How will computer technology affect the physics curriculum?

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Background

Changes in the physics curriculum depend in large part on the nature of society.

- What will be the background of our students?
- What should be the goals of the physics major?

Some of the challenges:

- Fewer opportunities for students to tinker.
- Need to increase our outreach to nonmajors.

Assumptions

- Changes in the curriculum should be based on developments in research in education and physics.
- There are no quick fixes, but new technology allows us to rethink the curriculum.
- Digital textbooks can change the way we teach.
- Changes are easier to make in advanced courses.

Change of emphasis

- Physics curriculum has been influenced by the importance and appeal of quantum mechanics, relativity, and particle physics.
- Examples of fields increasing in importance are condensed matter, biological physics, chemical physics, neuroscience, materials science, statistical physics, fluid mechanics, econophysics, and geophysics. All these systems have many degrees of freedom and exhibit nonlinear behavior.
- Why study physics when students can study these areas more directly?
- Need to change physics curriculum so that in other science students can learn physics beyond the introductory course.

Change will be slow

- . . . I have not embraced the object-oriented programming world the way many computer scientists have embraced it. As a matter of fact, I really dislike this method of programming.
- When I teach the senior/graduate-level on Computational Physics, my examples use Fortran 77 and IDL. I discourage the use of C++ . . . those are my feelings and they are unlikely to change.
- At a certain Big Ten school, the physics B.A. did not require a course in quantum mechanics until 1973.

What can we do to make the undergraduate curriculum more interesting and accessible?

- We should emphasize our strengths – physicists are good at developing simple models, asking questions, and developing new measurement and theoretical tools. Our courses should emphasize the development of these strengths. No other discipline has such a rich combination of rigor, room for imagination and creativity and interplay between experiment and theory.
- Stress the versatility of physics and its fundamental nature. This emphasis will always appeal to a minority of students interested in science.
- Simulations should be used to increase conceptual understanding, rather than to implement complicated black box, albeit more realistic models.

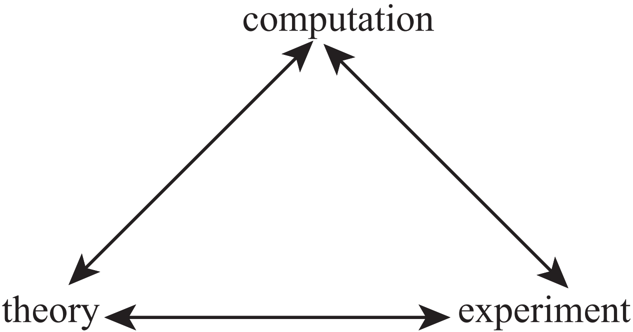
What have we learned from physics education research?

- Students learn much less than we think and have difficulty with fundamental concepts. Passive listening to lectures has little impact on student understanding. Active engagement with material is essential.
- Many advanced physics students do not learn from their mistakes without explicit intervention.
- Framing issues are often present when powerful calculators (Mathematica) are involved because of the way they influence student thought.
- Interactive tutorials can be effective.
- Impact of a computer simulation depends on the details of the program and the way in which it is implemented.

Advantages of digital books

- Digital books can be interactive and include audio, video, animations, tutorials, and test students while they read.
- Maybe students will start reading again.

Complementarity



(Compliments to David Landau)

Computers affect the way we think about nature.
Models are frequently expressed in terms of

- Finite differences
- cellular automata

Suggested curricular changes

- Offer a one or two semester project-oriented course emphasizing computer simulations.
  - Such a course can easily incorporate simulations important in biological physics, chemical phsics, neuroscience, materials science, statistical physics, fluid mechanics, econophysics, and geophysics.
  - New York Times, 2/8/2010, Samuel Wang, neuroscientist at Princeton. "I was at Caltech in 1985, and I took a class in classical mechanics and another in introductory cell biology. And I remember asking this physics instructor about second order corrections in Lagrangian dynamics. He said, 'Oh yes, thats been thought of,' while spewing out a bunch of equations on the blackboard. I then asked my biology instructor a question about neurotransmission. He kind of smirked at me and said, 'Nobody knows the answer to that."'
  - Course should teach programming. Teach an object oriented language such as Java (EJS) or (V)Python.

More suggested curricular changes

- Expand statistical mechanics course to two semesters. Alternate 2nd semester with fluid mechanics or astrophysics.
- Emphasize dynamical systems in mechanics and reduce required electrodynamics course to one semester.
- Emphasis importance of multiple length and time scales.
- Incorporate more experiments into all courses.
- Be cautious about incorporating interdisciplinary courses in the core of the major.

Reform lower division courses

- Although reform is easier in upper division courses, we can't wait to start active engagement until students are juniors.
- The biggest barrier to studying physics is fear of mathematics. Mathematics is too important to be left to the mathematicians. Offer a math methods course in lieu of or in addition to traditionally required courses math taught by the math department.

How can computation help teach statistical and thermal physics?

- Students have prior conceptual models of thermal systems. Gases and liquids are composed of objects that act like billiard balls and give off "heat" when they collide. Computer models can show students that the billiard ball model is inadequate and help them replace their models with another concrete model.

- Probability is a key concept in statistical physics. It is straightforward to illustrate important ideas in probability and statistics by computer simulations. Teach the central limit theorem.

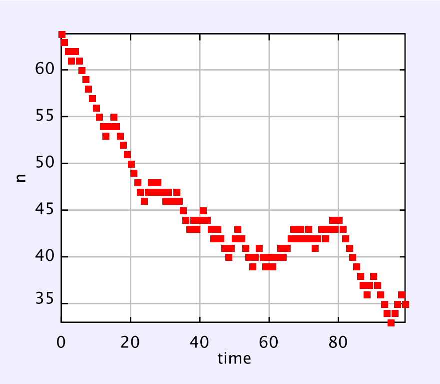
Why is Statistical and Thermal Physics Difficult to Teach?

No obvious organizing principle such as Newton's equations, Maxwell's equations, or the principle of least action. Statistical mechanics is frequently viewed as a collection of tricks.

- The nature of temperature.
- Entropy and the second law.
- The Boltzmann probability distribution.
- The partition function.
- The chemical potential.

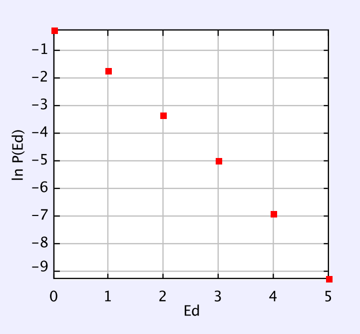
Statistical physics concepts: Algorithms and simulations

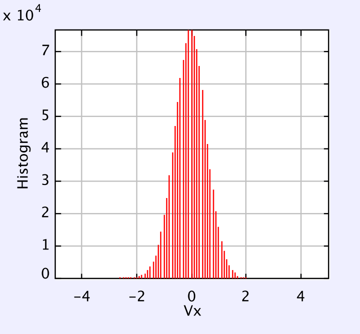
- Approach to equilibrium: simulation of particles in a box.



- Computer simulations show that thermodynamic quantities have statistical fluctuations in equilibrium.

- An ideal thermometer: the demon algorithm.





- Role of temperature: exchange of energy between two systems in a molecular dynamics simulation.

- Internal energy: kinetic energy and potential energy in a simulation of a Lennard-Jones system.

- Probability distribution: Monte Carlo algorithms.

- Examples of different ensembles.

More concepts

- Chemical potential: demon algorithm with particle exchange; Widom insertion method.
- Ergodic theory: Fermi-Ulam-Pasta simulation of the one-dimensional anharmonic chain.
- The density of states.
- Hysteresis: Heating and cooling in simulations.
- Critical points: finite size scaling, critical slowing down, correlation functions.

These simulations and concepts are discussed in *Statistical and Thermal Physics With Computer Applications* by Gould and Tobochnik, Princeton University Press, August 2010. Pdf files on <`compadre.org/stp`>.

Possible Implementations

- Run already written programs – effective if accompanied by good questions.
  - Examples: The *STP* Launcher package by Gould and Tobochnik and the *QM Superposition* Launcher package by Belloni and Christian, for teaching the evolution and visualization of energy eigenstates and their superpositions. Both packages are self-contained jar files.

- Provide programs and ask students to make some modifications. An example of open source software that allows modifications to be done easily is EJS.

- Discuss simulations in class as demos.

Summary

- As we make changes, we must not lose sight of the fundamental nature of physics. Physics is not the same as the study of physical systems.
- Just as students learn less about special functions, future students will learn less programming. Need to emphasize models and algorithms.
- We can use computers to make abstract concepts more concrete.
- All the software mentioned is on <`compadre.org`> and is part of the Open Source Physics project.