Available online at www.sciencedirect.com
ScienceDirect
Computer Physics Communications 177 (2007) 191–194
Computer Physics Communications
www.elsevier.com/locate/cpc

Computational Physics Education; why, what and how

Rubin H. Landau

Computational Physics for Undergraduates Program, Oregon State University, Corvallis, OR 97331, USA

Available online 22 February 2007

Abstract

Progress in developing, implementing, publishing, and refining a coherent set of education materials in computational physics education will be described. These materials form the binding for a four-year undergraduate degree program leading to a Bachelor's degree in Computational Physics. Also described will be the status of the conversion of these materials into electronic formats that may be used for online education and as electronic textbooks. The online materials are to be part of a proposed national repository of university-offered, undergraduate courses and modules in computational science gathered from various pioneering programs throughout the country.

Keywords: Education; Computational science; Computational physics; Computational education

1. Need for change in physics education?

This last decade has witnessed historically rapid advances in science, technology, and education driven by a dramatic increase in the power and use of computers. The long-range effects on undergraduate physics education engendered by these advances is an open question. In the past, educators were content to have undergraduates view scientific computations as "black boxes" and to wait until graduate school to learn what is inside the boxes. Yet our increasing reliance on computers makes this less true today, and much less likely to be true in the future. Accordingly, one response has been for schools to develop Computational Physics Education, where the hyphen indicates a union of computation and physics on pretty much equal footing, as individual courses or formal programs (Table 1). Another response, which we call Computational Physics Education, views the computer as a tool to advance physics education, without questioning what goes on inside the black box.

This paper suggests Computational Physics Education as a model for where physics education should be headed in the future. It integrates the tools and results from research into the education, and by using research-rich experiences to stimulate and activate students, is based on solid educational principles (also a hallmark of highly-ranked universities). It may be thought of as "Physics Education *with* Research", in contrast to Physics Education Research, which appears to focus on the ability and failures of students in learning various concepts of physics.

Evidence of the need for change in the "standard model" of undergraduate physics education has been presented by the American Institute of Physics [1]. They surveyed physics majors five years after graduation and queried them as to which aspects of their education are most valuable in their current employment. The results (Fig. 1) indicate that for graduates whose primary field of employment is engineering, mathematics and science, the three most important skills are scientific problem solving, synthesizing information, and mathematical skills. These skills remain highly important for graduates who find employment related to software, with this latter group also having a high need for computer programming and software development.

The importance of mathematics and computer skills is also examined in a National Science Board report. It indicates that only 35% of mathematics and computer-science bachelors work in the same field as their degree, whereas an even smaller number, 22%, of physical and biological science bachelors work in the same field as their degrees. A similar trend is seen at the doctorate level (74% versus 52%). One conclusion that may be drawn from these data is that requiring students to spend more of their time on physics, in an effort to get them to understand it the way professors do, deprives them of learning other things which may be equally or more important for their educa-

E-mail address: rubin@science.oregonstate.edu.

0010-4655/$ – see front matter
doi:10.1016/j.cpc.2007.02.040

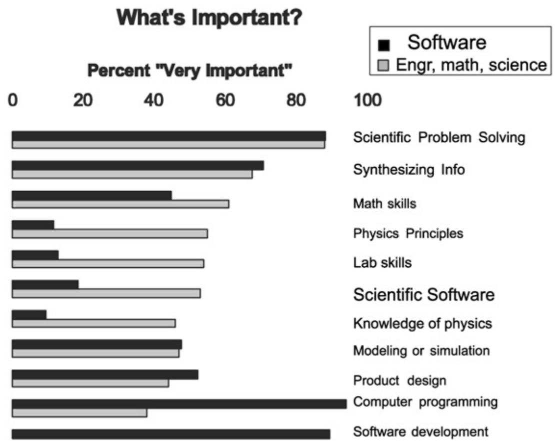


Fig. 1. Importance of knowledge and skills for bachelors, 5–7 years after degree for graduates. The order (light bars) is that of importance for physics majors whose primary field of employment is engineering, mathematics and science, the dark bars are for graduates employed in software. (Data courtesy of the American Institute of Physics.)

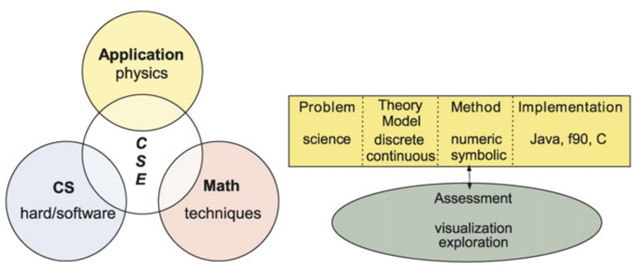


Fig. 2. Left: The three disciplines of computational physics and a bridge among them. Right: The scientific problem solving paradigm used in the educational materials.

tion. This may also be moving physics into the class of mature, classical subjects that are less relevant to society's needs. As viewed with this broader scope of science education and society, the President's Information Technology Advisory Committee (PITAC), the US Department of Commerce, and InfoWeek, have all indicated that Computer Science departments alone cannot meet the country's needs for computer professionals.

The computational science being referred to here is the mother discipline to computational physics (CP), the subject of this paper. As we view computational science (Fig. 2), it is a multidisciplinary subject that combines an application (physics), applied mathematics, and computer science in the course of solving realistic scientific problems (Fig. 2). As indicated in the recent PITAC report, the use of computation and simulation has now become so prevalent and essential as to make it the third pillar of science.

Although diagrams like Fig. 2 have been shown often enough to become visual cliches, we believe that they are particularly relevant to the topic of this paper. First, as CP has matured, we have come to realize that it is more than the overlap of physics, computer science and math to form the overlap region in a Venn diagram. It is also a bridge that connects the three disciplines and that contains core elements of it own, such as computational tools and methods. Second, as physics has matured, and physics education research and computational physics-education have tended to focus inward on the traditional concepts of physics and mathematical physics, they have moved away from the center of the Venn diagram (Fig. 2), and away from the problem-solving paradigm of science. In contrast, CP's commonality of tools and shared problem-solving mind set draws it closer to other computational sciences and outward to address a broad range of new problems. In addition, it has been found that incorporating technology within the problem-solving paradigm is a more effective way to teach science and technology than by focusing directly on individual components.

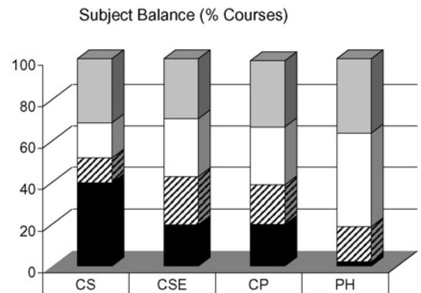
Table 1
Results from surveys of US undergraduate programs in the computational sciences [2,3]

BS/BA Degree Programs (22)	
Computational Physics	**Computational Math.**
1. Houghton C	1. Arizona State
2. Illinois State	2. CUNY Brooklyn
3. Oregon State	3. Michigan State
4. SUNY Buffalo	4. Miss. So State
5. Christopher Newport	5. Rice (App. & CM)
Computational Science	6. Rochester Institute Tech.
1. Stanford (Math & CSE)	7. Seattle Pacific
2. SUNY Brockport	8. Saginaw Valley State
3. Stevins Inst. Tech.	9. San José State (App. & CM)
4. UC Berkeley (C Engr S)	10. U Chicago (App. & CM)
Computational Biology	11. U Ill. Chi. (CSE & In Mth)
1. Carnegie Mellon	
2. U Pennsylvania	
UG: Minor, Concentration, Track, Emphasis, *etc*. (21)	
Computational Physics	**Computational Science**
1. Abilene Christian	1. Capital
2. North Carolina State	2. Clark
3. Penn State Erie	3. Old Dominion
4. U Arkansas	4. RPI
Computational Mathematics	5. Salve Regina
1. Princeton (App. & CM)	6. Syracuse
2. San Diego State (App. & CM)	7. U Wisconsin Eau Claire
3. U Central Florida	8. U Wisconsin LaCrosse
4. U Nebraska-Lincoln	9. U Wisconsin Madison
Computational Biology	10. Wittenberg
1. UC Merced	11. Wofford C
2. Center CB (Colo)	
Foreign Programs	
1. Australian Nat. Univ. (CSE)	5. U Calgary (CSE)
2. Kanazawawa U Japan (CSE)	6. U Erlangen-Nürnberg (CSE)
3. National U Singapore (CSE)	7. U Waterloo (CSE)
4. Trinity C, Dublin (CP)	8. Utrecht U (CSE)

CP = Computational Physics, CM = Computational Math, CB = Computational Biology, CSE = Computational Science.

2. Computational science degree programs and their contents

A bachelor's degree in any of the computational sciences is rare. In Table 1 we list all undergraduate computational science programs as determined by the surveys of Swanson [2], Osman and Landau [3] and Mariasingam, with some updates by us. Note, we have included only active undergraduate programs, and have excluded some programs that appear to be straight



	CS	CSE	CP	PH
Other	31	29	32	36
Application	17	28	28	45
Math	12	23	19	17
Comp	40	20	20	2

Fig. 3. The average percent of the total curriculum dedicated to (from bottom to top) computing, mathematics, application and other for BS degree programs in (from left to right) computer science, computational science, computational physics and physics.

dual-degree programs, without the bridge courses to draw the disciplines together. In 2001, when we assembled a similar list, we found 13 such program in the USA, *now that number has more than tripled*. So, even though computation is finding its place within many disciplines and courses, the need for multidisciplinary computational science programs still appears to exist.

Fig. 3 compares BS programs in Computer Science, Computational Science & Engineering, Computational Physics, and Physics [3]. The left column shows the strong Computing (black) but weak Application (white) components in the Computer Science degree; the right column shows the strong Application but weak Computing components in the Physics degree. We see that an undergraduate degrees in Computational Physics has a similar balance to one in Computational Science and Engineering; namely, approximately equal weights for Mathematics and Computing (∼20%), and a higher weight for Application (∼28%). This is a fairly uniform balance among components, and, as expected, a CP or Computational Science & Engineering degree contains less physics than a physics degree and less computing than in a CS degree.

The numbers appear to confirm our impression (prejudice?) that regular physics undergraduates may not be learning enough about computation, and that regular CS undergraduates may not be learning enough about math and science. In addition, although we have not done any surveys, we have seen some physics curricula get even more imbalanced, possibly as a consequence of physics educators efforts to eliminate students' misconceptions from the start, or to deepen students' understanding of the mathematical foundations of physics. We suggest that a better way to eliminate misconceptions may be by applying the physics to realistic problems.

The actual topics covered in the CP classes, and their connections to the other subjects, are shown as a concept map in Fig. 4. This map is essentially a fleshed-out version of Fig. 2 and was produced as part of the EPIC collaboration [4]. On the left are the hardware and software components from computer science; in the middle are algorithms of applied mathematics; on the right are the physics applications.

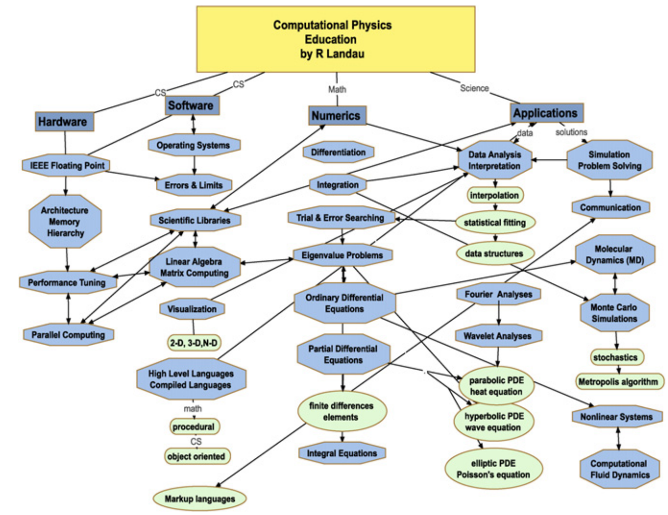


Fig. 4. A concept map of CP with some interrelations.

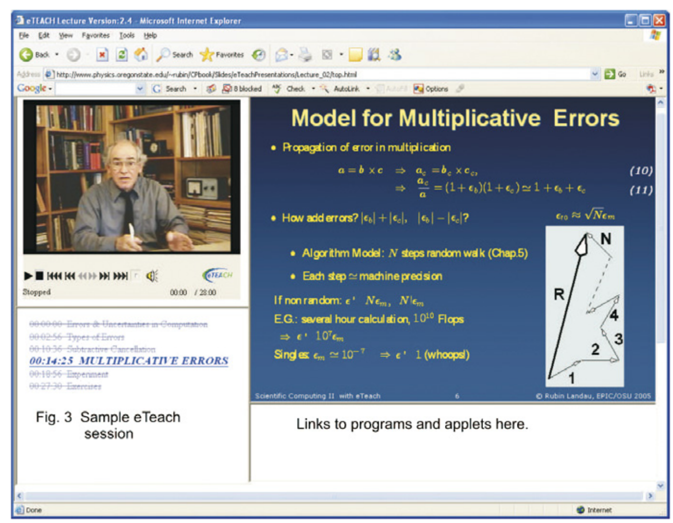


Fig. 5. A frame from an online class using eTeach, showing the video frame, the interactive table of contents, the synchronized and animated slide, and links to programs and applets.

2.1. Online courses and digital books

Although we do not view the web as a good teaching medium for general physics, or appropriate for students with weak self-discipline or limited motivation, we do believe that the best way to learn scientific computing is while sitting at a computer in a trial-and-error mode. As part of our EPIC work, we are converting some of our conventional courses into electronic forms appropriate for distant delivery [4]. Although there are numerous computational science tutorials, applications, applets, and reading materials on the Web, there is little in the way of complete courses. This ongoing work hopes to be a big step in disseminating the OSU courses, and one of the first steps in establishing a national repository of university-offered, undergraduate courses and modules in computational science. The repository would be a collection from various pioneering programs throughout the country, which together would cover the entire field of computational science at various levels. Once in place, other schools may adopt these courses as a way of including modern computation and multidisciplinary studies into their curricula, without having to hire specialists in the field, or to develop courses of their own for what is often a small number of students in any one location, or having to set up their own computational labs with all the requisite hardware and software (most would be straight-forward to serve over the Web from supercomputer centers or our labs). In Fig. 5 we show a screen dump from one of our first recordings done with eTeach [5]. It is in the informal format of a student questioning a professor in an office, with an actual office used as the studio.

3. Summary and conclusions

Beginnings are hard. We have assembled a curriculum for a BS degree in Computational Physics that focuses on a common "tool set" of subjects that have proven themselves useful in solving problems in a number of disciplines. Although most of the courses are taught by traditional departments, the five multidisciplinary, computational classes serve to put the tools in perspective, promote a problem-solving viewpoint, glue the disciplinary classes together, and promote a sense of belonging to a Computational community. Three text books and countless codes have been written to assist in the dissemination of our developments. While only time will judge the viability of programs such as ours, it does appear to attract new students and to provide students with a broad preparation for future career choices. We advocate this type of program as a model that keeps physics relevant to a changing society and that teaches it better with fewer credits.

References

[1] Skills Used Frequently by Physics Bachelors in Selected Employment Sectors, American Institute of Physics Education and Employment Statistics Division, 1995.

[2] C.D. Swanson, Computational Science Education Survey, Krell Institute, http://www.krellinst.org/services/technology/CSE_survey/, Nov. 2003.

[3] O. Yaşar, R.H. Landau, Elements of computational science and engineering education, SIAM Rev. 45 (2003) 787–805.

[4] S. Clark, S. Haerer, R.H. Landau, supported by Engaging People in Cyber Infrastructure, http://www.eotepic.org/; ..../moodle/course/category.php?id=8.

[5] eTeach, Learning on Demand, http://eteach.engr.wisc.edu/newEteach/home.html.