Integrating Computation into the Physics Curriculum

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Harvey Gould
Clark University
Worcester, MA 01610
hgould@clarku.edu
http://physics.clarku.edu/~hgould

collaborators:
Jan Tobochnik, Kalamazoo College
Wolfgang Christian, Davidson College
Joshua Gould, Clark University

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Challenges of incorporating computational methods into the physics curriculum

1. Teach methods of computational physics in the same spirit as presently teach mathematics.

2. Change curriculum to reflect new ways of thinking that have arisen due to use of computer technology. Specific project: Java (third) edition of the *Introduction to Computer Simulation Methods*, H. Gould, J. Tobochnik, and W. Christian with J. Gould.

3. Make use of Internet to make process of teaching more like that of research. Specific project: Development of curricular materials for teaching statistical physics and thermodynamics.

How do we teach mathematics?

The issues related to the integration of math into the physics curriculum are relevant to a discussion of how to integrate computation.

Requiring physics students to take courses in the math department does not work very well. If students learn to use a skill in one context, it is difficult for them to use the same skill in a different context. Engineers have come to similar conclusions about learning physics.

Should physics departments drop the math course requirements for the physics major and teach math ourselves?

Advanced Physics Courses

Debate on how to introduce mathematics is repeated in many physics courses, particularly theoretical courses such as classical mechanics, electrodynamics, and quantum mechanics.

Some textbooks and courses begin with a discussion of mathematical techniques. Other texts and courses integrate the math as needed.

Examples: Griffiths' electrodynamics text begins with a chapter on vector calculus. However, his quantum mechanics text starts with the physics and introduces the solution of partial differential equations, ideas of probability, delta functions, and linear algebra in later chapters as they are needed.

Conclusion: Best approach either depends on the material being covered or is a matter of taste.

How is Computer Used in Research?

Look how computer is used in physics research to determine importance in physics education.

1. Numerical analysis.

   Evaluate integrals, obtaining the roots of an equation, and matrix manipulations.

2. Collection and analysis of data.

   Extract signal from noise, Fourier transforms, fit and plot data.

3. Symbolic manipulation.

   Obtain classes of Feynman diagrams.

These uses of computers are applications of specific tools, much like an oscilloscope is used to make voltage measurements. We should integrate use of the tool with the physical application. Numerical methods courses in mathematics departments and computational physics courses that emphasize numerical analysis are not as effective as integrating specific tools directly into physics courses.

Computer Simulations

Computer simulation is a way of doing physics that is distinct from the way physics was done before computers. The style and motivation is analogous to a *laboratory experiment*.

1. Develop a model that can be represented by an algorithm. The model plays a role analogous to the physical system of interest in an experimental system.

   Examples: molecular dynamics, cellular automata models of fluids and traffic flow.

2. Test program and compare its outcome with known results in limiting cases (analogous to calibration of a measurement apparatus).

3. Collect, display and analyze data. In the real world, initial data frequently leads to further improvements in the program and more data collection.

Features of Computer Simulations

In experimental physics each new kind of measurement requires a new piece of equipment and may preclude other measurements. In a computer simulation a new measurement requires only some additional code within the existing program.

Simulations allow us to determine quantities that cannot be measured in a lab experiment.

Size and duration of simulation limited.

Advantage of analytical solutions is that a solution frequently can be written in terms of a parameter so that more than one case is readily available. In contrast, separate simulations frequently must be done for each value of the parameters of interest.

Advantage of simulations is that many modifications of the model require simple changes in the program, whereas even minor changes in a theoretical model can make an analytical calculation impossible.

Analytical calculations usually require approximations whose consequences are not known.

Simulations frequently use numerical procedures that are exact in principle, although the results are approximate due to statistical errors and limitations due to the effects of finite time and size.

Importance of computer simulations is reason enough to incorporate them in the undergraduate curriculum.

Computer simulations provide the easiest way of involving physics students in the process of scientific research. Writing and running simulations includes many of the aspects of scientific research such as model generation, testing, analyzing data, interpreting data, and drawing general conclusions.

Flexibility of simulations means that they can be done at many different levels for just about any field of physics as well as many fields outside of physics. Hence, we have much freedom in determining where in the curriculum to add computer simulations.

Integrating computer simulations

Most other uses of computers should be integrated into existing courses and discussed as needed.

Same issues arise as we discussed earlier in the context of integrating mathematics.

Some noteworthy exceptions at the introductory level:

1. Ruth Chabay and Bruce Sherwood.
   http://virtualphoton.pc.cc.cmu.edu/projects/visual/

   Use Python and have students write computer simulations with powerful 3D graphics. Graphics statements are largely hidden from users.

2. *Physlets*, Wolfgang Christian. Java applets built into Web pages using Javascript.

   Common user interface, ability of instructors to tailor physlets, and a good sets of questions.

   Students do not usually learn what is behind the simulations, but physlets help student learning and introduce students to possibilities of simulations.

Learning a Programming Language

In collaboration with Wolfgang Christian of Davidson College, Jan Tobochnik and I are writing the third edition of our computer simulation text in **Java**.

http://sip.clarku.edu

How can students learn a programming language?

Although, physics students frequently take courses from the computer science department, introductory programming courses are not very effective.

Just as we urge students to take mathematics courses to learn mathematics on its own terms, we should urge students to do the same for computer science. There are ways of thinking in computer science that provide a foundation to the tools we are using and that will become more important in computational science in the future. However, we should not rely on computer science courses as a prerequisite for learning to do computer simulations.

How can we expect students to learn programming while they are learning physics?

Focus on those parts of the language that are useful for doing computer simulations, and provide templates and utilities.

Should we teach a separate computer simulation course or integrate computer simulations into other physics courses?

The answer is **yes**!

Separate courses have not yet led to much use of computer simulations in other courses.

Reasons:

Course not required of all majors.

Faculty teaching other courses are unfamiliar with simulations or do not have the time to change their courses.

Lack of readily available resources for incorporating simulations. We are trying to rectify this last obstacle for thermal and statistical physics courses by developing applets and various Java utilities and templates and other curricular materials.

http://stp.clarku.edu

Real Changes

Real change will come when the use of computer simulations pushes us to broaden the focus of the physics curriculum. For example, can expand simulations of statistical mechanics models to include more general studies of complex systems such as traffic flow, epidemiology, and neural networks.

Extension of computer simulations beyond traditional topics in physics leads naturally to *computational science*. Including computational approaches such as genetic algorithms and cellular would provide a powerful pathway to understanding complex systems through computational science. Physics courses may be the most natural setting for introducing computational science because physics has been at the forefront in developing new ways of solving problems experimentally, theoretically, and now computationally.

Making Teaching Count

The use of the Internet as a vehicle for delivering curricular materials allows us to share course materials and our approach with instructors at other institutions.

One reason that teaching is not taken as seriously as research is that our teaching reputations are local and the quality is not easily evaluated. The advent of the Web has already started to change this situation.

We can use the Web to develop curricular materials in a way that takes advantage of the collective work of many people. Can there be “open source” curriculum development projects in physics and other areas?