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ARTICLE

A Rationale and Outline for an Undergraduate Course on the Philosophy and History of Science for Life Science Students

Philip E. Hockberger[1] **and Richard J. Miller**[2]

Departments of Physiology[1] and Molecular Pharmacology and Biological Chemistry[2] and the Institute for Neuroscience[1,2], The Feinberg School of Medicine, Northwestern University, Chicago, IL 60611

There are compelling reasons for teaching a philosophy of science course to undergraduate life science students. The main reason is to help them understand that modern science is not based upon a single, consistent philosophical system; nor is it based upon common sense, or a method, set of rules or formulas that can be used to make unerring predictions. Rather, science is a dynamic *process* that is constantly being modified and refined to reflect and encompass an ever-expanding set of hypotheses, observations, and theories. To illustrate these points, we developed a course that examined the history and philosophical underpinnings of modern science, and we discussed famous experiments that challenged the prevailing norm and led to Kuhnian revolutions in scientific thought. Building upon this knowledge, students investigated how different philosophical systems address controversial social issues in the biological sciences. They examined the teaching of intelligent design and creationism in public schools, the implications of legalized abortion and physician-assisted suicide, the potential impact of DNA fingerprinting on human rights and racism, the promise and pitfalls of stem cell research, and the neurobiological basis of consciousness and its relevance to mental health therapies and the animal rights movement. We believe undergraduate life science students should be exposed to these issues and have an opportunity to develop informed opinions about them before they graduate from college. Exploration of such topics will help them become better prepared for the inevitable public debates that they will face as science educators, researchers, and leaders of society.

Key words: natural philosophy; idealistic philosophy; process philosophy; case studies; social issues; science education

The daily life of a scientist is all too often isolated in thought and deed from the rest of society. Since most of our colleagues understand the importance and relevance of our work, we quite naturally assume that everyone else does or should. Unfortunately, this is an error that creates an even larger schism between scientists and society. We routinely hear politicians and supporters of science clamor for better communication between scientists and the general public (e.g., Leshner, 2005). Yet, few scientists are comfortable or prepared to follow this advice, thereby leaving a gaping hole in the public education of science.

In order to address this concern, we developed a graduate level course at Northwestern University to help students understand the philosophical foundations of science and their implications regarding a host of social issues impacted by developments in the biological sciences. We believe this course, with only slight modifications, could be made suitable for undergraduate students majoring or minoring in life sciences. In addition, it could be easily modified to accommodate students in the physical or social sciences.

There are many reasons for including a philosophy of science course into an undergraduate life science curriculum. The most obvious reason is to provide students with a philosophical foundation for their interest in science and an appreciation of the unique conditions that fostered its development. The foundation of modern science is embedded in Western civilization; in particular, in classical Greek philosophy and science (Irby-Massie & Keyser, 2002) and the medieval sciences of alchemy and astrology (Page, 2003; Newman, 2004). The Protestant Reformation of Christianity was another factor that helped to propel science to the forefront of intellectual development in Europe (Duffin and Strickland, 1990).

While there is evidence of scientific practices in ancient Egypt, India, China, the Middle East and Mesoamerica (Graham, 1973; von Soden, 1985; Teresi, 2002), their connection with modern science is tangential and discontinuous. Of course, civilizations do not exist in a vacuum, and ancient Greek culture was certainly influenced by many of the surrounding cultures, most notably those of Persia and India. Thus, another major reason for teaching a philosophy of science course is to stimulate interest in other cultures and to highlight their interdependence. The latter will foster integration with other academic disciplines including history, anthropology, philosophy, foreign languages, and education.

Another impetus is the growing number of graduate programs at universities in the history and philosophy of science (www.philosophylists.info/HPSDepartments.html). Exposing undergraduates to these ideas can help them make informed decisions about whether such programs might be appealing to them. The graduates of these programs are in a unique position to help frame the public debate concerning the role of science in society.

Life science teachers at religious institutions (high schools and colleges) are also likely to benefit from a philosophy of science course. Their students may be predisposed to view science with skepticism or hostility (Struthers, 2003). A strong philosophical foundation could help teachers come to grips with the impact of modern science on religious and ethical beliefs. As we show in this report, it can also provide context for such beliefs.

COURSE OUTLINE

Our course outline is presented in Table 1, and it had two parts. The first part began with a discussion of the historical roots of science in Greek philosophy and medieval science. This was followed by an exploration of the philosophical foundations of modern science. Three distinct philosophical traditions were identified with different biases (perspectives) and assumptions (axioms) leading to different predictions (hypotheses) – see Table 2. Case studies 1 and 2 were used to explore important discoveries that forced some scientists to abandon the prevailing system and develop an alternative. We describe these discoveries in greater detail below in the section on Case Studies.

Part I. Foundations of Modern Science
Topic 1: Historical Roots
Topic 2: Rise of Natural Philosophy
Topic 3: Emergence of Natural Science
Topic 4: Case Study 1 – see Table 3
Topic 5: Rise of Idealistic Philosophy
Topic 6: Emergence of Quantum Physics
Topic 7: Case Study 2 – see Table 3
Topic 8: Consistency and Completeness
Topic 9: Rise of Process Philosophy
Topic 10: Emergence of Psychological & Social Sciences
Part II. Social Issues in the Biological Sciences
Topic 11: Case Study 3 – Darwinian Evolution
Topic 12: Intelligent Design & Creationism
Topic 13: Case Study 4 – Origin of Life
Topic 14: Abortion & Physician-assisted Suicide
Topic 15: Case Study 5 – Eugenics
Topic 16: Human Rights & Racism
Topic 17: Case Study 6 – Immortality
Topic 18: Cryogenics & Tissue Replacement Therapies
Topic 19: Case Study 7 – Consciousness
Topic 20: Animal Rights & Mental Health Therapies

Table 1. Course Outline. These topics were selected for a quarter course that met twice a week for two hours per meeting (40 hrs total). For a longer semester course, one could lengthen the time devoted to case studies or include additional topics in Part II.

The second part of the course focused on social issues impacted by the biological sciences. Again, we used case studies to introduce a topic (e.g., Darwinian evolution) that related to a social issue (e.g., teaching of intelligent design in public schools). Each case study was followed by an open discussion of different viewpoints on the social issue. This part of the course could be easily changed to emphasize issues impacted by the physical or social sciences. For example, a case study on atomic energy could cover the basics of nuclear chain reactions and how the energy is captured, stored and transformed into useful energy. This could be followed by a discussion of the advantages and disadvantages of nuclear power versus coal or electric power. The goal is to start by reviewing the relevant science on a topic and then use it to form the basis of an informed discussion about the issues.

PHILOSOPHICAL SYSTEMS

One of the most important lessons in the course was the recognition that modern science is *not* based upon a single philosophical system. Rather, it encompasses several traditions: natural, idealistic, and process philosophies. Natural philosophy (not to be confused with nature philosophy, an offshoot of German romanticism) is a system based upon the belief that sense perceptions and experience are the most dependable means of obtaining knowledge. This approach can be traced to Aristotle, but it gained its current formulation with the studies of Galileo Galilei, William Harvey, Rene Descartes, and Isaac Newton during the 16^{th} and 17^{th} centuries. Their work inspired radically new ideas about the relationship between humans, God and Nature.

Natural science, derived from natural philosophy, is based upon the idea that knowledge can be obtained through a process of testing alternative hypotheses. That is, by using analytical techniques and inductive reasoning (inference), one can derive relationships that range from the most likely to the least likely explanation. This "scientific method" approach was bolstered by philosophical arguments underlying empiricism, physicalism (materialism), evolution, existentialism, and logical positivism. It also spawned the Industrial Revolution.

In spite of the unqualified success of natural science, there are problems in science that cannot be adequately explained within this system. One of the most vexing problems is the wave- and particle-like properties of light. This dual explanation is an unsatisfactory compromise devised to explain results which neither wave nor particle models alone can explain. The crack in the armor of natural science widened in 1900 when Max Planck proposed a quantum theory to explain black-body radiation. His theory assumed that light energy exists in discrete (quantized) states without intermediate states. The possibility of excluded energy states was, needless-to-say, totally unacceptable to many scientists and conflicted with the continuous, orderly states predicted by classical (Newtonian) physics.

Over the next 30 years, a scientific revolution occurred that produced a more detailed theoretical foundation and strong empirical support for Planck's idea (Gamow, 1966). This revolution eventually led to the creation of an entirely new field of science called quantum physics. This new field was first and foremost a theory-based discipline giving it a different philosophical foundation than classical, method-based physics (Ghirardi, 2004).

Quantum physics is grounded in idealistic philosophy with a fundamentally different worldview (Table 2). This view purports that introspection (ideas, intuition, mathematical certainty) is the most reliable means for obtaining true knowledge. Unlike natural philosophy,

	Natural Philosophy	Idealistic Philosophy	Process Philosophy
1st Principles: (perspectives)	Sense perceptions Inductive reasoning	Introspection Deductive reasoning	Both Both
2nd Principles: (axioms)	Only physical states exist (physicalism) Reality is objective (empiricism) There is a first cause	Metaphysical states exist (idealism) Reality is subjective (rationalism) Cause-effect is a complementary state	Existence is an emergent process Reality is social & historical Cause-effect is a relationship
3rd Principles: (hypotheses)	Universe is deterministic Causality is local Impersonal laws govern	Universe is discontinuous & probabilistic Causality is global Laws are approximations, not absolute	Universe is organic (evolving) Causality is multidimensional Emergent process obviates laws
Disciplines:	Biology, Chemistry, Geology, Classical Physics & Relativity	Quantum Physics	Psychological & Social Sciences

Table 2. Philosophical Systems. The first, second and third principles are listed for three distinct systems underlying modern science.

idealistic philosophy allows metaphysical speculation, and in the extreme case, it places greater emphasis on metaphysical states than physical states. This philosophical approach can trace its roots to Plato, but it was invigorated during the 17th century during one of the most innovative periods in mathematics since Pythagoras and Euclid. It stimulated new ideas underlying rationalism, idealism, neo-romanticism, nationalism, and utilitarianism.

The emergence of a new scientific worldview produced a rift within the scientific establishment that persists to this day. Nowhere was this rift more apparent than in the relationship between Albert Einstein, the champion of natural science, and Niels Bohr, the soft-spoken leader of the quantum revolution (Peat, 1990). Together with Werner Heisenberg, Bohr developed the Copenhagen Interpretation of Quantum Mechanics that remains the standard explanation of quantum physics. It is based upon Heisenberg's Uncertainty Principle, and states that the existence of subatomic particles (and everything comprised of them) is merely hypothetical until the moment of measurement. In this view, energy and matter do not exist in pre-configured states. Photons are neither waves nor particles *until* they are measured, and the act of measurement itself helps to define what is observed.

This idealistic view of science sent philosophers and historians into a collective frenzy. By the time the dust settled, a third scientific worldview emerged called process philosophy (Rescher, 1996). Derived primarily from the ideas of Alfred North Whitehead, this philosophical system encompasses the first principles of both of the other systems. Its second and third principles, however, offer unique views of how to interpret the world (cf. Table 2). By emphasizing that science is a *process*, rather than a method or a set of mathematically derived relationships, this worldview expanded the definition of what constitutes a scientific discipline.

Although resistant at first, an increasing number of scientists have come to see the merits of process philosophy and its emphasis on emergent properties, historical and social context, evolving systems, and multidimensional analyses of causation. This does not mean that the other systems have been superseded. They are still useful for understanding many aspects of the world, though not all aspects. By exposing students to the various philosophical systems underlying science, they developed a deeper, more mature appreciation of what it means to say that something is "scientific."

Introductory Topics	Advanced Topics
Case Study 1:	
Galileo's falling bodies experiments	Absolute v. Relative time Multiple universes
Michelson & Morley's speed of light experiments	
Case Study 2:	
Planck's analysis of black-body radiation	Entangled photons Gödel's theorem Superstring theory

Table 3. Case Studies on Scientific Revolutions. These are possible topics for case studies in Part I of the course. Selections for introductory and advanced topics will depend upon the previous coursework of the students.

CASE STUDIES

An invaluable part of the course was the student-led case study, modeled after the "investigative" case study approach to learning (Waterman, 1998). Students selected a topic from a list we prepared, researched it, and then presented it orally to the class. Cases were divided into two types: those related to scientific revolutions (1 and 2), as defined by Kuhn (1962), and those related to social issues (3 thru 7). Table 3 lists the revolutionary type segregated into introductory and advanced topics. The choices for case study 1 represent challenging ideas within natural science, and those for case study 2 address comparable ideas within quantum physics. In each case, students had the opportunity to discuss experimental results at the boundaries of the respective philosophical system.

The introductory topics in Table 3 focus on the work of Galileo, Michelson & Morley, and Planck that defy common sense and led to scientific revolutions. While Newton's Universal Laws of Motion accounted for Galileo's results, they too were not based upon common sense (Halloun and Hestenes, 1985a,b; Viennot, 2001), nor was Einstein's Theory of Special Relativity that took account of Michelson and Morley's results. By examining topics like these, students had the opportunity to come to terms with the realization that (1) modern science is not based upon common sense, and (2) some experimental results cannot be understood within the prevailing scientific worldview.

The advanced topics in Table 3 are among the most awe-inspiring ideas to emerge from 20th century science. The physics and math background needed to comprehend these ideas may be more suitable for graduate students, but they are worth discussing in an undergraduate course if only to wet their appetite for graduate school.

One of the long-term goals of science is to produce a complete, consistent description of the universe. Complete means a description that works under all conditions, and consistent means without contradictions. The advanced topics in Table 3 address these issues and help students to appreciate that none of the prevailing worldviews have been able to satisfy both conditions. This insight should enable them to understand the limitations and fluidity of science.

Case Study	Biological Topic	Social Issue
Evolution	Darwinian v. Lamarckian	Intelligent Design Creationism
Origin/End of Life	Pre-biotic soup Apoptosis	Abortion, in vitro fert. Physician-assisted suicide
Eugenics	DNA fingerprinting MitoDNA, Y chrom.	Human rights Racism
Immortality	Stem Cell Biology Tissue preservation	Tissue replacement Cryogenics
Consciousness	Split brain studies, Schizophrenia Animal behavior	Mental health therapies Animal rights

Table 4. Case Studies on Social Issues. Listed are examples of biological topics that impact contemporary social issues.

SOCIAL ISSUES

For this part of the course, students prepared a case study on one of the biological topics in Table 4 and presented it to the class. This was followed by an open discussion of the related social issue during the next class. Some students chose to present a case individually, while others preferred to work in pairs. For example, two students in our course shared the case on evolution by doing a comparison of Darwinian and Lamarckian views. After describing the original theses, one discussed the evidence for mutation as the driving force behind natural selection (neo-Darwinism), while the other presented several modern discoveries that could be interpreted as evidence for Lamarckian evolution, e.g., environmentally induced mutation, epigenetic mechanisms and prions. This dual approach to a topic allowed students to examine more than one view and facilitated a lively discussion.

The discussion on evolution made it clear that there is still considerable debate among scientists when it comes to the mechanism underlying evolution. This case provides a valuable lesson regarding the process of science and how it handles disagreement. While the process of science is grounded in theory and experimentation, it is also a social process with the same ambiguities and limitations that accompany other social activities. This is a useful reference point for comparing the teaching of evolution alongside alternative ideas, e.g., intelligent design and creationism.

A discussion of the pros and cons of teaching evolution, intelligent design, and creationism in a science course requires an appreciation of the philosophical underpinnings of each topic. While Darwinian evolution is firmly within natural philosophy, a more expansive view of evolution, e.g., cosmological, is more in line with process philosophy. Thus, evolution can be viewed from different philosophical perspectives and still be considered scientific.

Intelligent design is the belief in a supernatural influence on the creation of the universe that reflects intention and purpose. While this view has clear religious or spiritual overtones, its metaphysical basis is compatible with idealistic philosophy and, therefore, could be considered scientific. Currently, it lacks the requisite mathematical formulation and experimental support that distinguishes quantum physics from mere speculation. The important point, though, is that intelligent design is no more incompatible with science than any other idealistic concept including beauty, morality and justice. None of these ideas, however, presently has a framework that would allow it to be considered a scientific topic.

Characteristic	Science	Western Religions
Social Structure	Socialistic	Authoritative
Subject Matter	Nature	Sacred literature
Philosophy	Theoretical	Doctrinal, Legal
Verification Technique	Experimentation	Tradition
Conflict Resolution	Peer review	Decrees, Encyclicals

Table 5. Basic Characteristics of Science and Religion. Listed are five characteristics that distinguish modern science from Western religions.

Creationism, by comparison, is the belief that the origin and purpose of the universe is contained in sacred writings. This view is not compatible with any of the philosophical systems underlying modern science. In fact, it is a product of an entirely different worldview. The emphasis of Western religions (i.e., Judaism, Catholicism, Islam), in particular, on sacred literature, legal codes, and tradition sets them apart from modern science (Table 5). Creationism, which is grounded in Western religions, is not a scientific theory and does not belong in a science curriculum. Teaching it would create confusion in a science classroom.

As with evolution, the other cases listed in Table 4 were handled in a similar fashion, i.e., presentation of a biological topic followed by discussion of the relevant philosophical and social issues. While we chose to cover a broad range of social issues, one could choose instead to focus on select topics within a discipline, e.g., evolutionary biology or the neurosciences. The latter might include discussion of the mind-body problem, nature-nurture controversy, philosophical ideas about consciousness, and the social implications of mental health therapies and animal-based research. Clearly, there are a vast range of topics that could be integrated into such a course.

STUDENT AND COURSE ASSESSMENTS

Students were graded independently by two instructors who based their assessment on three measures: class participation (50%), presentation of a case study (25%), and a written report on the case study (25%). The first measure was highly subjective and intended to encourage students to ask questions and express opinions that facilitated group discussion. Students were rewarded for asking insightful questions and displaying critical thinking. The second and third measures allowed us to evaluate student performance using more objective criteria. The latter included oral and written communication skills (grammar, syntax, vocabulary), mastery of subject matter (literature review, accuracy of presentation, depth of understanding) and ability to integrate the different philosophical perspectives into their discussion. Their final grade was derived by consensus between the course instructors.

Although this form of student assessment is not as objective as traditional exams (essay, multiple-choice), it is appropriate for this type of learning environment that offers the possibility of better retention of the material (Dods, 1997). It also helps to build information gathering and communication skills that are valuable and often under-appreciated in science curricula. Another advantage of this approach is that it helps students build a portfolio of work, e.g., reports and publications, that will help them obtain employment and advancement in a science career.

Course assessment was performed using a standardize course evaluation form organized and distributed by the Integrated Graduate Program (IGP) at our university. The form asks students to evaluate course content (goals, format, materials), instructors, and testing methods. It also asks what students liked and disliked about a course and requests suggestions for ways in which it could be improved. Students filled out the forms anonymously and returned them to the course director. Copies were provided to the IGP for administrative purposes.

Course evaluations indicated that students enjoyed having two instructors with different yet complimentary styles who kept the discussions lively and on target without stifling participation. They were impressed with the breath of the course and found the class handouts and reading materials helpful and informative. They appreciated the amount of preparation required for each topic, and this was reflected in their conscientious efforts in preparing their case studies. Some felt the small class size (12) fostered an atmosphere of mutual respect for divergent opinions and contributed to the success of the course.

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Address correspondence to: Dr. Philip E. Hockberger, Department of Physiology, The Feinberg School of Medicine, Northwestern University, 303 E. Chicago Ave., Chicago, IL 60611. Email: p-hockberger@northwestern.edu

Science is nothing but trained and organized common sense - Thomas H. Huxley (1870)
Le sens commun n'est pas si commun (Common sense is not so common) - Voltaire (Francois-Marie Arouet, 1764)