Physics and computing have been associates since the beginning of the computer era. From John Atanasoff’s development of the first electronic digital computer in the late 1930s to the Manhattan Project’s use of computing as a calculation aid to propel Metropolis into algorithm design to the ground-breaking simulations of Enrico Fermi, John Pasta, and Stanislaw Ulam, physicists have been at the forefront of computational science. The close relationship between physics and computation has grown spectacularly since the mid-20th century, to the point where computational physics is arguably on par with theory and experiment as a research methodology in physics.

The same cannot be said of computational physics education (CPE), at least at the undergraduate level in the United States. By this, I mean teaching young physicists in their first four years of postsecondary education the concepts, methods, and experience of approaching physics problems with computational tools, just as we’ve done for more than a century with theoretical and laboratory experimental physics. Examples of CPE goals might include, among other ideas, teaching students to

- model physical systems for computational solution;
- understand computational algorithms and techniques;
- have familiarity with numerical analysis, computer architecture, and simple complexity theory;
- implement models and algorithms as efficient code;
- use appropriate diagnostics to analyze simulation data; and
- communicate results via data visualization and beyond.

I do not include in CPE learning aids in physics, such as computer-aided instruction systems, animated modules.
Richard Martin is one of the pioneers in computational physics education (CPE) and has been a prime stimulant for my initiation of a computational degree program at Oregon State University. Trying to change the traditional physics curriculum can be most challenging, and it’s a pleasure to recognize Martin’s sustained efforts (I would give him a prize if I had one to give). As Martin notes, and I wholeheartedly second, the physics education community has been less than welcoming to this innovative change in what a physics degree should contain, and in my experience, the research community in general has shown resistance to recognizing the “computational” part of computational physics in talks and articles. As if we need further examples of the difficulties in establishing a CPE program, Martin also notes that the CPE degree program at Oregon State was terminated due to “low enrolment.” Although this occurred after I retired (and could argue the program’s case), it’s worth noting that the termination resulted from an administration mandate that all university degree programs with fewer than 12 graduates per year be terminated. This clearly made little sense for a specialized area, especially considering that the entire physics department itself tends to have just a few more graduates than this. Although many challenges to CPE remain, I would be most interested in disseminating information about other computational science education programs, especially ones that appear to be working.

— Rubin Landau, Education department editor

Where Have We Been? A Brief History of CPE

Physicists are a creative bunch, and it isn’t surprising that there were “early adopters” in the classroom of the new methodology they had used in research. Alfred Bork was one such pioneer who influenced a generation of CPE advocates. In his 1963 article entitled, “A Physics Independent Study Course with Computer,” Bork presented several reasons why physics faculty and students might want to have some familiarity with the computer (all quotes are from the article):

- “The modern computer makes workable problems which were for all practical purposes impossible only a few years ago.”
- “Using numerical analysis permits the consideration of material beyond the students’ analytic ability.”
- “The ‘feel’ of numbers promotes understanding of analytic relations.”

The first two represent a statement of the power of computation in both physics and education. Keep in mind that this was a time of mainframe computers programmed with cards. Bork’s course at the University of Alaska used an IBM 1620 computer. Students programmed in Fortran with punch cards and a “typewriter” for I/O. Ditto masters were used in the typewriter so that output could be reproduced for the whole class. Students had no prior training in programming and received only the briefest introduction in this class. Despite these limitations, Bork clearly understood the consequences of the new technology. Indeed, the course he developed in 1962 doesn’t look that different from a first course in CP you might find today. The third quote above indicates that Bork appreciated the improved insight and enhanced physical intuition obtainable by simulating physical systems.

Bork’s article is characteristic of what we might call the “first generation” of CPE: a devoted advocate developing course modules or, rare at that time, a special course designed to give students their first experience in solving physics problems computationally. It would be interesting to know the future of the students in his 1962 class: How many of them would go on to be computational research physicists or to further develop CPE as future faculty?

If not Bork’s students, there were others who followed in his shoes. The 1970s and 1980s saw an

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explosion of single course development. Like with Bork, this was frequently a single faculty member enthusiast, often experienced with computational research, who saw the writing on the wall: computing is here to stay, and we owe it to our students to prepare them for that future. This “second generation” of CPE also began to formalize the content of such courses in several textbooks. CP texts (and CP courses) tend to differ significantly from the traditional numerical analysis text by being more physics- and project-oriented. While still explaining the algorithms involved, CP texts tend to begin with a physics problem, explaining how to select a solution technique that fits that problem. From discussing CPE courses with physics colleagues, a fair generalization might be that more time is spent on code testing and verification based on physical constraints, such as conservation laws and checking simulation behavior against known limiting cases and your own physical intuition, rather than focusing on analytic error estimation, for example.

Around the late 1980s and through the 1990s, a “third generation” emerged, with a movement toward developing degree sequences in CP. The 1988 Computers in Physics Instruction was an early conference devoted explicitly to CPE and stimulated many of its participants to implement their new ideas as courses and programs. In the US, this momentum was reinforced by a demographic issue—namely, a significant enrollment dip nationally in undergraduate physics programs. One of the proposed remedies emanating from community discussions and conferences, such as the 1996 AAPT Physics at the Crossroads conference and the 1999 APS/AAPT/NSF Physics Revitalization Conference: Building Undergraduate Physics Programs for the 21st Century, included providing more breadth to undergraduate physics programs. Degree options and sequences in CPE fit that recommendation nicely. In this time period, new degree programs in CP were initiated, CP was integrated into regular physics major courses, and interdisciplinary degrees, such as dual degrees in physics and computer science, were created. (The next section explores three such programs in more detail.)

The first decade of this century saw new collaborative momentum, new programs, and a continuing trend toward a wider comprehension that future physicists must have CP experience. An explosion of conferences and journal special issues served to both chronicle and stimulate this new energy:

- American Physical Society (APS) March meeting session, “Computers in Physics Education” (2004),
- American Association of Physics Teachers (AAPT) cracker barrel session, “Building a Physics Computing Community for Undergraduate Education” (2005),
- AAPT session, “Computation in Physics Courses” (2006),
- Computing in Science & Engineering, special issue on CPE (Sept. 2006),
- AAPT topical conference, “Computational Physics for Upper-Level Courses” (2007),
- American Journal of Physics, special issue on computation and computer-based instruction (Fall 2007), and
- Gordon conference, “Computation and Computer-Based Instruction” (2008).

### Three Comprehensive Programs

The last two decades’ CPE developments promised to produce lasting reform of physics curricula. A few short case studies can shed some light on the reality of the dream.

**Integration or Specialization?**

Lawrence University, in Appleton, Wisconsin, is a small, liberal arts-oriented university with a Carnegie classification of “Baccalaureate Colleges: Arts & Sciences Focus.” The physics department has five faculty and offers a BA in physics and a “3-2” joint engineering degree with a partner engineering university (three years of physics at Lawrence and two years of engineering with the partner). Its innovation, beginning in 1985, was to integrate computational methodology into its regular physics courses, a stated goal being “to embed the use of general purpose graphical, symbolic, and numerical computational tools throughout our curriculum.” The program had two explicitly computational courses, Computational Mechanics and Computational Physics, with many CP methods integrated into physics major courses. The program’s primary architect, David Cook, disseminated the program well through talks, articles, and a self-published customizable textbook, available on the author’s website; Cook is now retired and remains active in the AAPT. The CP integration program is now absent from the Lawrence University physics department website and from the course catalog, although the Computational Mechanics course remains required for all majors, and the Computational
Physics course is now integrated with an Advanced Mechanics course, the combination being a senior elective class.

Oregon State University is a large university in Corvallis, Oregon, with a Carnegie classification of "Doctoral Universities: Highest Research Activity." The physics department, with 17 faculty, offers a BS and a BA in physics, as well as MS and PhD graduate degrees. In 2001, a full BS in computational physics was initiated. Under the leadership of Rubin Landau, this program consisted of five CP courses (Scientific Computing I and II, Computational Physics Lab, Simulation I and II), two numerical math courses, and two related computer science courses. In addition, a senior research thesis was required of all students, and CP students did a computational project. This program was one of the most comprehensive CP degrees and was well disseminated. A CP textbook is now in its third edition, and online courseware is available through the author's webpage. Landau has gone further in CP pedagogy, arguing that CP methods are better for learning physics; he is now retired, remaining active in CP. The Oregon State BS in CP had been eliminated due to insufficient enrollment. However, CP remains as one of eight options in the regular physics degree, with two dedicated courses.

Illinois State University is a mid-sized university in Normal, Illinois. Although the university carries a Carnegie classification of "Doctoral Universities: Higher Research Activity," the physics department is undergraduate only. With 10 faculty, the department offers four BS degrees: physics, CP, physics teacher education, and engineering physics (also a "3-2" joint program). Beginning around 1990, a team of three faculty, George Skadron, Robert Young, and I, initiated a program of integrating selected CP methods into physics major courses. Student feedback encouraged the development of a full CP degree track, which began in 1998. Students take between three and five CPE courses and two computer science courses. This program wasn't as well disseminated as the other two, but an early article describes the initiative. Of the originators, two are retired. The program continues under the leadership of younger, computation oriented faculty.

A Closer Look at the Illinois State Program
I'm naturally most familiar with the Illinois State University CP degree and will discuss it more in depth as an example of a longer-lived program. Although the CP BS began in 1998, its roots go back to the second generation in the late 1970s, when Robert Young first offered a single course using computational methods, entitled Computers in Physics. In the late 1980s, we started integrating CP into physics courses, guided by a skills matrix that mapped out which CP topics, including basic numerical, simulation, and visualization methods, would naturally be used in which courses. For example, both the over-relaxation method for Laplace's equation and 3D surface plotting were in the intermediate electricity and magnetism (E&M) matrix cell. In a short time, our students were graduating with significantly more modeling and programming experience than their peers at other institutions. Graduates who went on to graduate school and those who entered the technical workplace both reported how their computing experience served them well; several said they wish they could have done more. With concerns about physics enrollment at the time, we decided to develop a degree program. The US National Science Foundation funded our Undergraduate Computation Science Lab in the mid-1990s, a project to develop the BS degree and enhance computational undergraduate research. The CP BS became official in 1998, and its first graduates, preparing ahead for the requirements, appeared a year later. The degree's name, incidentally, was changed from computational physics early on after surveying high school physics students who thought "computational" meant "mathematical." "Computer physics" cleared up any ambiguity.

The degree sequence requirements include all the core physics courses that regular physics majors take: three semesters of introductory physics and courses in intermediate mechanics, E&M, quantum, mathematical physics, and laboratory physics. This is complemented by the same five math courses that physics majors take, one chemistry course, and two advanced physics courses (Thermal Physics and either Senior E&M or Quantum Mechanics). Beyond these common classes, CP majors take the dedicated CP courses Methods of Computational Physics, Advanced Computational Physics, and a capstone project course, Computational Research in Physics. These are supplemented by computation oriented electives (one required), such as Nonlinear Dynamics, and one or two courses from the Information Technology Department (Programming for Scientists if the student has no programming experience and Hardware and Software Concepts, an introductory computer architecture overview). With additional computing integrated into regular physics courses, the program gives

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students a strong mix of physics and computation. For those seeking research participation, several faculty offer computational research topics, and the majority of CP majors do get involved. Indeed, both of the department’s finalists for the APS LeRoy Apker Award were working on computational problems.

I’ve highlighted courses taken by CP majors, but what physics material was “sacrificed” in favor of this material? This question is a common one from colleagues who are skeptical of CPE, and it deserves a straight answer. We dropped the following requirements: one senior lab course, one senior physics course, one senior elective, and one semester of chemistry. Table 1 summarizes the tradeoffs. Both sequences require 21 courses and are within one semester-hour total.

The basic methods course, Methods of Computational Science, is frequently team-taught by one physics and one chemistry faculty, motivating the computational methods by problems in those fields. Sample topics include discretization and numerical errors; numerical integration for dynamic bridge stability; solutions of differential equations for molecular vibration, nonlinear oscillations, and chemical kinetics; Fourier methods for magnetic resonance spectroscopy; and Monte Carlo methods for neutron shielding.

The Advanced Computational Physics course is a projects course taught by three faculty, each one presenting a five-week project. Students are responsible for writing the code, analyzing the results, and producing a written report. A variety of projects has been covered over the years, including neural networks for time-series prediction or pattern recognition, molecular dynamics simulation of microclusters, an original classical ensemble method for calculating time-dependent quantum wave functions, Monte Carlo simulation of light scattering off a turbid medium, and finite element simulation of heat transfer in nonuniform solids. The projects are chosen to display the power of simulation physics and to open the students’ eyes to computational thinking. One graduate returning several years postgraduation told stories of tech industry job interviews requiring immediate problem analysis. Initially panicking at one of these, he realized that a neural network might solve the problem he was assigned. Based on his one experience with neural nets in this course and his own creativity, he succeeded in the interview. It doesn’t take many cases like this to convince you that CPE is essential for today’s physics graduates.

The capstone research project is a chance for students to really innovate: they have more or less complete freedom to choose a topic, all they need is a faculty mentor to agree to work with them. The student is responsible for the modeling, coding, and analysis and for presenting a talk to the department or to an appropriate research venue. Topics are often physics-based, such as particle-in-cell plasma simulation with parallelized code, galaxy classification in Hubble Space Telescope deep-field images using image processing and pattern recognition, and slab geometry atomic scattering using matrix methods. Non-physics projects encompass many other student interests. One student was curious about gerrymandered US congressional districts and decided to compute their correlation dimension to see if they’re complex enough to have a fractal boundary. A student athlete designed a project to analyze some common weight lifts. She was able to get experimental data from the kinesiology department, developed a simple model of two basic lifts, and analyzed the data relative to her model. Another project entailed a 2D rule-based (cellular automaton) model of traffic flow and was able to reproduce the effect of a simple yield growing into a major traffic jam. While not physics, per se, all these projects are precisely the kinds of problems we’d like to think physicists could solve.

The program’s original goals were to fill a perceived need reported by graduates, provide a recruiting tool for attracting new physics majors, and serve as a retention tool to offer flexibility to current students. We did a program assessment in

| Table 1. Comparison of courses required for the computer physics and physics degrees. The numbers of courses included in the category are in parentheses. |
| Computer physics | Physics |
| Core physics (8) | Core physics (8) |
| Math (5) | Math (5) |
| Chemistry (1) | Chemistry (2) |
| Computer science (1) | Advanced physics (3) |
| Advanced physics (2) | Advanced lab (1) |
| Methods of CP (1) | Senior electives (2) |
| Advanced CP (1) | |
| Senior elective (1) | |
| Capstone CP project (1) | |
2004 that included a survey of graduates that we continued informally, with more formal studies in 2008 and 2014. The surveys' typical response rate was about 35 percent, although the first one was closer to 50 percent. Survey questions covered course and program satisfaction, perceived value in career, and open-ended general questions.

Respondents reported high satisfaction with CP courses, with an average of 4.1 on a 5-point scale over the three dedicated CP courses. Satisfaction was somewhat lower for the computer science courses. The introductory computer architecture course was rated at 2.5, with student comments indicating the course wasn't very challenging. Our students, however, don't take all the prerequisites that would allow them entry into a more advanced architecture class. The question is under discussion in the physics department. Regarding course utility in respondents' current position, the CP classes were rated somewhat lower, at an average score of 3.3 on the 5-point scale. Comments indicated that students have learned much more postgraduation that is relevant to their current position, so this decrease is understandable. Next, graduates were asked to rate their satisfaction with the methodologies they were taught in the program. Not surprisingly, computational methods were ranked highest at 4.2 out of 5, with research a close second at 4.0, and theory and modeling tied at 3.8. Interestingly, experimental techniques were rated lowest at 3.3. Perhaps this is telling us that facility with programming and developing numerical models is a rather different skill than building and using experimental instrumentation. CP graduates ranked their overall satisfaction with the degree at 4.5 out of 5.

Some basic student data provide further assessment details. Graduation data (see Figure 1) show that the fraction of CP graduates grew rapidly from inception in 1998 to about 20 percent of the department's total graduates (which averages 18 to 20 per year).

Fluctuations are large due to the small numbers, but 20 percent means roughly four CP students graduate per year, not insignificant for a department this size. Comparing the number of incoming freshman physics majors over all four degree sequences to the number of graduates gives another useful bit of information (see Figure 2): the program isn't meeting our original expectations that it would attract majors from high schools.

In fact, Figure 2 implies that the majority of CP graduates are internal transfers from other programs. It's actually the only one of the four degrees that has more graduates than incoming freshmen. The other three programs show noticeable attrition, especially the engineering physics degree, simply indicating that 18-year-olds don't always make the right choice of future career. This argues that the CP degree program is more of a retention tool than a recruiting tool. We have anecdotal evidence that those who switch to CP from another physics program would have left physics had the CP program not been there.

Graduates of the program distribute themselves in similar percentages as physics majors to graduate school (roughly 40 percent) and directly to employment (roughly 60 percent). Of those taking jobs directly after graduation, 75 to 80 percent go

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Figure 1. Annual percentage of total graduates in each of four physics degree programs at Illinois State University. The black bar is the computational physics (CP) degree.

Figure 2. Number of incoming freshmen physics majors (left) and number of physics graduates (right), 2000 to 2014, shown for each degree sequence. The black bar is the CP degree.
into a technical field (35 percent computer related, 40 percent engineering, 25 percent other), with nearly 12 percent of those attempting to organize startup companies. Graduate school-bound graduates are less likely than their physics degree counterparts to study physics. About half go on into physics, while 40 percent choose to switch fields into electrical engineering or computer science, and 10 percent into other fields.

**Why Isn’t This Easy?**

We’ve seen some indication of why computational physics programs don’t exist in every physics department. First, the fact that such programs to date have required one or more devotees to champion the cause implies that there isn’t universal acceptance of CPE in physics departments. Indeed, discussions at topical conferences indicate a relatively high rate of recalcitrance toward CPE among physics faculty. The fact that the Oregon State and Lawrence programs didn’t survive their creators’ retirement could be symptomatic of this issue. Perhaps due to the long tradition of theory versus experiment, the fact is that many of our colleagues find computation a “lesser” approach to physics and are unwilling to replace theoretical and/or experimental training, either in specific courses or in curricula. In a web and email survey that included input from 252 physics departments a decade ago, Robert Fuller found that even though a significant fraction of respondents agreed that computation is important in physics, when it came to actually teaching CP in physics departments, fewer than 20 percent included any graded CP assignments in their courses. Another issue affecting faculty perception of the field is that CP can change rapidly and physics faculty aren’t used to this. The discipline changes remarkably slowly on the timescale of a faculty career: Newton’s laws aren’t going to disappear even though their domain of validity has been significantly restricted. But computation is different. When I started programming, the idea of writing code to be efficient on a multicore parallel architecture machine wasn’t on my radar screen. The point is that there are reasons why some non-computational colleagues aren’t friends of CPE, and we might need to deal with this in creating a new CP program.

A second point is implicit in the decision to terminate the CP BS at Oregon State: low numbers. The Illinois State program only graduates three to four students per year. Viewed as an independent program, this would be difficult to justify. The administration at Illinois State is able to look more globally and treat the CP sequence as one component of the overall physics department educational output, which also includes three other degrees and a large service course and general education load. Administrative support is also important in how curricular reform is valued in tenure and promotion decisions. If you aren’t rewarded, the hard work of creating something new might not seem worth the effort. CPE requires resources, both human and hardware. If colleagues and administrators are open to faculty searches for computationalists, and if funds are available for computing needs, the cause of improving computation education is made that much easier.

Finally, it’s worth accounting for student attitudes toward CPE. Surveying high school students in physics classes, we found that such students don’t have computational physics on their radar. They simply don’t know what it is and why it might lead to exciting research or an employable degree. This is consistent with the Illinois State finding that most CP majors come through internal transfers, and it argues that spending a lot of time and funds on recruitment at high schools for CPE majors might not be a high priority. Some students already majoring in physics actively dislike computing when they encounter it embedded in a physics course. Others find it difficult to distinguish computational physics from computer science, seeing them as more or less the same field but perceiving a computer science degree as easier and more employable. Being aware of these attitudes can help faculty advise students more effectively.

It’s not all bad news, though. The number of conferences and journal special issues in the past decade or so indicate an increasing energy in the CPE community. A web search for physics departments that have any sort of CP in the curriculum shows a growth in the number of such programs. Nineteen programs advertise full degree programs as well as CP concentrations (also called options, tracks, specializations, and so on). Table 2 summarizes some findings. The number of physics courses “lost” was estimated by comparing the CP degree course requirements with those of the physics degree. The last row gives information on the basic Carnegie classification of the institutions, which gives a sense of their primary mission.

There is a clear distinction between the institutions that offer two or more CP courses and those that offer zero or one course. The latter group requires more computer science and/or computer math courses, with little actual computational physics. In that respect, a physics major and a computer science...
minor, which could be done at many universities, might be a similar experience for students. Of the two institutions in this group advertising a BS in CP, one has no CP courses and no indication of CP integration, while the other doesn’t have a separate physics degree, so this degree in “Physics and Computational Science” is the only program with any physics courses. The institutions offering two or more CP courses read more like a program concentrating on CP. Several have some CP integrated into other physics courses, and some have senior theses that can also be computational. Of the 19 total institutions with a web presence in computation physics education, only 7 are classified as primarily research universities (R/VH), indicating that curricular reform is just as likely at less research-oriented universities.

Developing a curriculum including computational physics in a meaningful way is not straightforward. I’ve extracted some relevant information out of a short history of CP education at the undergraduate level, out of direct experience with one program, and out of a search for current programs. I summarize below what might be worth thinking about if your institution wants to create such a program, and what can be expected along the way:

- As with most new projects, a dedicated team of proponents is usually necessary to get started. Then a broader team of supporters can help keep the program viable as it matures.
- Recalcitrant faculty might need to be brought along by educating them on the value of CP for physics students both in future research and in future employment, as well as CP’s place in the discipline now and that perhaps some experiment and theory can realistically be replaced with CP.
- Administrative support is important in clarifying the value the institution places on curriculum development and in taking a broad view of the standard measures used to allocate resources.
- CPE community discussions (conferences and so on) can be very motivational and allow like-minded people to communicate what works and what doesn’t.
- Don’t expect CP curricula to enhance recruitment of students to CP out of high schools, but it can work as a retention tool, offering those not satisfied with traditional physics a very viable option.

Table 2. Characteristics of US computational physics programs.*

| Characteristic     | ≥ 2 CP courses | < 2 CP courses |
|--------------------|----------------|----------------|
| Degree type        | 4 BS, 7 concentration | 2 BS, 5 concentration |
| Mean no. CP courses | 2.4 | 0.8 |
| Mean no. CS/math courses | 2.7 | 3.9 |
| “Lost” physics courses | 4.2 | 3.0 |
| Carnegie class     | 4 R/VH, 2 R/H, 3 M | 3 R/VH, 3 R/H, 3 M |

* R/VH indicates a very high level of research, R/H is a high level, and M is for institutions that grant MS degrees as their highest degree.

Do expect that student satisfaction can be quite high for those who find a home in computational physics.

Nineteen current programs advertising CP curricula were discovered via web search. Of those, none are programs that integrate computation into existing physics courses, 11 are physics-based CP programs with two or more CP courses, and 9 seem more like joint physics-computer science-math programs, with one or no CP courses. Fewer than 50 percent of the institutions with CP programs are classified as primarily research universities.

Already we’re seeing techniques from high-performance computing and big data finding their way into undergraduate courses. Can machine learning and computational model building be far behind? With so many recent conferences and special journal issues devoted to CPE, as well as many new CP programs being created and tested, it’s a time of energy and innovation in the field. If momentum continues, I suspect that the value of applying computational thinking to teaching physics will begin to be better appreciated. The time would be right for physics education researchers to include computational pedagogy in their purview. I, for one, look forward to CPE making a major impact on how physics is taught and learned.

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