“Physics for Poets” — Teaching physics to non-scientists

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Abstract

Many US universities have a course intended to introduce physics concepts to non-scientists. Ideally, such courses are taught at a high intellectual level but use little or no mathematics. This note will discuss the philosophy behind such courses, and describe a particular course taught at Iowa State University in spring of 1993.

Introduction

Students at American universities choose to “major” in one or more subjects to be studied in detail. Physics courses for students majoring in physics, other physical sciences, or engineering emphasize formal theory, numerical work, problem solving, and laboratory experience [1]. However less than half of the material studied during a student’s time at university will be in the student’s “major” or in a supporting subject. The rest will be “General Education.” A student must select a minimum number of General Education courses from each of several groups. At Iowa State University, all students, whatever their major might be, are required to take two or three courses chosen from the “Natural Sciences” group, which includes physics and several other sciences.

Many general education courses offered by physics departments are just simplified versions of the more technical courses, with a similar emphasis on numerical problem solving. This may be the easiest approach to teaching a general education course in physics. It is often justified by a remark such as “anyone who cannot solve problems does not understand physics.” My experience suggests, however, that students can learn how to solve problems and still have no understanding of physics.

Is there a better way of teaching physics to someone whose major is in the humanities (literature, history, foreign languages, philosophy, music, journalism, etc.) or the social sciences (psychology, sociology, anthropology, economics, etc.)? These students often do not think quantitatively, but they may be highly skilled at analyzing concepts verbally. Most politicians, lawyers, teachers, and businessmen belonged to this group when they were students. Educated citizens in a democracy (perhaps especially politicians, lawyers, teachers, and businessmen) need some appreciation for science and technology in order to make rational decisions in life. However very few educated citizens ever need to solve numerical problems in elementary physics.

For these reasons, many American universities have introduced a different kind of general education physics course, emphasizing the concepts of physics with a minimum of mathematics and none of the traditional problem solving. Probably the first of these, and certainly the most famous, is the course “The Ideas of Modern Physics,” developed in 1963 at University of Wisconsin by Professor Robert March. This and similar courses elsewhere came to be known as “Physics for Poets.”

The targeted students are those who are likely to become leaders in a modern society dominated by science-based technology, but who themselves will have no great scientific or technological expertise. Such people will be responsible for major decisions involving important scientific or technological matters. They will have to depend on advice from professional scientists or engineers, who however, are not trained to consider societal issues, such as quality of life, the structure of society, politics, and economics. How should such decision-makers evaluate the expert scientific and technological advice on which they must depend? It is human nature for the expert to believe that his or her advice should take precedence over all other considerations, for after all is it not based on *science*? Yet the “best” scientific advice is different today from what it was thirty years ago, and it will be different again in a few decades.

With this in mind, what should be the goals of a course such as this one? First, let us say what goals are *not* appropriate. The ability to solve the equation of motion for a simple pendulum will not help either the President of Russia or her Parliament to make sensible decisions concerning the disposal of nuclear waste, or the appropriate amount to spend on high energy physics research, or any of the

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innumerable problems involving science or technology which face the country. Having once performed simple experiments in an elementary teaching laboratory will not help in deciding how much to spend on nuclear fusion research. Therefore a traditional problem-solving approach, with or without a teaching laboratory, is not the best approach. Neither does it help for society's and the nation's leaders to remember, with little or no understanding, a large number of unconnected physics "facts" from thirty years ago but to be totally ignorant of the developments in physics since then. Therefore it is also inappropriate to teach a superficial survey of much of physics, without developing an appreciation for the historical development or the logical structure of the subject. It is far better to follow the example of Victor Weisskopf, who would often say at the start of a course, "I will not cover the subject, I will try to uncover part of it." [2].

What then should one try to teach? I suggest the following, not necessarily in the order of their importance:

1. Students should learn that scientific understanding is not static, but has evolved through many centuries. For this reason, an appropriate physics course should emphasize how concepts have developed over time. Thus the teaching should respect the history of physics, without turning the course into one devoted to entirely to history.

2. Students should learn the importance of observation and controlled experiment. Thus where possible the instructor should perform demonstration experiments in front of the class. When this is not possible, one should describe historically important experiments. Whenever possible, this should be done using visual aids. In America there are some excellent laser disc collections which are useful for this purpose.

3. Students should learn to appreciate the role of rigorous rational analysis in developing an understanding of the physical world. Therefore there should be an emphasis on how concepts are developed, partly from the analysis of experiments and partly by imaginatively creative but nevertheless rational extrapolation from existing ideas.

4. Physics is highly quantitative. Therefore students should learn something of the relative sizes of things. For example, one could relate the energy scales in various fields of physics—human scale kinetic energies, energy in chemical reactions, nuclear energy, etc. Thus if every atom in a cube of ^{235}U the size of a sugar cube were to undergo fission, the energy released would be of the same order of magnitude as the kinetic energy of the whole population of China after falling from a height of 3 meters. Such unexpected comparisons grab the attention of students!

5. Students should learn to appreciate the role of mathematics in physics. Therefore one should not be afraid to use mathematical reasoning *at the level appropriate to the students*—typically elementary algebra and geometry—not as a substitute for a verbal presentation of the material but as supplement to it. Mathematics should not be used unless the instructor believes that the students can follow the argument without serious difficulty, and students should not be expected to reproduce mathematical reasoning in tests.

6. Students should learn that every experiment is subject to error, and that the numerical agreement between theoretical predictions and experimental measurement is rarely if ever exact. The instructor should try to show how physicists decide when disagreement should be ignored (at least temporarily), and when it is of fundamental significance.

7. Students should come to understand the unity of physics. The course should help them to appreciate the historical development of physics from a collection of disconnected topics towards a grandly unified understanding of the physical world.

8. Students should appreciate the aesthetic aspects of physics. This is best demonstrated by the enthusiasm of the instructor, who should attempt to explain *why* a particular experiment or a particular theoretical idea is "beautiful."

9. Last but by no means least, students should appreciate the extent to which physics is relevant to the environment in which we live. In industrialized nations, this is largely dominated by technology based on physics and other sciences. Try to imagine life in Moscow without electricity! Technology is rapidly changing traditional ways of life even in developing countries.

No "Physics for Poets" course will meet these goals in their entirety. The particular mix found in a particular course will depend on the personal biases of the teacher.

The course at Iowa State University

The version of "Physics for Poets" taught at Iowa State University is called "The Challenge of Contemporary Physics." It is taught at a somewhat more sophisticated level than is usual for such courses, since several general education courses are also offered at an elementary level. For this reason, students in the course are expected to have already completed at least one year of study at the university.

Since this course is not intended as a prerequisite for further study of physics, its structure and content may change from year to year. This article describes the course as taught by me in spring of 1993, immediately before my retirement from teaching. The general structure of the course is described in the preamble to the syllabus distributed to students at the beginning of the course, and reproduced as Appendix A. The numbers refer to the class periods, 45 in all, each lasting 50 minutes. Two of these were used for exams, the rest for lectures. There was also a two-hour final exam during a special week set aside by the university. In addition, students were expected to write an essay of about 2500 words on a topic which they had researched on their own. To assist students in this task, they were provided with an extensive annotated bibliography of "popular science" books and journals[2]. (The course instructor revises this each year to include recently published books and to remove books which are getting too dated.)

Because no previous study of physics is assumed, and because the course is advertised as finishing at an active research frontier, the presentation had to be strongly focused. In 1993, the research frontier chosen was the interpretation of quantum mechanics.

Lectures 1–15 began with classical mechanics and rapidly moved through narrowly selected topics in electriciy and optics to the beginnings of modern physics, the nuclear atom, Bohr's model of the hydrogen atom, and an introduction to wave mechanics. Robert March's *Physics for Poets* was the primary textbook for this segment, and was occasionally supplemented with printed materials prepared by myself. This segment included a considerable amount of historical development, including the contributions of Copernicus, Galileo, Brahe, and Kepler, leading up to Newton's mechanics. In the course of this development, I gave a simple (if not quite rigorous) derivation of the formula for centripetal acceleration ($a = v^2/r$), and used this, assuming circular orbits, to derive an inverse square law of gravity from Kepler's laws. Then a simple numerical calculation related terrestrial gravity to the period of the moon's orbit. This illustrated mathematical reasoning, the unification of apparently diverse phenomena, and the fact that observation and theory may be close but practically never agree perfectly! The treatment of quantum physics was also largely historical.

Intelligent students should remain skeptical about quantum theory after the rushed presentation in class periods 10–15. Therefore class periods 17–30 were used to study various applications of quantum physics, using M. Y. Han's *The Secret Life of Quanta* as the primary text, supplemented by additional printed materials. Among other things, this segment of the course was intended to demonstrate the importance of quantum physics in modern technology. However it also provided a place to teach some atomic physics and some solid state physics, with an emphasis on band theory. The lecture titles in the syllabus for periods 17–30, together with the questions in Exam #2 (included in Appendix B), give an overview of the topics discussed in this segment.

The final set of lectures — class periods 32–45 — dealt with the interpretation of quantum mechanics, using F. David Peat's *Einstein's Moon* as the textbook. The syllabus gives a good outline of how the subject was developed. Heisenberg's version of quantum theory gave an opportunity for developing more mathematics. Each physical quantity is represented by an array in which each entry is associated

[2]A copy of the 1993 bibliography may be requested by e-mail from dlpursey@mwci.net. Please request either LaTeX or postscript.

with a frequency. Although I did not feel free to use the complex exponential representation of the frequencies, it was quite possible to recreate Heisenberg's (re-)discovery of matrix multiplication, then to lead the class through non-commutation of quantum operators. The presentation of Schrödinger's version was necessarily more qualitative. In addition to the traditional "Copenhagen interpretation," the course briefly discussed David Bohm's "hidden variable" interpretation and Everett's "many universes" interpretation. The course concluded with an account of the very recent "quantum histories" interpretation developed by Robert Griffiths, James Hartle and Murray Gell'mann, and Roland Omnès [3].

How does one test what the students have learned in a course such as this? In America, students' learning is evaluated using written exams, usually with one or two during class periods, and concluding with a "final exam" during a week designated by the university for this purpose. A "term paper," researched and written in the student's own time, may also be required. In a course such as this, I believe that exams should involve no mathematics and should require the students to express their understanding of the subject in their own words. In the final exam I also wished to test the degree to which students could place what they had learned in the course in the broader perspective of human knowledge and human society as a whole. The exams that I created for the course in 1993 are presented in Appendix B. They give some idea of the intellectual level of the course.

In 1993 the class was small—only ten in number—and made up of students with a wide variety of majors. At Iowa State University, students are asked to evaluate each course at the end of the semester. Despite the challenging nature of the course, the student evaluations were very positive.

I concluded the final lecture with two quotations from Roland Omnès. I reproduce them here because they represent much of my own thinking about the adventure which we call physics.

> "... physics is not a complete explanation of reality, which would be its insane reduction to pure unchanging mathematics. It is a *representation* of reality that does not cross the threshhold of actuality."
>
> "... it is wonderful how quantum mechanics succeeds in giving such a precise and, as of now, such an encompassing description of reality, while avoiding the risk of an overdeterministic insanity."
>
> —Roland Omnès, Ref. [3], page 380.

Acknowledgment

I wish to thank Professor Robert March for information about the course that he initiated at the University of Wisconsin in 1963.

Appendix A: Syllabus

PHYSICS 302 SPRING 1993
THE CHALLENGE OF CONTEMPORARY PHYSICS
Instructor: Dr. Derek L. Pursey

Required Textbooks[3]:

1. Robert H. March, *Physics for Poets*, 3rd Edition (New York, 1992, McGraw-Hill Inc.)
2. M. Y. Han, *The Secret Life of Quanta* (Blue Ridge Summit, 1990, TAB Books)
3. F. David Peat, *Einstein's Moon* (Chicago, 1990, Contemporary Books)

Clientele: The course is intended primarily as a General Education elective for students in the humanities or social sciences, but it is open to all students. No mathematics or science prerequisites are assumed beyond the admission requirements for the College of Liberal Arts and Sciences, stated on page 100 of the general catalog. The course is intended to be challenging, however, and experience shows that it is unlikely to be suitable for freshmen[4].

[3]Brief descriptions of these books will be found in the Bibliography, available by e-mail on request from dlpursey@mwci.net.

[4]That is, first year students.

Style: The course can be regarded as a sophisticated "popular science" course. While this precludes some of the depth appropriate to a more technically oriented course, it permits the discussion of some topics at the frontier of current research. Instruction will be mostly by lecture, supplemented by lecture demonstrations, audio-visual aids, and class discussion.

Structure: The course as planned will fall into three major divisions. The first will present elements of "classical" physics necessary for the appreciation of quantum physics, which latter will be the main concern of the course. The second will survey the wide range of quantum physics and its many applications in modern technology. The final section of the course will deal with the interpretation of quantum mechanics and its revolutionary implications for our understanding of the nature of reality.

Grading: Grades will be based on two mid-term essay exams, a term paper, and a comprehensive final essay exam. All of the exams will allow a choice of questions. The topic for the term paper will be chosen by the student subject to some specified guidelines and the approval of the instructor.

Term Paper: A term paper of approximately 8 to 10 pages double spaced typescript and including an appropriate bibliography is due on the Monday of dead week[5]. The topic for the student's term paper must be related to the material of the course, must have the instructor's prior approval, and must involve some significant independent reading and library research on the student's part.

Additional resource: An annotated bibliography of selected popular science magazines and books will be made available through a local copy center. This is intended to be a resource for students choosing a term paper topic. Students should begin browsing in some of these titles very early in the semester.

TENTATIVE SYLLABUS

This syllabus may be modified during the semester to take advantage of any special opportunities which may arise.

1. Introduction to the course.
2. Galileo and the science of motion.
3. Groping towards a science of mechanics.
4. Isaac Newton's triumph his Three Laws of Motion.
5. The Heavens from antiquity to Johannes Kepler.
6. Newton's apple and the falling moon.
7. Energy and its conservation.
8. Electricity and magnetism.
9. Waves and light.
10. Early ideas about atoms.
11. Ernest Rutherford eats the plum pudding.
12. The problem with light.
13. A wave is a particle and a particle is a wave or what?
14. It's a chancy business.
15. Catch-up and/or review.
16. **FIRST EXAM**: Material from Class Period #1 through Class Period #15.
17. The anatomy of atoms.
18. Electron shells, the structure of atoms, and chemistry.
19. Molecules.
20. Crystals, solids, metals, and insulators.
21. Semiconductors and semiconductor devices.
22. Diodes and transistors.
23. Atoms and light.
24. Lasers. **DEADLINE: SUBMIT TENTATIVE PROPOSALS FOR TERM PAPER TOPIC.**
25. Superconductors.
26. The nucleus of the atom.
27. The four forces of nature.
28. Nuclear technologies.

[5] "Dead week" is the week preceding the university's "final exam week."

29. More nuclear technologies.
30. Catch-up and/or review. **DEADLINE: FINAL APPROVAL OF TERM PAPER TOPIC.**
31. **SECOND EXAM**: Material from Class Period #16 through Class Period #29.
32. Retrospective.
33. Heisenberg's quantum theory.
34. Uncertainty and complementarity.
35. Schrödinger's quantum theory.
36. The Copenhagen interpretation.
37. The Bohr-Einstein controversy. Are "hidden variables" the answer?
38. The Einstein-Podolsky-Rosen "paradox."
39. Some rival interpretations of quantum theory.
40. David Bohm's variation on the EPR experiment.
41. John Bell's remarkable insight.
42. What do the experiments show?
43. Well, what DOES it all mean? **DEADLINE: TERM PAPER IS DUE NOT LATER THAN TODAY.**
44. Is ANYTHING real?
45. Catch-up and/or review.

FINAL EXAM[6]

Appendix B: Exams

PHYSICS 302 SPRING 1993
EXAM #1 Monday, February 22, 1993

Write essay answers to **ANY TWO** of the following **THREE** questions. Credit will be given for no more than two answers.

1. "If I have seen farther than others, it is because I have stood on the shoulders of giants." — paraphrase of a remark attributed to Isaac Newton.
Identify some of the "giants" referred to in the above quotation, describe how Newton incorporated concepts borrowed from them into the theory of dynamics presented in his *Philosophiae Naturalis Principia Mathematica*, and discuss what in Newton's work was new rather than borrowed.

2. Describe the development of the scientific understanding of electricity and magnetism during the 19th century. Include a very brief account of how this understanding has affected 20th century society.

3. Write an essay on Niels Bohr's theory of the hydrogen atom which identifies both Bohr's original insights and the ideas that he borrowed from others, and which makes plain why his theory was so important.

PHYSICS 302 SPRING 1993
EXAM #2 Monday April 5, 1993

Write essay answers to **ANY TWO** of the following **FOUR** questions. Credit will be given for no more than two answers.

1. Describe how physicists understand the structure of atoms, especially atoms more complex than that of hydrogen. Include an account of "atomic shells" and "sub-shells," the relevant "quantum numbers," their allowed values, how the electron energy depends on the shell it is in, and what determines how electrons are distributed among the shells.

2. In the "tight binding" approximation to the theory of crystalline solids, electrons are not confined to single atoms although they are still associated with particular atomic shells. Explain how this is

[6] During the week scheduled by the university for final exams.

consistent with the fundamental principles of quantum physics, and how it leads to the idea of "energy bands" in solids. Use the idea of energy bands to distinguish between solids which are good conductors of electricity, those which are electrical insulators, and those which are intrinsic semiconductors, explaining how the electrical properties of the solid can be understood in terms of the energy bands.

3. Discuss the distinctions between intrinsic semiconductors, n-type semiconductors, and p-type semiconductors, describing how small differences in their structure at the atomic level produces differences in their electrical properties. Use the properties of these different kinds of material to explain how a semiconductor diode and a p-n-p transistor work. Very briefly, describe a few applications of diodes and transistors.

4. Describe any two of the following applications of quantum physics to technology: lasers, magnetic resonance imaging, radioactive dating. Include accounts of the essential physical principles involved in the technology and of how these principles are applied.

PHYSICS 302 SPRING 1993
FINAL EXAM Tuesday May 11, 1993

PART I: Write essay answers to **ANY TWO** of the following **FOUR** questions. Credit will be given for no more than two answers. Each answer in **PART I** is worth a maximum of 20 points.

1. Discuss the Copenhagen interpretation of quantum mechanics. Include an account of the essential features of this interpretation, together with a description of some of its strengths and some of its weaknesses.

2. Describe the principles of a modern, experimentally realizable version of the Einstein-Podolsky-Rosen thought experiment. Give a brief account of the result of Bell's theorem (no proofs are expected!). In the light of Bell's theorem, discuss the significance of recent EPR-type experiments for the interpretation of quantum theory.

3. Compare and contrast the two approaches to quantum theory developed by Werner Heisenberg and Erwin Schrödinger. What considerations motivated these two "quantum pioneers?" What were the major influences on their thought, and how did this affect the versions of quantum theory which each produced?

4. Describe David Bohm's "quantum potential" approach to the interpretation of quantum mechanics. Discuss the reasons why Bohm was dissatisfied with the Copenhagen interpretation, and how his own reinterpretation overcomes the difficulties he perceived with the conventional view. Finally, express with reasons your own preference for either the Copenhagen or the Bohm interpretation (there is no uniquely "correct" answer for this last part).

PART II: Write an extended essay answer to **ANY ONE** of the following **THREE** questions. Credit will be given for no more than one answer. Your answer to **PART II** is worth a maximum of 40 points. Consider this in preparing your answer.

1. What is real? Human understanding of the nature of "reality," as represented by the work of philosophers and scientists, has changed considerably from the time of Aristotle until the present. Describe some of these changes, illustrating your account with specific examples drawn from the material studied in this course. You may include comments as appropriate on how developing scientific concepts are influenced by and in turn influence other aspects of human thought and social behavior, such as philosophy, religion, political organization, etc., provided at least 50% of your essay demonstrates a good grasp of the material studied in this course.

2. Is science driven by technology, or is technology driven by science? Use material studied in this course to discuss this issue. Be sure to consider technology based on "classical" (that is, pre-quantum) science as well as technology based on modern science. It is acceptable to include ideas derived from your study in other courses or from your general reading as an educated individual, such as the effect of economic and political pressures, even though we did not specifically discuss these issues in class.

However at least 50% of your essay should demonstrate thoughtful consideration of material discussed in this course.

3. Science progresses, but is it progress? In everyday language, the word "progress" commonly refers to some improvement in the human condition broadly understood (that is, not necessarily restricted to the material aspects of human existence). Basing your discussion on the material studied in this course, consider to what extent the development of physics and physics-based technology over the centuries represents "progress" as that term is commonly understood. If you choose this question, you will have to spend some time discussing what is commonly meant by "progress." However at least 50% of your paper must demonstrate an understanding of the material discussed in this course.

References

[1] See the article by T. A. Weber and D. L. Pursey on page 20 of these *Proceedings*.

[2] Victor F. Weisskopf, *The Privilege of Being a Physicist* (W. H. Freeman and Co., New York, 1989), page 32.

[3] For a review, see Roland Omnès, Rev. Mod. Phys. **64**, pp. 339–382 (1992); see also Roland Omnès, *The Interpretation of Quantum Mechanics* (Princeton University Press, 1994).