# Presenting the Scientific Process

## Introducing Philosophy, Theory, Methods, and Ethics

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*In a course titled Scientific Process, we introduce undergraduates to the philosophy and practice of science and initiate them into a 2-year undergraduate research track. Engaging exercises and discussions help students understand the scientific process and ultimately produce a research proposal in grant application format. Students defend their written proposal during a 15-minute oral presentation.*

The strongest foundation of scientific research requires a thorough background in the theory, history, and philosophy of science (Keeports and Morier 1994). Students benefit from an ability to recognize change in the scientific method through time, as Karl Popper did regarding the status of evolutionary biology as a science (Ruse 1996). In the absence of such a foundation, inexperienced scientists frequently fail at basic elements of experimental design or in the structure of inductive or deductive arguments.

Theory and philosophy of science are not typically emphasized in undergraduate education, despite clearly demonstrable benefits to students, including a better understanding of the process of scientific inquiry and its applications. The demystification of science can be a critical cognitive step for an undergraduate; once science is demystified, students can begin to perceive science as a process to be followed rather than just a collection of facts.

Perhaps even more importantly for nonscientists, a rudimentary understanding of the scientific process has profound implications for helping them understand and make political and social decisions (e.g., regarding cloning, genetic modifications of food, bioterrorism, and so forth). Finally, at a societal level, a fundamentally sound scientific education reduces the effective "scientific elite" established and perpetuated by a focus on factual memorization in education. The demystification of science into its constituent processes and reconstruction into a nearly universally accessible phenomenon is critical to the advancement of society itself (Lindell and Milczarek 1997).

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### Course Design

To address the above concerns, the Florida Gulf Coast University (FGCU) offers a course titled Scientific Process, which is required of all students in the junior year of a natural sciences degree program. The intent of the course is to prepare students for a 2-year research track in which they become practitioners of science. Previous science courses ensure that students have already been exposed to scientific research and primary literature.

This course, then, marks the beginning of either a required independent-research senior thesis in biology or marine science or an optional thesis for environmental studies students. Senior research papers prepare students for many future challenges, including graduate study and independence in the workplace. Students frequently tout their senior thesis work to prospective employers as evidence of strong project-management and analytical skills.

The course objectives are to introduce students to the methods and philosophies of science and prepare them for independent research. Facilitated by the development of a rigorous scientific proposal, students and faculty discuss and debate in a peer-group setting. By the semester's end, students lead classroom sessions, which is possible in part because they have acquired an understanding of the process.

The course emphasizes four concepts or skills—philosophy of science, ethics of science, critical evaluation of scientific research, and the design of a semester-long scientific study. Throughout the course, students are actively engaged in the scientific process through researching and producing grant proposals, which may serve as designs for their theses. Assignments are geared toward completion of the grant proposal, and course topics exemplify the history and philosophy of science and successful research and grant applications.

The first third of the course introduces students to several major facets of science's conceptual framework, all of which resurface later in the course. We explain important features in the philosophy of science (detailed below) and subsequently help students independently identify these topics by evaluating scientific literature devoted to the subject. The major topics discussed are well addressed by leading philosophers and essayists and present modern scientific pursuits (available online as Web Figure 1; see Editor's Note at the end of the article).

*Science versus nonscience and pseudoscience* is the first topic. The debate over what actually constitutes science was perhaps best developed by evolutionary biologists. Due in no small part to the efforts of philosophers such as Popper (1979 and 1985) and Hull (1988), evolutionary biology literature demarcates the borders of science and consequently articulates the features of pseudoscience. The phenomenon known as "scientific creationism," for example, facilitates among students enthusiastic discussions about the components of science. More generally, Sagan (1996) discusses the boundaries of science, and Hull (1988) discusses the development of science and its influences on scientists. These readings help students perceive scientists as individuals, which helps students develop the self-confidence to imagine themselves becoming scientists.

*Falsificationism versus inductivism* is the second topic. Traditionally, students are taught about science using Popperian falsification as a model. Falsification demands that science proceed through experimental manipulation of single variables in controlled settings, as is common in laboratory chemistry, for example. Consequently, historical events such as extinctions, forensics, and much of biology are excluded from scientific investigation. This framework is frequently called the scientific method in primary education in the United States, giving the fictitious impression that science proceeds under this solitary paradigm.

However, as argued by Whewell (1999) and advocated by many others, inductive (or Baconian) science can serve equally well as a framework for valid scientific research. Baconian inductivism proceeds by seeking preexisting natural evidence that contradicts a hypothesis about a natural phenomenon. As data accumulate and relevant experiments are conducted for the purpose of analogy, hypotheses are rejected or refined, ultimately leading to theories that are consistent with all known examples of the phenomena. Again, evolutionary biology serves a particularly important role in the description of this scientific paradigm, although the majority of scientific disciplines can serve as examples of inductivism.

As students explore Popperian falsificationism, they are typically encouraged to consider the importance of falsification through reading the analyses of experts (such as Chalmers 1982). Students and faculty discuss whether or not their own research designs and past experience in science support Popper's contention that science must be characterized by falsification. Subsequently, students further weigh the benefits of falsificationism versus inductivism by studying evolutionary biology as an example of inductive science. The nature of science is made clear to students through the study of such evolutionary phenomena as mass extinction events. Ultimately, students see the two approaches to science as complementary.

*Problems of assumptions* is the third topic. Conscious identification of assumptions is a critical feature of sound science, although many fail to grasp this concept without direct exposure. Kelvin's infamous dismissal of an entire subfield of geology is an excellent case in point (Gould 1985). Students learn the importance of assumptions through the realization that it is possible to follow the scientific method without fault and still arrive at erroneous results due to a faulty assumption. Subsequently, students must identify critical assumptions in the papers they read and assess the validity of the assumptions.

*Importance of a mechanism* is the fourth topic. Historical science is replete with cases in which strongly supported inductive hypotheses failed to gain widespread acceptance because of the lack of a mechanism. Wegener's hypothesis of plate tectonics, for example, was widely supported by evidence, although the theory was not accepted until a mechanism for plate movement was first accepted (Stanley 1989).

*Progress in science* is the fifth topic. One of the most influential philosophical topics of the past several decades has been Kuhn's (1962) discussion of progress in science. We teach Chalmers' analysis of Kuhn's work (1982) and challenge students to identify historical and present iterations of Kuhn's "pre-science," paradigms, and crises. Evolutionary theory typically emerges as the paradigm of choice, although breakthroughs in chemistry (development of atomic theory) and in astronomy (heliocentric solar system) are equally applicable.

*Scientific design frameworks* is the sixth topic. Structure of scientific

**TABLE 1**

**Course objectives and means of implementation.**

| Instructor objectives | Tasks for students (or faculty where noted) |
|---|---|
| Introduce students to the practice of science (theoretical basis, philosophy, and practical and theoretical methodology). | 1. Read and discuss the writings of prominent philosophers and critics of science.<br>2. Define and discuss the differences among science, nonscience, and pseudoscience.<br>3. Compare different scientific practices and disciplines.<br>4. Present, discuss, and apply a model for the framing of a scientific project. |
| Develop the ability to critically evaluate science and relate evaluations to peers through the application of the above principles. | 1. Discuss and critique the scientific structure and validity of primary journal articles.<br>2. Take turns moderating the discussion of individual papers.<br>3. At the conclusion of each critique, suggest qualitative design changes. |
| Transform creative scientific questions into testable hypotheses (scientific design). | 1. Explore the hypotheses development by analyzing the design of others in published papers.<br>2. Work collaboratively to design a research project. |
| Develop skills associated with the presentation of scientific information (e.g., proposals, primary journal articles, and poster and oral presentations). | 1. Draft, review, and redraft a unique research proposal and critically evaluate those of peers.<br>2. Present proposals, either orally or as posters, and defend them individually late in the semester. |
| Make students and other faculty aware of individual faculty research interests and expertise. | 1. Each science faculty member provides a brief research presentation or prospectus.<br>2. Faculty not teaching the course may visit and participate periodically. During these visits, faculty make brief presentations about their research interests. |
| Help students define their research discipline and identify potential research mentors. | 1. The informal setting coupled with science faculty participation and online resources developed for the course helps students learn the research interests of faculty and helps define their own interests.<br>2. The published material reviewed during the semester will cover a diverse array of scientific topics, thereby exposing students to a wide range of research disciplines. |
| Students develop a research proposal by the semester's end. The proposal is presented and scrutinized by peers and faculty. | 1. After identifying a research question, work collaboratively with other students and faculty members to develop a research plan that will then be transformed into a proposal.<br>2. Proposals and presentations will be peer reviewed. |
| Students are introduced to methodological techniques used by researchers in the sample disciplines represented among the sample research used in the course. | 1. The published papers reviewed during the course introduce participants to various methodologies and technologies, allowing students to learn about methodologies unique to different fields.<br>2. Throughout the semester, faculty, students, or guest speakers present their specialized research methodologies and technologies. |
| If possible, members from the scientific community outside of the university participate in this course. | 1. Course faculty periodically invite local or visiting scientists to join the day's discussion.<br>2. Reading lists may be altered to include literature relevant to visiting scientists. |
| Instill within students an understanding of the ethics of scientific practice. | 1. Read and discuss essays addressing ethical issues in science.<br>2. Throughout the semester, when journal articles and research projects are reviewed, consider ethical issues concerning scientific practice. |

investigations is typically dealt with by example and a thorough critique of student projects. Both inductive and deductive methods are fostered, and research projects integrating both methods are particularly encouraged.

*Scientific ethics* is the seventh topic. Scientific ethics covers a diverse array of subjects, ranging from plagiarism and falsification of data to considerations of how scientific research affects society. Swazey, Anderson, and Lewis (1993) argue that scientific ethics are, in large part, developed under the tutelage of students' scientific mentors and role models. In recognition of this argument, the ethics section of the course is considered to be critical.

For organizational purposes, we grouped ethical issues into the same categories as described by the National Academy of Sciences (Swazey, Anderson, and Lewis 1993), although the addition of a fourth category was deemed necessary to meet the needs of undergraduate students. The categories include:

- Fraud (falsification of data, plagiarism, and so forth);
- Questionable scientific practice (poor record keeping, honorary authorships, and so forth);
- Ethical issues not unique to science (sexual harassment, illegal use of funds, and so forth); and
- Societal implications (weapons, cloning, and so forth).

Students typically engage these issues sequentially by reading and discussing the opinions of prominent scientists and ethicists. Discussions are enhanced by faculty members giving their insight into the psychology of ethical breaches and sharing discrete anecdotes. We have found that, even as undergraduates, students are exposed to and aware of scientific breaches of ethics approximately as frequently as were the graduate students studied by Swazey, Anderson, and Lewis (1993), although no systematic records have been kept.

## Using the Model

The most practical course component is the training of students in critical evaluation (CE) of scientific research. CE allows young scientists to gain confidence in their own abilities and improve the precision of their own research goals and designs (Janick-Buckner 1997). Specifically, science and scientists intimidate many students, likely because of a superficial understanding of the process. The recognition that an introduction to the scientific process provides the individual with the ability to differentiate good science from bad, across disciplines, is encouraging to young scientists.

Research papers for CE are carefully selected each semester to illustrate flaws in scientific design as well as other features of various scientific disciplines, including hypothesis generation and specificity, problems of assumption, data collection and reduction, falsification and inductive approaches to scientific design, and data interpretation and speculation.

We select readings from the primary scientific literature, which spans traditional discipline boundaries. In addition, students must submit articles they have encountered while developing their proposals. Qualitative assessment indicates that student satisfaction with CE is high, although students feel that they have mastered the method well before each of the five major areas above has been addressed. Although some students attain a strong grasp of the process, mastery of all areas is not typically achieved by all students in one semester. A major intent of this course is to provide students with experience in the CE of primary scientific literature, a skill that is expected to develop over much of a scientist's career.

The primary assessment is derived from a semester-long assignment to develop and defend a research proposal in the format of a grant application. Early in the semester, students are surveyed to identify broad areas of research interests. Subsequent assignments (Tables 1 and 2) are designed to help students more precisely define their own areas of interest and introduce them to relevant literature. Students then draw the information (and also preliminary data for advanced students) together in the form of a grant proposal.

The format of a grant proposal provides students with a realistic understanding of the scientific community's expectations, and proposal guidelines are strictly enforced. Proposal guidelines closely mirror those of the National Science Foundation and have subsequently been adopted locally by small community groups providing local student grants.

Individual or small group discussions help students focus on specific

**TABLE 2**

**Mile-marker assignments.**

These assignments are sequentially arranged to ensure adequate progress toward completion of the project during the semester. Failure in any one assignment may warrant intervention on the part of the instructor to ensure that future deadlines are met. More importantly, consistency of performance may be assessed and allow identification of other student needs during the course.

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|---|---|
| Opening questionnaire | Informal assessment of student expectations and pre-instruction knowledge of relevant subject areas. |
| Research interests questionnaire | Begins the process of targeting research, allowing both students and instructors to begin individualizing the course. Feedback from the instructor may be required to hone student interests to manageable projects or areas where novel research is likely possible. |
| Journal title list | Students identify 12 scientific journals publishing research in the area of interest established previously. Instructors may clarify the differences between primary and secondary literature sources. |
| Bibliography | Students generate a preliminary bibliography of journal articles (minimum of 12) directly relevant to their intended area of study. Where warranted by library resources, instructors should set this assignment early enough to allow sufficient time for interlibrary loans, travel, or otherwise delayed access to articles. Instructors can clarify the differences between primary and secondary literature at this juncture. |
| Annotated bibliography | Students annotate each of the articles identified above in the bibliography assignment. Instructors may find that students' research plans begin to redirect at this point as they become acquainted with the literature. Individual assistance may be necessary for some students to identify frontiers in their field. |
| Proposal outline | Students prepare a formal outline of the proposal, following the guidelines, illustrating both the logic and need of their proposed research and its experimental design. Instructors may find it particularly important to reinforce to students the concept of outlining as a means of providing a structured, cohesive argument. |
| Proposal first draft | Students submit a completed proposal, exactly as if it were the final version. Instructors provide feedback regarding the literature review, structure and logical presentation of the proposal, experimental design, and correspondence to proposal guidelines. |
| Proposal final version | Students submit a completed proposal, including any necessary supporting documentation. Instructors evaluate the proposal based on proposal guidelines, scientific merit, and students' response to criticisms provided throughout the course. |

projects that might be conducted as senior theses (including those by secondary education majors, who often explore pedagogical questions). We suggest that project designs be realistic and that students consider university facilities, equipment, time, and other constraining factors (such as Institutional Review Board and Animal Care and Use Committee criteria). Students must adhere precisely to proposal guidelines; failure to implement the guidelines is dealt with aggressively to mimic the proposal phase of the scientific process as accurately as possible (proposals are rejected as unacceptable and returned ungraded).

After proposal drafts have been submitted, each student gives a 15-minute oral presentation outlining his or her intended course of study. All students attend all presentations, as do course faculty, and the structure mimics scientific conferences; there are time constraints, aggressive questioners, and so forth.

In preparation for the defense, students view a sample proposal defense given by one of the course faculty. Typically, students give computer-based presentations, although format is not mandated by guidelines. To minimize anxiety over public speaking, students can briefly practice their defense in an early, peer-reviewed class session. This helps strengthen the group support network and ensures that constructive criticism is well intentioned and received.

Proposal presentation is a critical portion of student research plans. As a consequence, significant peer criticism is acquired, which students may use to improve the final version of their proposals (Web Figure 1, see Editor's Note). Students are encouraged to seek honest feedback about their proposals and may revise and implement their projects with faculty mentors.

## Team and Rotational Teaching

*Team teaching* provides students with a plurality of opinion and interdisciplinary insight into science as a process; this insight is critical to a well-rounded scientist. Each semester, Scientific Process is taught by two faculty members in the natural sciences, usually from different subdisciplines. As a consequence, classroom discussion is frequently lively. Scientists with different opinions on topics (e.g., honorary authorship) participate in the discussion in opposition to one another, stimulating discussion and discovery. At the advanced undergraduate level, students welcome this plurality and engage the subject readily.

Equally important to presenting multiple viewpoints is the necessity of demonstrating the interdisciplinary nature of science. No science functions in isolation, although the typical young scientist rarely articulates such an understanding. For example, a student planning a study of Duchenne's muscular dystrophy was able to apply evolutionary methodology to a biomedical problem after focusing on interdisciplinary reading.

*Rotational teaching* involves the passing of course duties among faculty members in an academic unit sharing core courses. In this case, we originally designed and taught the course in the first year. In subsequent semesters, the authors team-taught the course with other faculty members for the purpose of training additional faculty. The "apprentice" instructors are required to participate fully, and the "master" instructor ensures that the course objectives are not compromised by changes made by the apprentice; this allows changes and ensures academic freedom.

Eventually, the former apprentices will train additional apprentices, and the course will diverge from its origins. Whereas the breadth of topics covered in the course increases through time, the objectives are ensured through the master-apprentice relationship. Varied content helps to keep the course fresh and ultimately provides a database of appropriate papers upon which any instructor may draw. This conservative evolution of the course ensures that learning objectives are met regardless of instructor.

Rotational teaching presents several challenges to faculty and administrators alike. Primary among these is allocating sufficient faculty resources to implement the master-apprentice design. Although the financial costs are real, the institution benefits from the cohesiveness imparted by such a system. Likewise, faculty members are challenged to release their hold on intellectual property that they contribute to such a course.

Administrative support and understanding of faculty rights is obviously critical, as faculty require a reward system to function in such a structure. At FGCU, the reward system is currently limited to the benefit of shared teaching responsibilities in the master-apprentice semesters and the reward of supervising students with relatively advanced skills.

## Evaluation and Assessment

Student performance is primarily assessed via the completion of the research proposal (collectively, more than 50 percent of the course grade) and participation. We also assess a series of "mile-marker" assignments designed to further student progress on the written proposal and presentation. Finally, students moderate classroom discussions during the CE portion of the course, emulating a scientific panel discussion.

Mile-marker assignments are sequentially structured to give students implicit and explicit guidelines for producing their final research proposals. Each assignment counts toward the overall grade, ensuring completion of the assignment and consequently of the project (Table 2).

A presentation is made of the oral proposal defense, and a substantial portion of the overall course grade reflects a student's ability to verbally communicate scientific ideas and concepts. Rehearsal greatly improves performance, and presentation rules are strictly enforced.

The final paper is the research proposal and constitutes the largest portion of the overall grade; students are expected to demonstrate a thorough understanding and application of all concepts developed in the course. Graded rough drafts ensure that adequate attention is given to the final paper, and students failing to incorporate recommended changes can expect assessment to reflect such choices.

The importance of participation in a seminar course cannot be over-emphasized. Consequently, grade allocation in this area is substantial. Participation has been assessed both qualitatively and quantitatively with high correlation between assessment forms.

Student moderation of discussion demonstrates individual ability in the areas of critical evaluation, communication, and planning. Assessment is necessarily qualitative, although students are expected to demonstrate a number of recommended strategies for discussion moderation and course learning objectives.

We assessed the course's success by administering pre- and post-course surveys designed to measure student comprehension of the major topics. Preliminary data show marked improvement in student ability to articulate the features of science, discriminate nonscience from science, and construct experimental and/or inductive research designs.

To date, relatively few students have pursued their Scientific Process proposals as senior thesis topics, primarily because of difficulties associated with faculty support of such diverse research programs. However, those who have based their senior thesis work on their Scientific Process proposal design have exhibited unusual success. One student, for example, had her research on the status of an endangered orchid funded by local government agencies and pursued this work under the supervision of the state fish and wildlife agency. The proposal itself garnered national attention after being published in a college journal and was chosen by the Scott Foresman Research Web as an example of how to do research in college (Hariston, Ruszkiewicz, and Friend 1999).

## Conclusions

In 4 years, Scientific Process has been taught eight times. From this experience, it is clear that the majority of student objectives are being met through the course design (Web Figure 1, see Editor's Note). The most difficult elements to evaluate are those that primarily extend beyond the scope of undergraduate education, such as fostering strong scientific ethics.

In recent exit interviews, students have commented that the course helped them understand the process of science, gain more confidence in their ability to critically evaluate information, and prepare a written argument. Feedback from faculty members supervising student research indicates a strong relationship between performance in this course and quality of subsequent research activities.

Although Scientific Process is designed as a stand-alone course, we recognize the difficulties other science programs might have in accommodating a new course of this type. In such situations, programs should consider incorporating certain learning outcomes within the context of courses already required of their students. As long as the outcomes are sequenced logically, the entire package can be achieved through a 2- to 4-year curriculum. For example, a consideration of the philosophy and methodology of science should occur early in a student's tenure, perhaps in an introductory level course. The ethics of science and scientific practice must occur much later, after students have practiced science and read primary journal articles. If students are required to conduct a senior research project, asking them to prepare and defend a research proposal is a logical milestone. Alternatively, the preparation of a proposal could be an upper division course's capstone experience.

### Editor's Note

NSTA members can access the web figure via the online version of this article. Please go to *www.nsta.college*, scroll to the bottom of the page, click on this article, and the live link will take you to the web figure.


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### References


Chalmers, A.F. 1982. *What Is This Thing Called Science?* St. Lucia, Queensland: University of Queensland Press.

Gould, S.J. 1985. *The Flamingo's Smile—Reflections in Natural History*. New York: W.W. Norton and Company.

Hariston, M., J. Ruszkiewicz, and C. Friend. 1999. *The Scott Foresman Handbook for Writers*. Boston: Addison Wesley Longman.

Hull, D. 1988. *Science as a Process*. Chicago: University of Chicago Press.

Janick-Buckner, D. 1997. Getting undergraduates to critically read and discuss primary literature: Cultivating students' analytical abilities in an advanced cell biology course. *Journal of College Science Teaching* 27(1):29–32.

Keeports, D., and D. Morier. 1994. Teaching the scientific method. *Journal of College Science Teaching* 24(1):45–50.

Kuhn, T.J. 1962. *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press.

Lindell, T.J., and G.J. Milczarek. 1997. Ethical, legal, and social issues in the undergraduate biology curriculum. *Journal of College Science Teaching* 26(5):345–349.

Popper, K. 1979. *Objective Knowledge*. Oxford: Oxford University Press.

Popper, K. 1985. *Realism and the Aim of Science*, *Volume I*, *Postscript to The Logic of Scientific Discovery*. New York: Routledge.

Ruse, M., ed. 1996. *But Is It Science? The Philosophical Question in the Creation/Evolution Controversy*. Amherst/New York: Prometheus Books.

Sagan, C. 1996. *The Demon Haunted World: Science as a Candle in the Dark*. New York: Ballantine Books.

Stanley, S.M. 1989. *Earth and Life Through Time*. New York: Freeman Press.

Swazey, J.P., M.S. Anderson, and K.S. Lewis. 1993. Ethical problems in academic research. *American Scientist* 81:542–553.

Whewell, W. 1999. *Philosophy of the Inductive Sciences*: *Works in the Philosophy of Science 1830–1914*. Bristol: Thoemmes Press. Reprint of the 1840 edition.