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A first course in the history and philosophy of science

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Abstract. A philosopher (WR) and a physicist (KF) have been team teaching a history and philosophy of science course every other year over the past twelve years at Indiana University Southeast. Our approach has been to spend about half the semester talking about the development of the Sun-centred system of Copernicus, covering some important developments in astronomy and physics during the period from Copernicus until Newton's death. The second half of the course examines modern views of scientific method, the scope of scientific knowledge, and observations about science and values put forth by various philosophers (for example, Popper, Ziman, Thagard, Carnap, Hempel, Quine and others). Students are asked to write essays critiquing these philosophical views using historical examples from the earlier readings as support for their arguments. The last time we ran the course we placed the papers (anonymously) on the web and had participants in the class make suggestions to each other on improving the essays of their fellow students. We feel this was a valuable exercise and intend to try it again. Our paper includes a discussion of our method and a sample of issues raised.

1. Introduction

The goal of the course we describe here is to examine differing philosophical opinions of what constitutes science and scientific method and compare those ideas to a well known historical example which most scientists and philosophers can agree as exemplifing good science. As we discuss in the course and this paper, an accurate and precise definition of science and scientific method is difficult to formulate. Most scientists will admit that science historically has rarely followed the naive 'scientific method' exemplified by a rigid procedure consisting of hypothesis, testing, publication and acceptance. History shows us instead that important scientific discoveries more often have a serendipitous component involving informed guesses and dumb luck rather than following a formalized procedure which is laid out in advance. Scientific discoveries also occur in and grow out of a cultural milieu and are thus affected by social factors. The objective of the course is to examine these kinds of questions and thereby help our students to develop reasonable perspectives on science and scientific method.

We have conducted the undergraduate seminar described here every other year for the past twelve years with a typical enrollment of between ten and fifteen students. We prefer to have students who have had at least one science course and one other philosophy course at undergraduate level, but the course is open to all interested parties. Students enrolled in this class typically have had at least one science course but most are not science majors and it is seldom the case that they have all had an identical or even similar exposure to science. So we cannot assume much in the way of common knowledge at the beginning of the semester. Even the students who have completed several semesters of study in one or more of the sciences

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often have not picked up more knowledge about scientific method than is required for setting up some fairly simple experiments and interpreting results in their lab sections.

On the assumption that to discuss science intelligently it helps to know something of what one is talking about, we devote the first six weeks of the semester to studying some of the well known scientific activities of astronomers and physicists during the Copernican revolution. This provides the students with some shared knowledge of an extended period of scientific activity during which a great deal of progress was made. During the rest of the semester we make use of this study as a basis for examining and assessing various claims made by philosophers of science about scientific explanation and prediction, laws and theories, technology, the roles of observation and testing in science, the speculative and creative aspects of science, science and values, and other matters. Again, our purpose is to help our students improve their understanding of what science is and how it is related to other human activities.

The main texts in the course are T S Kuhn's *The Copernican Revolution* [1] and *Introductory Readings in the Philosophy of Science* [2], a collection of essays by 20th century philosophers of science edited by E D Klemke, R Hollinger, D W Rudge and A D Kline. These are supplemented by readings in the history of science placed on reserve in our library for the semester.

One student is designated to lead our discussion of each assigned reading and provides notes and introductory comments for that chapter or essay at the meeting during which it is discussed. In addition to the classroom presentations the students write three essays and a final examination. Potential essay questions for the final are handed out in advance so that some preparation can be made on the students' part.

2. The Copernican revolution

We start the course with a very brief introduction to the characteristic which makes the ancient Greeks the true forerunners of modern scientific thought. A salient feature of early Greek thought is the idea that progress in the world of ideas can be achieved by first learning then correcting and improving on the thoughts of your teachers. This is apparently a feature unique in the ancient world to Greek thought and has become a hallmark of modern science.

After this initial introduction of early Greek thought we begin with a careful study of the two-sphere universe of Eudoxus and Aristotle in Thomas S Kuhn's *The Copernican Revolution*. From that model we trace in a fairly detailed way the various permutations and modifications which lead up to Kepler's final improvements of Copernicus' Sun-centred model. We end our historical discussion with a brief examination of Newton's synthesis of celestial and Earth-bound mechanics.

We believe it is important for students to get a feel for some of the technical problems facing earlier astronomers and the attempts to solve them. How did the ancient two-sphere universe develop and become the basis for Copernicus' heliocentric model? What features were not explained by the two-sphere picture of the universe? What kinds of observations were available to the ancients and how precise were they? How exactly did Eratosthenes measure the diameter of the Earth? What was the precision of measurements made by Tycho Brahe as compared to ancient calculations? Why were epicycles, deferents, equants and eccentrics introduced into the two-sphere universe and how good were the results? Are there any direct, naked-eye observations which preclude a model of the universe that has a stationary Earth at the centre?

It is also important to help students to gain some understanding of what was at risk with a shift from an Earth-centred universe to a Sun-centred one. Not only did astronomical observations have to be seen in a new perspective but most of ancient physics had to be abandoned. Aristotle claimed things fall towards the Earth because its centre is the absolute centre of the universe and it is the nature of Earth-like materials to move towards that point. If the Sun was now to be the centre of the universe a new physics of falling objects had to be invented. In addition, Copernicus' model was not proven to be more accurate than Tycho

Brahe's until Kepler modified it to have elliptical orbits over half a century after Copernicus' death. As this latter example shows, any explanation of how science develops must incorporate external factors beyond naive arguments based on accuracy.

Thus there were good scientific reasons outside of astronomy for rejecting Copernicus' heliocentric model. In order to highlight this fact, we raise the sorts of questions in class that were raised by Ptolemaics at the time: Why doesn't the Earth fall into the Sun if the latter is **A** at the centre of the universe? And if the Earth is orbiting the Sun at high velocity, why don't we fall off of it? Answers offered by our students generally depend upon notions of inertia and gravity which were not available to astronomers and physicists until Newton's time. Our intent in the historical readings is to provide the student with an accurate, detailed example of science being done well by a community of scientists over a significant period of time. We also spend some time on the problems Copernicans had with people outside the scientific community—in particular the Catholic and Protestant churches.

Again all of this is intended to serve as grist for our mill when we turn to our philosophical readings later in the semester. In recent decades a number of philosophers of science have come to see scientific method as best defined not as a method which individual scientists follow, but as a set of rules and procedures which defines a community. To be a member of this particular community is to be a scientist. When we discuss these views we can expect to have to address several issues which our historical readings may help us to deal with: What are the membership requirements for this community? What are the goals and commitments of the scientific community, and how are these connected with the goals and commitments of the individual scientists who are members of it? What role, if any, does the wider community (the general public) have in science? Scientists are also members of other communities and they may have commitments which are not commitments of the scientific community and which might even conflict with them. Galileo, for example, was a Catholic as well as a physicist and as a result experienced conflict of loyalty between two communities. A parallel modern example might be the conflict felt by many scientists who are also members of business communities, such as the pharmaceutical industry, where the free inquiry of science is restricted because of patent issues.

Tycho's elaborate equipment for increasing the accuracy of astronomical observations and, later, Galileo's telescope are also useful to cite when we turn to discussion of relationships between technology and theory building. Finally, the fact that Kepler (a Copernican) used a Ptolemaic's (Tycho's) data in support of his own theory of planetary motion is useful to consider when we discuss claims by philosophers as to the significance of the idea that observations are 'theory laden'. Does the fact that Tycho viewed the Sun as rising but Kepler viewed the Earth's horizon as sinking have any bearing on their attempts to compare astronomical observations they might have made? The (surely reasonable) idea that how people report their observations is affected by the beliefs they have about the world is sometimes cited in support of the view that such observation reports cannot be neutral to competing theories. Kepler's use of Tycho's data raises the question as to whether there is something wrong with this inference.

3. Readings in the philosophy of science

Once the class has spent some effort examining the historical development of what is considered to be a classic example of good science, we start reading various philosophers' views about what science is and how it works. Our first collection of essays tackles the problem of defining science; the problem of demarcation. We would hope that a good definition of science would enable us to include what is generally regarded historically as examples of good science but exclude certain types of pseudo-science such as astrology or pyramid power. To give the reader a flavour of the kinds of answers philosophers have posed for answering this question, **B** we briefly summarize three of the essays [2] read in the section of our course pertaining to the **C** definition of science.

The first essay we read on the demarcation problem is by Sir Karl Popper with whom many scientists have at least some passing familiarity. Popper claims that the distinction between science and non-science lies in the possibility that scientific theories can be falsified (that is, disproved). He demonstrates the dissimilarity between testable and non-testable theories by claiming that Freudian psychology is not scientific because it is an example of a theory which is non-testable. In Freudian psychology all cases of psychological disturbances can be accommodated by the theory; there is no conceivable occurrence which could arise which would prove the theory wrong. No matter what the psychological disturbance, the theory can interpret it. Freudian psychology explains too much according to Popper; all evidence confirms the theory with no possibility of disconfirmation. In contrast, Popper points out that the theory of special relativity, which originated during approximately the same time frame as Freudian psychology, makes very risky predictions. Special relativity predicts occurrences which can be measured and which, if not correct, prove the theory to be wrong. So according to Popper's essay the most important aspect of science which sets it apart from other non-scientific endeavours does not lie in confirmations of the various theories contending for scientific status but in the degree of vulnerability to testing inherent in the theories. A few of the difficulties with this idea will be discussed below.

A second approach to answering the question of what is science appears in an article by John Ziman. In this essay Ziman argues that the salient feature of science is consensus among the practitioners of science. He argues that scientific facts must be tested by a community of 'competent and disinterested individuals'. This implies that there is a social aspect to science; unlike art or technology, a single individual cannot 'do' science. For Ziman, the review process, beginning with peer review in a published journal followed by subsequent discussion and evaluation by the community at large, is the scientific method. Oversight of the content of what should and should not be considered science (achieving rational consensus) is a give and take process which requires complex social structures.

A third essay by Paul Thagard raises the point that astrology is testable (indeed there have actually been attempts to determine if there is any statistical correlation between star signs at birth and accomplishments later in life). Thus Popper's testability criterion is actually met by astrology and so it cannot exclude astrology as pseudo-science. In order to remove astrology from the ranks of scientific theories, according to Thagard, it is necessary to examine both the historical progress of the theory and the attitude of its supporters and practitioners. His conclusion is that it was quite reasonable (and within the bounds of scientific behaviour) for Kepler and Ptolomey (both of whom wrote about astrology and cast horoscopes) to believe that astrology was a scientific theory because there was no alternative theory of psychology which worked any better than astrology. Thagard goes on to argue that scientists today would be totally *un*justified in believing in astrology as a science because the theory has not made substantial progress since the time of Kepler and, additionally, the practitioners make no attempt to solve various problems currently facing the theory. This is in sharp contrast with astronomy which has shown very significant historical progress and whose practitioners are today trying earnestly to solve unfinished problems. For Thagard, science must be progressive, and to assess progress requires an historical perspective.

The examples above and other essays in the selections we read show that there is no consensus among philosophers as to a precise definition of science although many of the salient features of the scientific mode can be clearly stated. After concluding our discussion of what science is, we move on to consider additional collections of readings in the areas of scientific explanation and law, theory and observation, confirmation and acceptance, science and values, and measurement theory.

4. Assignments for the class

By the middle of the semester students have been exposed to a clear historical example of good science and have begun to examine questions about the nature of scientific method. We then ask them to write a series of essays comparing the ideas of various philosophers with the actual history of science they have read. The intent of the written assignments is to motivate the student to assess the views of each philosopher in the light of the factual history of science to determine if the views accurately reflect, or at least are consistent with, what scientists actually do. The following is the first of three essay assignments.

> Write a four to six page paper assessing the claim of Karl Popper (in Klemke, pp 19–27) that 'the criterion of the scientific status of a theory is its falsifiability'. The paper should be based on a careful reading of Popper and include historical evidence (from Kuhn's book) in support of your thesis (which may be in favour of or against Popper's claim).

We consider the following questions in grading papers.

(a) Did the paper show a thorough understanding of the following?
  (i) The portions of Kuhn and other readings in the history of science cited.
  (ii) The theses of the article in Klemke which was used.
(b) Was the assessment well done?
  (i) Was the assessment interesting (non-trivial) and well thought out?
  (ii) Were theses in the article clearly supported or refuted by appropriate citation of Kuhn and others?
  (iii) Could a stronger case have been made by citing more?
(c) Were any organizational and mechanical (grammar, spelling, etc.) hindrances to the clarity of the paper minor, or were they so bad as to get in the way of communication?

Surely Popper's ideas about the testability of science have some merit. However, there are many points which can be brought up in an analysis of his essay and we discuss several of these in class. The following is a partial list of the kinds of things we expect students might consider in a critique of Popper's article:

(a) How much testing is necessary? At some point most scientists begin to regard a theory as true, quit testing it and put the theory in the textbook, but Popper doesn't tell us when to stop. In Popper's view, scientific theories can only be tentatively true since the possibility of further testing is never closed, yet most scientists seem to regard certain theories as correct. A related question is the problem of accuracy. All scientific measurements have some experimental error. So how exact do the results of the test have to be in order to qualify as a valid test?
(b) According to another essay we read, theories are bundled. Most theories are tested using or against pre-existing theories. We assume the theories governing the behaviour of voltmeters are perfectly correct when we use the voltmeter to test theories about quarks in an accelerator. Popper's article does not indicate how to proceed in the case where several theories are intertwined.
(c) What do we do with theories which have been proven wrong? Much of what Galileo said and did has been tested and shown to be wrong. Would Popper have us dismiss Galileo (or any other early scientist) as having done no science or bad science since he has been proven wrong? In general, Popper's view does not address the question of how it can be seen as progress for one incorrect theory to replace another incorrect theory.
(d) It is pointed out in Ziman's essay that science requires consensus. Popper does not elaborate on the question of who or how many people must agree that a theory has or has not been falsified, yet the history of science clearly shows it to be a community project.
(e) We would like theories to have an explanatory function as well as a predictive one. Yet Popper's essay does not include any comments to this effect.
(f) Do scientists always discard incorrect theories even after they are falsified? History shows us that scientists sometimes hold onto theories that are clearly problematic because there is nothing better available at the time. Likewise, some incorrect theories (Newton's laws, for example) work well enough in many situations so it seems entirely justified to keep them in the textbooks.

(g) Which ideas are worthy of testing? Contrary to much public perception, science is an extremely creative process. A great deal of creativity goes into deciding exactly which theories to test, what makes a good test of the theory and how the data should be gathered, but Popper doesn't tell us how to evaluate those issues. As the editors of our textbook ask, is a detailed examination of the correlation between umbrellas and their existence and use in Manhattan an example of science? It would seem that such a project could, if carefully defined, fit under Popper's criteria yet somehow we know it is not science.

(h) Do you have to participate in the falsification process to be a scientist? Some scientists (Einstein, for example) do no experiments. Does that mean they are really not scientists according to Popper's essay?

We pursue these and other issues in further readings and discussions throughout the rest of the semester.

5. Online peer review of student papers

E We ask students to turn in two versions of their papers. Each of us reads the first version of each student paper and, without consulting the other, writes comments on the paper and assigns a tentative grade. Then we meet to discuss each paper. Our experience has generally been that we have nearly identical ratings of the papers and very little compromise or modification of our individual evaluations needs to be made to arrive at a single, jointly awarded grade for each paper.

We allow students to rewrite the first paper for an improved grade after they have received feedback in a conference with us. In the past, the feedback consisted exclusively of these meetings, and the written comments we made directly on the papers. Two years ago, however, we decided to encourage feedback from other students in addition to our criticisms. To do this we set up a Web page where student papers were posted (names were removed). Other students in the class were invited to read the draft papers and add comments with the intent of helping the author improve the paper. Comments were solicited from student groups outside our class enrollment through a request to instructors on the Phys-L physics teachers listserv (we did not, however, receive any comments from this source).

There were some unanticipated difficulties with this approach. For example, in our initial round of student criticisms we found the students were too harsh in their critiques and some students felt somewhat demoralized as a result. In using this method of peer review in this and other courses, we have come to realize that it is exceedingly important to give the students some guidance before asking them to make comments on other students' papers. Lacking this, even students who are capable of writing nice tightly argued papers are liable to offer glib or dismissive remarks rather than well thought out criticism when they are reviewing the work of other students. We now spend several minutes of class time explaining the purpose of peer review in the academic environment. The enterprise of scholarship is one that, like science itself, depends on critical review and dialogue, and this has become an important part of the learning process in our course. In the future we intend to share examples of reviewers' comments on our own papers, which have been submitted to professional journals, as examples for our students.

6. Conclusion

Much like pornography, giving a precise definition of science and scientific method is problematic, yet scientists seem to know science when they see it. Working scientists are able to function adequately, perhaps even brilliantly, without addressing the sorts of questions
F our course focuses on. To paraphrase a remark of Aristotle, scientists, *qua* scientists, do not wonder what science is and how it is possible—they do it. But scientific knowledge seems to be the most secure of any we have at present and its methods are emulated in many other fields.

What is it about scientific method which makes it so successful? Why have scientists been so productive? Can the method be stated in such a way as to include the creative aspects of science? Can a method be elucidated which closely corresponds to the actual historical process which gave us this knowledge? Serious and sustained pursuit of these kinds of questions is possible, and worthy of interest whether we are scientists, students of science or simply laymen who are aware of the importance science has for the community at large. We feel our course is an important step towards pursuit of these questions and a valuable component of a liberal undergraduate education regardless of the student's major.

References

[1] Kuhn T S 1957 *The Copernican Revolution* (Cambridge, MA: Harvard University Press)
[2] Klemke E D, Hollinger R, Rudge D W and Kline A D (ed) 1998 *Introductory Readings in the Philosophy of Science* (Amherst, NY: Prometheus Books) 3rd edn