding, not just a collection of facts. The literature on teaching science emphasizes the importance of student research—teaching students to develop new knowledge, rather than solely assimilating facts. As student research becomes more widely integrated into curricula, there is an ongoing opportunity to develop and refine explicit techniques and tactics for facilitating authentic research by students. Here, we draw on our experience as instructors in the tropical biology field course at Dartmouth College to provide specific strategies and approaches that we have used to help students conceive and conduct original research projects. We organize our suggestions around the stages of the research process, from generating and refining questions, optimizing methods, and interpreting data, through presenting findings and placing research in a broader context. Although research skills often develop organically through immersion in research environments, it is our experience that explicit instruction can expedite the development of these critical skills.

Introduction

Building new knowledge is the cornerstone of science. Successful scientists are those who ask and answer creative and interesting questions. For decades, there have been calls to provide undergraduate students with authentic research experiences—creative explorations in which the answers are unknown and experimental design is student-driven (Novak 1964, Germann 1991, Haury 1993, Lopatto 2004, Seymour et al. 2004, Hunter et al. 2007, Casotti et al. 2008, Sadler et al. 2010). Numerous studies show benefits to undergraduates who are explicitly taught research skills (Dirks and Cunningham 2006, Coil et al. 2010, Beck and Blumer 2012). However, teaching undergraduates the skills they need to engage in authentic research—question formulation, experimental design, problem solving, data interpretation, scientific writing and communication, collaboration, critical analysis of the literature—is a tall order for faculty. Few college science departments offer a formalized curriculum for teaching science process skills, and faculty themselves may have had little or no formal training and few models of how to teach these skills to others (Feldman et al. 2013).

This essay is intended to aid instructors who would like to engage students in scientific inquiry but are deterred by the specter of students running amok studying who knows what. We use the tactics described here to mentor groups of undergraduates each year while they investigate scientific questions of their own conception. The learning environment is experiential, which makes for deep learning, and we find that the rewards for our students and ourselves are extraordinary—engaging, challenging and enlightening students at a level no PowerPoint lecture can match. We think that experience doing original research is crucial even for the many students who will not become professional scientists. Knowledge in biology—in all of science for that matter—is growing so quickly that the factual details we teach today are less important for the success of our students tomorrow than understanding the process by which science grows (e.g., how questions are asked and answered and how new knowledge is integrated with existing knowledge) (Germann 1991, Marbach-Ad and Sokolove 2000, Marbach-Ad and Claassen 2001, Hunter et al. 2007, Pellegrino and Hilton 2013).

Here we draw on experiences teaching scientific inquiry in learning environments that are highly intensive and less intensive: a nine-week tropical field course where students do about nine research projects and publish a book containing their final research papers, and as part of on-campus lab courses, where students do one or two slower-moving projects that culminate in a public poster session at the end of the term. We acknowledge that some classroom structures are more amenable to teaching inquiry skills. When classes are large, natural areas are hard to access, instruction is done remotely, or class time is tightly constrained, it is more difficult to integrate open-ended inquiry. However, it can still be possible to retain elements of the process. For example, students in large classes can generate questions and refine them in small groups or practice testing questions using data from an external class-wide dataset. Journals such as TIEE (Teaching Issues and Experiments in Ecology), BioScience and CBE Life Science Education provide a variety of resources for active learning as well as exercises targeting specific stages of inquiry. This guide is aimed at class structures that lend themselves more easily to teaching inquiry, and we have organized it in the typical order of the inquiry process, providing tactics and guidance in each section.

Generating questions

(“*I don’t have any questions. All I see is plants.*” *“Can I find a question online?”*)

Good science begins with careful observation and good questions (Novak 1964, Marbach-Ad and Sokolove 2000, Valiela 2001). Good questions flow from creative thinking and from practice. Teaching students to become researchers includes training them to look closely, think deeply, and exercise creativity within the framework of hypothetico-deductive science (Marbach-Ad and Sokolove 2000, Marbach-Ad and Claassen 2001). If we are to teach students to develop new research questions they need to come up with ideas we do not have ourselves, and that creates a challenge. But there are tactics that facilitate this kind of creative thinking (Loehle 1990, Herrmann 1991, Root-Bernstein and Root-Bernstein 2001, Marbach-Ad and Claassen 2001, D'Avanzo 2003). In our courses, we relentlessly challenge students to ask questions, discuss their ideas with others, and identify novel ways to get answers (Wuchty et al. 2007). We discuss questions and ideas as they emerge and try to help students become better at filtering out the jewels. We encourage students to find good ideas the way photographers find the best pictures—have lots of them and throw most away. We have found the best tactic is simply to give plenty of room for young scientists to explore and practice what it means to be creative. Students have an innate capacity to think of things that we never would have.

Below are some strategies to promote and reward creativity.

- Show students biology that takes their breath away. We have the privilege of teaching a field course in Costa Rica and the Caribbean, where there are monkeys, toucans, and coral reefs to inspire our students. However, we teach with the same strategy in the late winter of New Hampshire where students are inspired by red squirrel middens; consortia of chickadees, nuthatches, and downy woodpeckers; the thermal ecology of *Bombus*; the phenology of spring ephemerals; breeding frogs and salamanders; the population biology of galling insects; the ontogeny of foliar defenses. Fascinating biology abounds in forests, fields, lakes, streams, parks, and gardens, and each of these settings invites student inquiry. The experience can be especially profound when students learn to make new natural history observations in familiar environments.

- Ask students to focus on an organism, species group, or phenomenon—ideally something they can observe in the moment. Challenge them to generate as many questions as possible in three minutes. Share the questions, group them by theme, and encourage the group to add to them. Discuss how to identify candidates for good research questions.

- Send students outside for an hour or a morning with instructions to generate 20 questions inspired by their observations of organisms and habitat. Reconvene to share observations and ideas.

- Have students consider a research apparatus (e.g., infrared gas analyzer, digital scale) or style of experiment (e.g., food supplementation). Challenge them to envision projects using the apparatus or research tactic. In addition to providing them with practice in creative thinking this helps them develop basic technical skills that can inspire and facilitate their projects.

- Have students identify features of organisms and environments and ask, "Why is it like this?" We try to answer on the spot with what we know and can see. The questions we can't answer are candidates for research. Many useful leading questions fall into the category of noticing what is not there: "Why is this part of the river clear instead of algal-dominated? Why isn't anybody eating these fruits? Why aren't other species doing what this species is doing? Why aren't there any termites in this part of the forest?"

Biology is a diverse field. Most of our students lack training in entire subfields of biology. We strive to give diverse examples of research approaches and core principles relevant to what we are observing but drawn from fields of biology with which the students are less familiar. This empowers students during question formation and project conception. Below are a few of the subfields of biology that we frequently draw from along with some prominent theoretical concepts (Table 1) as well as a sampling of research approaches that are readily adapted to student projects (Table 2). Journals such as TIEE (Topics in Ecological Education) and BioScience provide a useful reference for additional topic areas and approaches.

Table 1. A sampling of subfields and theoretical concepts that lend themselves to short student projects.

Topic	Example	Theoretical concepts
Physiology and biomechanics	Speed and locomotion patterns of organisms relative to body size, diet, or morphology	Life history theory, trade-offs
Habitat occupancy	Distribution of organisms across habitat	Competition, predation, patterns of resource distribution, optimal foraging
Environmental effects on signals	Color of visual signals depending on the light environment; match between acoustic characteristics and structural complexity of habitat, or timing of signaling	Sensory ecology, acoustic adaptation hypothesis, sexual selection
Allometry	The scaling of metabolic rate, leaf number, behavior, appendage length, etc. with body size across a range of sizes (within or between species)	Functional morphology, resource allocation, life history evolution
Social behavior	Effects of group size on vigilance, feeding rate, and interactions among individuals	Game theory, sociobiology, trade-offs
Predator detection	Behavioral responses based on the presentation of visual, acoustic, vibrational, or chemical cues of predators	Learning, context-dependence
Coloration and camouflage	Appearance with respect to habitat and predator visual system	Crypsis, predation, sensory systems, natural selection
Chemical ecology	Effects of adding or obscuring scent	Sensory ecology, foraging, predation, semiochemistry

Table 2. A sampling of research approaches amenable to student projects.

Example	Theoretical concepts
Manipulating resource availability in different environments, times of day, types of food (sweet, odiferous, dung, floral, etc)	Optimal foraging
Predation trials offering food of different sizes, types, nutritional quality, or escape speed	Optimal foraging, trade-offs
Comparing distributions of attacked and non-attacked individuals to infer the strength and direction of selection (can use discarded shells, herbivory, or other evidence of predation)	Resource allocation, balancing and directional selection
Measuring fecundity: Counting the number of eggs or seeds relative to parental size, habitat, etc.	Resource allocation, life-history theory, environmental heterogeneity
Inferring metabolic processes: Proxies include mass change, amount of food consumed, residuals from mass: length relation, consumption of resources of differing quality	Metabolic efficiency, allometry, additivity vs. interactions
Examining age or stage structure of populations	Demography, r/K strategists, survivorship curves
Use of painted clay models to assess preferences of predators or frugivores (e.g., examining bite marks left in clay)	Foraging, sensory ecology, camouflage
Using analytical models or computer simulations to test hypotheses for patterns in nature (Do these hypothetical drivers produce patterns that match nature? What is the expected optimum for a trait given theoretical costs and benefits?)	Useful for diverse questions

TACTIC 1: Encourage them to work on the cool stuff

Student research projects are most successful when novice investigators are fascinated by the study system. To encourage this, we introduce students to the organisms and ecosystems that inspire our own scientific curiosity, then focus on helping them identify projects that spark their interest. We encourage work that is challenging and a little risky rather than safe, easy, and a little boring. As instructors, we brainstorm among ourselves to imagine tractable, theoretically compelling projects working on the systems that have attracted student interest. We drop hints to help students discover and explore possibilities and suggest alternatives to questions that cannot be addressed within the constraints of time or resources. Many students are happy to find a different research question if their system of interest remains the same: e.g., curiosity about sloth foraging becomes a study of homeothermy; fascination with basilisk lizards running across water becomes a comparison of population structure in small vs. large streams.

TACTIC 2: If they’re not engaged, none of the other stuff matters

“Be safe. Enjoy the quest. Do cool science,” is our regular reminder to students. We monitor morale carefully and insert rest and recreation as needed to keep student spirits high. We foster celebrations after our Research Symposia (and we love to hear students talk about their projects while socializing with their friends). Most of all we do anything we can to help them enjoy the process of engaging in productive scientific inquiry, in part by sharing with them the satisfaction and pleasure we take in it ourselves. We encourage them to become good at talking about science and provide opportunities for informal science-talk throughout the course. In an ideal world, students would work on research that fascinates them in groups that exploit the power of teamwork, and we have observed that the best research is generally conducted by the teams that are having the most fun. Of course, students sometimes find research frustrating or tedious, and even some highly motivated and science-interested students can become overly focused on the end result. We regularly remind them to make the research process itself gratifying and enjoyable.

Developing Projects

(“*Didn’t Janzen already do that?”*)

We urge students to design projects in which any outcome will be novel and informative (Chamberlin 1965, Anderson et al. 2000, Anderson 2008). This opposes their tendency to design studies to validate a single favored hypothesis, which can foster a false sense of success or failure depending on whether the study turns out as the investigators guessed (Moshman and Thompson 1981). To debunk this flawed concept of research design we share our personal experiences of learning the most when we discovered we were wrong (and regularly note that we learn the least when we simply affirm what we already guessed). We also raise the concept of critical tests (Giere, 1981), which flow naturally from the presence of competing hypotheses. We encourage students to conceive and explain their research in terms of multiple working hypotheses (Platt 1964, Chamberlin 1965, Anderson et al. 2000, Elliott and Brook 2007, Anderson 2008). Instructors can promote this attitude by applauding initial hypotheses then pressing for competing possibilities: e.g., “How would you know if these leaves are bigger because they are in the shade or if leaves in the sun are smaller because of water limitations?” Or, “If you think result A would be interesting, then it must also be interesting if you get result B, but how would you explain it?” Our mantra is “The best questions are those with more than one plausible answer.” Student research questions usually evolve as competing hypotheses are identified and refined. We find that projects are almost always rewarding when the investigation is motivated by two or three competing visions of how nature might be, and are often disappointing when the study begins with but a single biological hypothesis in mind. Critical tests and multiple working hypotheses are advanced topics that can be challenging to teach. However, students understand the simple argument that time is better spent on research that may yield novel, informative surprises. With a well-conceived study, success is ensured (given good data) because any possible result will address a fundamental question, but we won’t know the answer until we collect the data, which of course is the point.

As lack of ideas can lead to student anxiety, seeing too many avenues can also be paralyzing. Sometimes students have problems settling on a question because they have unrealistically high standards (a curse of the perfectionist; Karban et al. 2014). High standards can be good but also crippling. "Don't you think you'll learn more by going to the flower patches and trying something rather than sitting on the porch debating the perfect pollination study?" We remind hesitant starters that these are small-scale projects geared toward exploring research skills not just generating answers. We also emphasize that innovative research questions frequently flow from observations made while investigating other questions. ("The most valuable things you learn in a good study are often not the answers to the question you started with.") Once students begin projects, we challenge them to be alert for unexpected observations, new questions, novel insights, and opportunities for simple additional measurements that develop along the way (Root-Bernstein 1989).

Research ideas often arise in forms that are hard to test. For example, 'How do ants follow a path?' is a promising topic but does not suggest clear alternative possibilities. It can help to have students generate hypotheses for phenomena then work backwards to refine the questions. Maybe ants use vision to follow the ant in front of them. What if I turn out the lights? Maybe ants use chemical cues to detect the trail. What if I let the ants develop a path over an index card and then turn the card 90°?

We encourage students to consider both proximate questions (how do organisms do what they do) and ultimate questions (what is the adaptive consequence and demographic or evolutionary significance of behavior, morphology, or life history).

Our strategies to help students with project development include the following.

- When students struggle with research design, try offering "breadcrumbs"—partial ideas that lead them to a new way of thinking. "Have you seen the infrared temperature sensor we have in our research supplies?" Or, "Have you noticed those ants on your *Aphelandra* blossoms? I wonder what they're doing there?" Or, "I wonder what it would be like if you also measured this pattern in Habitat B (or for Species X)?"

- If a team is in agreement about how a study will turn out, encourage the group to develop more refined versions of the question until they don't all agree. If the expectation is that plants with more flowers will have more pollinators, will the relationship between flower number and pollinator visits be linear, logistic, or exponential?

- Before students settle on one idea, we encourage them to choose two and develop them into mini-proposals that specify the question, hypotheses, data to be collected, possible findings, and interpretations of the different alternative findings. This helps students learn to consider and choose among multiple research paths. It can also inspire off-shoot projects by other student groups and provide a fallback option if the first-choice project fails. We find that students generally like their projects more when they are deliberately selected from among alternatives, rather than being the first thing that they came up with.

- Identifying and refining alternative hypotheses is a stage in the inquiry process where group thinking is a particularly powerful tool (Hong and Page 2004). Brainstorming to identify all imaginable outcomes and interpretations is useful. Group members can practice articulating the logical expected outcomes derived from alternative hypotheses. It can be useful for students to try championing a hypothesis that they find less convincing— sometimes they surprise themselves with the valid arguments in favor of a hypothesis that was not initially their favorite. A proposed study gains favor when there are a few different possible outcomes, each of which would favor a different theoretical model (i.e., general conception of how nature works). Knowledge gain tends to be greatest when different possible outcomes seem about equally likely before the test is done.

TACTIC 3: Help them release the power of the team

Research in our courses, like contemporary ecological research in general, is almost all conducted by work groups. Learning to be a good team member is a prescription for professional success in science. We make teamwork part of the curriculum by promoting group interactions when the challenges require creativity and problem solving (e.g., Tactic 1 and 8), and advising on effective division of labor (Watson 1992, Knabb 2000, Michael 2006). We encourage students to seek co-investigators different from themselves, and we help them notice how diverse teams are good at problem solving (D'avanzo 2003, Hong and Page 2004). The goal is for students to become better at cultivating the power of human teams (e.g., creativity, problem solving, and division of labor) without succumbing to the hazards (e.g., documents that appear to be have been written by committee, duplication of effort, petty acrimony, rancor and lasting enmity, etc.) (Heller et al. 1992).

TACTIC 4: Extract the hidden hypotheses

Our students often describe a potential project by stating their guess of the results they expect and calling this the "hypothesis." A bit of pressing usually reveals that their guess is a prediction derived from an unstated theoretical model. We ask, "Why do you think that?" and lead them to articulate the theoretical basis for the prediction. We help them develop their logic so that the prediction being tested is deduced from an explicit theoretical model (or biological hypothesis). For example, students may guess that leaves will be larger in the shade, but with additional prompting will recognize that this prediction could flow from one of several underlying models (light limitation favoring adaptations to maximize light acquisition, difference in herbivory pressure, etc). It takes time for even sophisticated students to recognize that it is not *their* prediction but rather the logical consequence of one way that the world might be. We frequently chide them (in good nature of course!): "No one cares how you think it will turn out. It's about how competing theories predict it will turn out."

TACTIC 5: Don't be The Mentor on the Mountain

We give lectures and conduct other structured activities, but we probably teach the most when we have our boots on, helping students develop their research project in the field (Kirschner et al. 2006; Schamel and Ayres 1992). Whenever we can, especially when a team might benefit from a boost

(Tactic 6), we try to help them find the antbirds, catch the lizards, identify the insects, measure the trees, calibrate the oxygen probe, record the bats, etc. Sometimes we show off our savvy. Frequently we're as much in the dark as our students. They learn at least as much from the latter as the former. On those occasions we say, "I don't know," followed by "What do you think?" Then we teach them how to figure something out. We value the occasions when an instructor becomes a full team member, missing meals while slogging through hard fieldwork, and being a coauthor on the manuscript. This enables us to model the aspects of scientific inquiry that are easier to prescribe than to do (D'avanzo 2003).

Refining Methods

(*"We couldn't find enough caecilians." "Do we have an eddy covariance tower?"*)

No matter how carefully planned, the methods for research rarely work perfectly the first time. Thinking, talking, and planning help, but only to a point. We encourage students to collect pilot measurements as soon as possible and to expect modifications after they discover what can actually be measured, how hard it will be, and how long it will take. When students head out expecting to exactly implement an untested protocol, they usually return to announce that their project is unworkable. When instead, students anticipate that methods will be revised pending initial experiences they are less likely to become frustrated and more likely to have the confidence to adapt rather than abandon a promising project. Measurements that are hard to make the first few times usually become easier and more repeatable with practice. We find it is often better to let students discover problems via pilot sampling rather than to have their untested ideas shot down by a skeptical instructor (and we can be pleasantly surprised when students make something work that seemed improbable to us). Of course we are more active in questioning sketchy plans if the self-learning seems likely to be long or painful.

Novice investigators can become obsessed to their detriment with using a protocol that was initially associated with the project. We lead students back to the underlying motivation and help them look for another path to address the same question. If the leaf beetles are too rare to count directly perhaps one can measure their feeding damage on plants. Often preliminary methods "don't work" because the question no longer makes sense given what students learned in the pilot sampling. In this case, we help students appreciate the new paradigm-altering knowledge and adjust their questions and hypotheses accordingly. We challenge students to sketch mock figures of different possible results and talk through their interpretations. This can neatly expose mismatches between questions and methods when they are still easy to fix. Having the students explain mock data figures also helps us see ahead to the statistics that might be employed and to identify easy ways to strengthen inferences (examine the same number of leaves in total but spread them out over more plants). It is common for our students to spend about half of their field time on a research project refining the methods—and adjusting their research questions. As methods are resolved, as organisms and tasks become more familiar, data collection proceeds more quickly and the process becomes more gratifying.

Once methods are finalized and data collection begins in earnest, there is a tendency for young investigators to submerge themselves in the mechanics of the protocol. We encourage students to keep thinking, looking, and questioning as they do the work. What questions will your colleagues ask later and how will you answer them most directly and effectively? What simple additional observations could be recorded to enrich the results section or address the next tier of questions inspired by the project? We require teams to provide a few high quality images of their study system and data collection, partly because it requires them to look through a different lens than that of their measurement protocol.

Our students are sometimes held hostage by the allure of manipulative experiments. They have learned that experiments are powerful tools for determining cause and effect, which of course is correct (Underwood 1990). However, not all questions and study systems lend themselves to experiments, and the range is even smaller with the typically short duration of student projects. To help inspire our students, we provide examples of creative, elegant research that relied on insightful design rather than expensive equipment (some of our favorites include Heinrich 1979, Marden and Chai 1991, Brodie 1993, Hurly and Oseen 1999, Ellers and Boggs 2003, Wong et al. 2005, Svensson and Gosden 2007). We also cultivate facility in using non-manipulative observations to test intriguing research questions. To aid our students in developing research designs we encourage them to consider all genres of scientific inquiry (Carpenter 1998, Valiela 2001) and to favor measurements that will be easy and informative.

- Manipulative experiments can be powerful and satisfying when the study system and time frame are appropriate. Successful experiments by our students have included: demonstration of kairomone-based avoidance of termites by army ants; velocity as a function of loading in leaf-cutter ants; increased pollinator attraction with increased height of inflorescences; influence of vegetation on sound localization capabilities of primates; removal and replacement studies of territorial lizards.

- Non-experimental approaches are valuable in short-term exploratory projects. Correlation analyses, arguably the simplest of the non-experimental approaches, can be a powerful tool for obtaining quick answers. Determining the presence, absence, and form of correlation can support or falsify many hypotheses and provide direction for future investigation. Gradient analyses, study of spatial pattern, and modeling allow richer possibilities. The inference from non-experimental data can be very strong when associated theoretical models predict details of the mathematical relationships against which empirical data can be compared: e.g., accelerating function, slope = 1, dispersion follows Poisson distribution, stronger effect in habitat A than habitat B, etc. Satisfying studies by our students exploiting natural variation to answer research questions include: tests for niche partitioning among antbirds; evidence that fish-eating bats benefit from a commensalism with sharks; seed predation by specialists and generalists in the center and edge of a stand of masting oak; intensity of display coloration and parasitism in male Tetras inhabiting pools with more or less input of plant carotenoids.

TACTIC 6: Frustration is a double-edged sword

Being an effective researcher requires effective management of frustration. Frustration is an adaptive emotion—it limits time wasted on hopeless endeavors and indicates that a task is difficult or unclear. On the other hand, most scientific breakthroughs are preceded by periods of frustration. We encourage students to expect frustration and to practice channeling its energy toward finding creative solutions to the inevitable challenges of conducting original research. We try to modulate frustration by encouraging independent problem solving when investigator morale is good and providing proactive help when frustration runs high (sometimes including honest counsel to drop something that probably will not work, preferably while suggesting an attractive alternative). Developing resilience to frustration serves students well, both in biology and more broadly.

Analysis

(“We got a p of 0.02. Did we win?” “What’s wrong with JMP today?!”)

Helping with data analysis is challenging and even intimidating for instructors. Most of our students have not had a class in statistics. Some have had one statistics course. Our strategy is to (1) develop analytical skills that do not depend on p-values, (2) cultivate interest in statistics, and (3) facilitate growth in analytical abilities from wherever a particular student is beginning. Regardless of their statistical literacy, we advise students to begin by visualizing their data in various and creative ways to find a presentation that permits easy interpretation of the results with respect to the hypotheses.

Sometimes, the answer becomes self-evident without reference to p-values, AICs, etc. In other cases, the interpretation remains ambiguous (watch for the instructive cases where investigators on the same project disagree about the interpretation while looking at the same data); this opens the door for students to be impressed by the power of statistics. It can be challenging to identify good statistical approaches for the stunning diversity of projects that our students conceive. As instructors, we do lots of work among ourselves thinking, talking, and learning about different potential analyses of student data. We favor statistics that match the data visualizations developed by the students and that the students can understand and perform. We emphasize that p-values by themselves are rarely the answer (Box 1). We avoid situations where students watch us run an analysis and then walk away with a p-value. We take every opportunity to develop fundamental concepts from statistics (central limit theorem, derivation of F-statistics, additivity vs. interactions, etc.) at moments when students are attentive to the method’s utility for present purposes. While doing their projects, most of our students develop at least basic proficiency with statistics software and an assortment of statistical approaches. Students comment favorably on becoming empowered by statistics during the research experience, and many are inspired to take the next available statistics class. To broaden their exposure to statistical tools, we watch for natural applications within student projects of topics that are commonly useful but do not necessarily appear in Stats I or Stats II: e.g., nested models, random effects, principle components analysis, randomization tests, multiway contingency analyses, fitting nonlinear models, and multimodel comparisons.

TACTIC 7: When the answer to their question isn’t what they need

Our interactions with students on statistics often begin when they ask “Which one of these p-values should I use?” or “Why isn’t ‘Fit model’ working?” We have learned to resist offering a quick and simple answer. Instead we invite them to explain their data, their question, and the logic of their proposed statistical approach. This is time well spent. Often their initial question becomes moot because the students determine that a different approach would be better.

Communicating Findings

(*"It's all very complex." "I don't think we have any conclusions."*)

We find it crucial that student research culminate with public presentations (Schamel and Ayres 1992). Knowing that they will be presenting to their peers inspires the investigators from beginning to end. The presentations are engaging for everyone and cause for celebration afterwards (Tactic 2). Depending on the course structure and environment we have a poster session or symposium of talks. With our intensive field course we also have students write, revise, and publish a book of their well-polished research papers. Our course structure includes frequent modules on science communication. Most university science professors are accomplished authors and presenters, and good references exist (Mack 1986, Strunk Jr and White 2000, Valiela 2001, McMillan 2011, Pechenik 2012, Karban et al. 2014). Here we simply highlight a few strategies relevant to students presenting original research.

Whether the presentation is a talk, poster, or manuscript, we encourage students to follow the basic structure of starting broader than the study system, funneling in to the study, and funneling back out to broader implications (Box 2). Most studies are inspired by a local system so students can be challenged to find the broader context that makes it relevant outside our local site but not so broad that the audience scoffs. This is partly an exercise in creativity. Group brainstorming can be productive (Tactic 3). We do exercises in which students briefly describe their study system and question, and the rest of us suggest as many potential parallels as we can with other systems (the more remote the better) and try to identify general theoretical concepts that are relevant. Students particularly enjoy this (especially when done in a good swimming hole or equivalent) and it is usually successful in generating ideas that enrich the context of students' scientific communications.

When the course structure includes writing and revising manuscripts, students spend perhaps 30% of their time working on their manuscripts and instructors spend >50% of their time reading, commenting, and editing. Most manuscripts go through three submissions and revisions before being accepted for publication in the course book. Student patience is taxed if the editors are not efficient, constructive, and good-natured. We work hard to ensure that different editors (typically Professors and Graduate Students) do not give conflicting messages. Below is our checklist for evaluating the first draft, which we find to be a crucial phase.

First draft checklist:

<u>Results.</u> Are the figures and tables well-constructed and well-chosen? Are the analyses appropriate and properly presented? Are narrow sense conclusions defensible (Box 1)? Does the prose describe biology with reference to statistics rather than vice-versa? What is missing? If there were surprises that changed the project, are they captured in the Results? Were there informative findings that should appear but do not appear because they were not answers to initial questions and were not a result of formal data collection?

<u>Introduction</u>. Does it include background, theory, technical approach, and predictions? Does it begin broader than a particular study system? Does it match the results in logic and order? Is there anything missing? (e.g., relevant details of study system)

<u>Discussion</u>. Does it address the questions raised in the introduction? Does it match and complement

the results? Does it funnel out to end broader than the particular study system?

Methods. Does it match the introduction and results in logic and order?

In our system, each first submission is read by one instructor, who later summarizes the manuscript to other instructors in a closed meeting, and then we confer on data presentation, analyses, interpretations, and logic. Later we have a meeting with the student investigators and discuss and return the annotated manuscripts. We repeat the process with subsequent submissions, but with each step the attention increasingly concerns details of vocabulary, sentence structure, and paragraph development. This process takes time but is worth it. More than 150 alumni of our field ecology course have gone to graduate school and they tell us the writing skills they developed were crucial to their success in graduate school. The collected works from our field ecology course are available online (http://biology.dartmouth.edu/foreign-studies-program).

TACTIC 8: Help them see the big picture

Solid research becomes profound when the intellectual context of the inquiry is broader than the particular study system. We encourage students to frame their research broadly by insisting that they start and finish their presentations, posters, and manuscripts in terms more general than their study system (Box 2). We teach that theories are the tool for the job. When research tests a theory more general than the study system there is basis for inferences more general than the study system. We promote breadth of context by playing the analogy game. Students briefly describe their candidate study and colleagues respond with ideas of other biological systems that are like that: e.g., Macaws are like Tetras because they both need carotenoids for coloration; leaf-eating katydids are like anteaters because both have to move on after a few bites due to the rapidly induced defenses of their "prey." Identifying systems that share features can suggest theoretical concepts that link them (e.g., sexual selection), which can suggest competing general hypotheses (e.g., honest signals vs. runaway selection) and ways of framing the research to be an inquiry more general than the immediate study system. People unfamiliar with the project are uniquely qualified to see broad connections (Wuchty et al. 2007, Woolley et al. 2010). The more diverse the people looking for connections the more diverse will be the suggestions of potential parallels (Tactic 3).

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BOXES

Box 1. So what's the answer?

A matrix of possible research results. One likes to land in the upper left box or the lower right box, but the upper right and lower left are also common. Authors should agree on where the results fall within this matrix and use vocabulary and tone in describing the results that conveys their judgment.

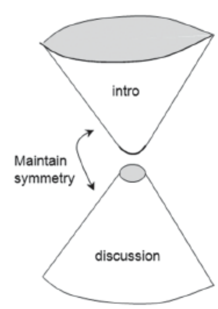
Is the relationship between X and Y biologically relevant if real?

Do the statistics indicate a relationship between X and Y?	No	Maybe	Yes
No	"There were no differences." "Treatments were very similar." "Nectar addition had no effect." [This box is a good place to be when the question was interesting]		"Higher." "Tended to be higher" "40% higher" [A syndrome of too few data]
Maybe			
Yes	"Effects were small but significant" [A syndrome of too many data]		"Species richness was higher" "Was significantly higher, much higher, 2x higher" [This box is a good place to be when the question was interesting.]

Box 2: A template for communicating science

Introduction. Funnel in.

- Begin with broad framework; big question; relevant theory. A good paper is relevant beyond the species and place.
- Provide enough background about the study system to understand hypotheses, predictions, and technical approach.
- Articulate the research questions, alternative possible answers, and related biological hypotheses.
- Foreshadow potential consequences of different possible answers.
- Summarize the logic of hypothesis tests and the technical approach.



Discussion. Funnel out.

- Give clear direct answers to your research questions. Describe the fate of hypotheses that were tested. Discuss the causes and consequences of patterns that were revealed.
- Note any unexpected results (not foreshadowed in introduction) and their causes and consequences.
- Consider the rigor of inferences, potential caveats, and strengths and weaknesses of the technical approach.
- Finish with the most cosmic conclusions: e.g., broad causes and consequences of what you have learned (relevance to other species, systems, contexts?). Connect the reader back to how the paper began.

Dartmouth students learning ecology and scientific inquiry near the La Selva Field Station, Costa Rica. Photo by Matt Ayres.