

Integrating computation into the undergraduate curriculum: A vision and guidelines for future developments

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There is substantial evidence of a need to make computation an integral part of the undergraduate physics curriculum. This need is consistent with data from surveys in both the academy and the workplace, and has been reinforced by two years of exploratory efforts by a group of physics faculty for whom computation is a special interest. We have examined past and current efforts at reform and a variety of strategic, organizational, and institutional issues involved in any attempt to broadly transform existing practice. We propose a set of guidelines for development based on this past work and discuss our vision of computationally integrated physics. © 2008 American Association of Physics Teachers.

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I. INTRODUCTION

Physics education needs to respond to changes in science and engineering unleashed by the ready availability and the power of computing. This paper documents that need and offers a vision of how computation might be integrated into undergraduate physics curricula. We recognize that one size will not fit all ways to realize this vision, and we offer a set of guidelines in Sec. IV for coordinating future developments of any relevant curricular reforms. We hope that the guidelines are sufficiently general to accommodate many approaches, yet specific enough to hold promise of coherent reformative outcomes that will mutually support one another.

This paper is the result of a two-year study of computation in undergraduate physics—past and present—and presents the possibilities for increasing its presence in the future. The results of this study have a history and are the basis for our guidelines. The first part of this paper relates how, starting with a recognized need, we identified interested faculty and formed a community for developing information about current computation practices. The second part describes a representative sample of this information along with pointers to more detailed information developed in the study. We then present guidelines inspired by the aggregate results of the study.

Although we use the terms “we” and “our,” the authors are only spokespersons for the many contributors who have engaged in the study at various levels. These contributors are listed in the Acknowledgments section.

II. THE NEED

The American Institute of Physics Statistical Research Center conducts surveys and drafts reports based on survey results. A 2002 report entitled “The early careers of physics bachelors”¹ occupies a particularly relevant place in the historical development of our study of computation in undergraduate physics. This report was based on a survey of physics bachelor majors in the nonacademic workplace five+ years after graduation. Figure 1 from the report compares the relative importance of reported workplace activities to the

relative ratings of educational preparedness in four work categories. The largest discrepancies between workplace requirements and educational preparation appear in two of the four categories: use of scientific software and skills for software programming.

These bachelor physics graduates had to learn in the workplace what they did not learn in the classroom. They were able to learn these things outside the domain of their formal education, which though a credit to the current physics curriculum, is hardly optimal for a future evermore dependent on computation. A majority of survey participants said that they would still major in physics if they had to do it again. We propose an alternative to the status quo. We suggest reshaping curricula so that computational methodology becomes a means of understanding the physics as well as useful training for the future, while retaining qualities characteristic of physics education, such as abilities for integrative understanding and adaptive learning.

The need for reform is evident, but the definition of what constitutes suitable reform is far from clear. Our introductory service courses influence students in engineering and other sciences, which number far more than our own majors. Many graduating physics majors end up working in other sciences and engineering, where they flourish and are welcomed as distinctively useful, but where they must engage in computation. Although we have an evident need to include computation at the undergraduate physics level, how to include computation is an open question. This tension between traditional practices and new needs motivated our study of contemporary computational use and future possibilities.

III. THE STUDY

We initially tentatively divided the reform question into several parts. For example, what might a canon of numerical and computational elements in a reformed, standard curriculum look like? Should the changes be additive or transformative? Should they be part of a specific course or integrated into the entire curriculum? What would be needed at the individual, departmental, and institutional levels to implement change? Given our understanding of past reform move-

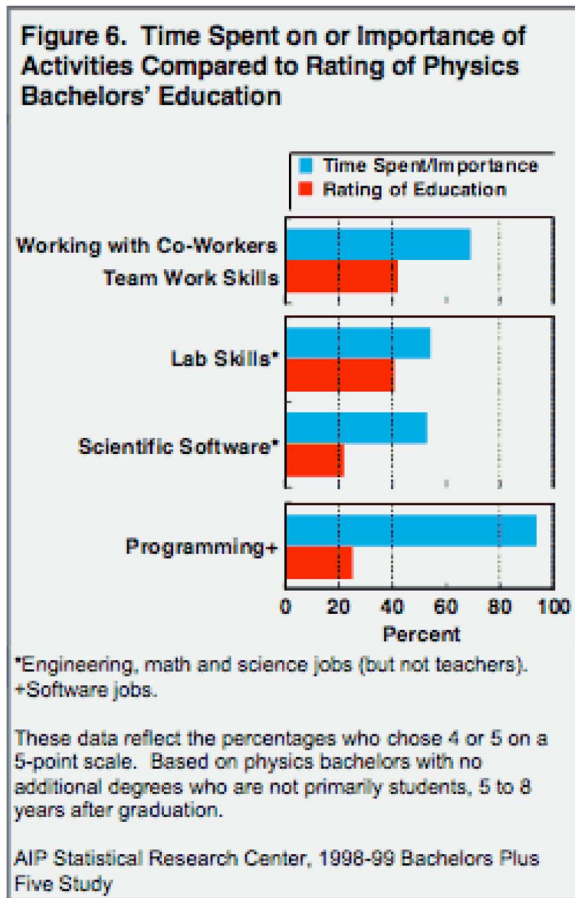


Fig. 1. Time spent on or importance of activities compared to rating of physics bachelors' educational preparation. (Figure 6 from Ref. 1. Reprinted with permission.)

ments and the complexity of the issues involved, we started with little else than the evidence of need and our own experiences with computation in physics. We kept an open mind by conducting an open study, starting at the grass roots. Table I summarizes the sequence of our activities and their essential features.

With the sponsorship of the AAPT Committee on Educational Technology (CET) and the Communities for Physics and Astronomy Digital Resources in Education (compADRE) pathways project, we convened an informal "cracker barrel" discussion at the AAPT Summer 2005 meeting at the University of Utah. Our agenda consisted of a single question: What is a proper role for computation in physics?

Given the generality of this question, the ensuing discussion was wide-ranging. Some would have computation on the first day of the first undergraduate course. Others argued it is only useful in research, where graduate students learn on their own what they would need for their thesis work. Still others pointed out that, unlike traditional physics, every other science now uses and depends upon numerical modeling. Most felt that, because our graduates often end up studying and working in these other sciences, we owe it to our students to prepare them better.

The participants did agree on an agenda for the coming academic year: Have Computing in Science and Engineering (CiSE) magazine sponsor a study of the current computational practices nationally and generate a report. Also, ask

the AAPT-CET to sponsor invited and contributed sessions on computing in physics at the 2006 summer meeting in Syracuse. These points and a synopsis of the discussions are contained in a report that was circulated to the attendees.²

The CiSE editor in chief, Norman Chonacky, and its Education Department editor, David Winch, engaged a physics education researcher, Robert Fuller, to conduct a national survey of current uses of computation in physics courses.³ The survey results provided considerable data on many physics faculty who were doing serious educational work with computation, including those whose work was not well known.⁴ It also revealed patterns of current computational educational practice.

We then used these data to enlarge the discussion of computation by recruiting fresh voices whose works and ideas were not well known to the broader physics education community. These data revealed a wide spectrum of approaches to computation in curricula and a large a variety of implementations, strongly suggesting that a one-size-fits-all approach to reform and a single standard model for computationally infused curricula would not be workable. Instead, we decided to develop broad guidelines that might be useful for setting goals and promoting coherence in the future diverse development efforts that were likely to be needed to move computation into physics curricula.

From descriptions of the survey respondents' work, we extracted four paradigms, which are being used to implement computational use in curricula. We separated respondents according to these four paradigms and identified four instructors whose work was representative of each paradigm. These physics faculty were invited to speak at the AAPT summer meeting in Syracuse.⁵⁻⁸ Table II summarizes the paradigms and their representatives. Papers based on the invited talks and abstracts for the invited posters have been published as a collection.⁹

In addition, we invited 20 faculty respondents, whom the survey data indicated to be very active users of computation in their courses, to attend a working dinner and prepare a poster for a special session. The dinner continued the Utah discussion within this larger group, who were asked to set future priorities. A report on the important community discussions at the dinner is in Ref. 10.

Two principal recommendations for the coming academic year surfaced at the dinner meeting:

- Create venues for the refereed publication of computational education development work and for a stable repository of peer-reviewed education resources.
- Articulate and discuss pedagogy, methodology, and issues relevant to integrating computation into undergraduate physics curricula.

A response to the first recommendation is a current effort to establish a computational physics collection and community in compADRE. A significant response to the second is an informal partnership that coalesced soon after the meeting, the Partnership for Integration of Computation into Undergraduate Physics (PICUP).¹¹ PICUP consists of several physics faculty volunteers under the sponsorship of The Shodor Education Foundation,¹² the Education Committee of Supercomputing 2007 (SC07),¹³ the TeraGrid Project,¹⁴ and CiSE.¹⁵

PICUP's first activity was organizing a cracker barrel discussion on high performance computing for physics and as-

Table I. Sequence of activities for the development of a long-range vision and guidelines for the integration of computation into undergraduate physics.

Date	Activity	Participants	Issues	Outcomes
August 2005	AAPT Cracker-barrel: Building a physics computing community.	~15 faculty and two AAPT administrators including a half-dozen pioneers in computational physics, personally invited, and director of compPADRE.	What is a proper role for computation in undergraduate physics?	<ul style="list-style-type: none"> •Have CiSE sponsor an outside study of current computational practices nationally. •Ask the Instructional Technology Committee to sponsor invited and contributed sessions on computing in physics at 2006 summer meeting. •Create a computation community in compPADRE.
Autumn 2005 - winter 2006	CiSE survey of computational practice in undergraduate physics courses.	~250/750 US institutions that offer undergraduate physics majors represented mostly by individual faculty.	What are you and your department currently doing with computation in your courses?	<ul style="list-style-type: none"> •Identified faculty early-adopters of computation. •Established detailed database of computational activities. •Confirmed importance attributed to computation in courses. •Manifest how insular these beliefs are within departments.
July 2006	1. CiSE working dinner: Future of Computation in Undergraduate Physics. 2. Invited session: Computing in Undergraduate Physics Curricula. 3. Invited poster session: Computing in Undergraduate Physics Curricula.	~25 physics faculty. Four selected physics faculty + one who conducted the CiSE survey. ~25 physics faculty.	<ul style="list-style-type: none"> •Why do computational physics? •What works? •What needs to be done next? 	<ul style="list-style-type: none"> •Present four paradigms for current use environments. •Set up forum to discuss pedagogy, methodology, and issues relevant to integrating computation. •Insure venues for refereed publication of computational education work and materials.
January 2006	AAPT Cracker-barrel: High Performance Computing in Undergraduate Physics/Astronomy.	~20 physics/astronomy faculty, ranging from community colleges to research universities	Isn't it only for research? Why are we inviting you to talk about high performance computing?	<ul style="list-style-type: none"> •Because high performance computing is widespread in the sciences and parallel computing power is coming to the desktop, we must prepare physics education to adopt it in some way.
May 2006	Argonne National Lab: PICUP-produced Visioning Workshop.	~20 physics faculty selected as representative of institutional types and computational use.	Vision and guidelines for undergraduate computational integration?	<ul style="list-style-type: none"> •Goal/objectives for computational integration into undergraduate physics. •Guidelines for future and diverse materials and faculty development projects.

tronomy education at the joint American Astronomical Society winter 2007 meeting in Seattle. Until the entry of SC07 and TeraGrid into PICUP, high performance computing was not part of the discussion. Notably, there was no explicit mention of high performance computing among the computational activities described in the national survey data, even

though high performance computer clusters are now commonplace in science and engineering. Consequently, we expanded the community for integrating computation into physics to include both astronomy educators and those engaged in high performance computing.¹⁶

PICUP committed itself to designing a workshop as the

Table II. Summary of computational development paradigms and their representatives who were invited to give talks at the AAPT Syracuse meeting and write papers based on them for CiSE.

Development paradigm	Representative faculty member	Institution
Computational physics major within the department	Rubin Landau	Oregon State University
Institution-wide commitment and departmental cooperation	Martin Johnston	University of Saint Thomas, St. Paul
Department-wide collaboration	Jaime R. Taylor and B. Alexander King III	Austin Peay State University
Lone individual in a department	Kelly Roos	Bradley University

capstone of our study and to select its participants from among our survey respondents. A planning group drew several conclusions from the Syracuse and Seattle meetings that helped shape the workshop. The three goals of the workshop were to (1) develop a vision of what integrated computation could do for physics education, (2) develop general guidelines for framing a wide variety of future development efforts, and (3) collect illustrative examples of computational modules, as well as calibrate the effort required to produce them.

Most participants were physics faculty selected to balance institutional type, research field, and departmental size, and were organized into small workgroups. The workshop also sought representatives from funding agencies, institutional administrations, and workplaces to constitute an issues panel. The task of each workgroup was to design an instructional module involving computational physics and electricity and magnetism. Details of the organization and content of the workshop are available.¹⁷ A workshop overview and synopsis of its functions are also available.¹⁸

IV. THE OUTCOMES OF THE VISIONING WORKSHOP

Our study provided extensive data on current computational practice and also revealed many issues associated with the serious integration of computation into physics curricula. The vision that emerged is that all physics students should have computational physics as an integral part of their education. Because this vision and our subsequent guidelines for developing it constitute only one interpretation of these data, we wish to share them, the basis for our vision and guidelines, so that others may draw their own conclusions. In this section we present the practices and issues that we extracted from our data, viewed from eight perspectives. More detailed versions of these perspectives appear in EPAPS material referenced in this paper.

(1) Terminology and tacit knowledge. The survey responses and our discussions with faculty indicated a lack of agreement on technological terminology.¹⁹ To avoid confusion we offer our own definitions of terms that might engender misunderstanding:

- Computation: calculations that produce numerical results and render/visualize them.
- Scientific computation/computational science: Two different but related aspects of work with computation. The first is developing methods and algorithms suitable for the second, solving scientific problems by numerical modeling.
- Analytic/symbolic and algorithmic/numerical representations: Two different but related ways of formulating physical laws and modeling physical systems. The first uses the language of continuous functions and differential equations for expression. The second uses discrete functions and difference equations.
- Programming languages: Syntactic sets of words for expressing calculations for computers to perform. Examples are C++ and FORTRAN.
- Computational tools: Packages designed to aid computations by obviating the need to specify explicit algorithms for them. Examples are MATLAB and MATHEMATICA.

(2) Content. Discussions of reforming curricula commonly begin with how topics might be changed and/or rearranged.

However, computational reform will require more.²⁰ Whether the objective is to introduce computations into existing curricula or to integrate computation in radically new curricula, students will need to learn new representations of physics and acquire skills to move easily between new and traditional representations. Change in the organization of content topics will not suffice where change in the content methodologies is the goal.

From the workshop, several findings on methodologies emerged as near-consensus statements. Euler's method for solving difference equations is basic. The fact that it is not symplectic offers motivation to formally study numerical analysis. Finally, the reusability of methods, skill sets, and topics for use in other courses and/or for other disciplines emerged as the most significant criterion for their inclusion in revised content.

(3) Pedagogy. Unlike agreement on content, differences on instruction were a source of major division among workshop participants.²¹ Some favored "teaching the algorithms" as the best approach and others favored "teaching the tools." The underlying differences lie in how one conceives that students construct their understanding of nature. Arguably, constructing algorithms that describe physical processes requires a deeper level of thinking about the underlying fundamental physics than constructing relations that connect physical processes at a higher systemic level. The former approach is fundamental and is necessary for basic science, while latter is pragmatic and well suited for engineering and the applied sciences.

This division in approaches to instruction reflects a well-known split between a scientific computing approach and a computational science approach to computation in physics instruction. Indications of it run throughout the survey data where we see various admixtures of both approaches. Curricular reforms will need to accommodate both approaches. The workshop participants concluded that using both approaches together is better than either alone.

(4) Structure. Changing the way we think about organizing and staffing physics courses is an essential step in deciding what we might modify to fully integrate computation into curricula.²² What possible curricular structures can support some degree of integration? In our studies we have encountered different structures that fall into roughly three different patterns:

- One special course and/or modifications to some or all of the traditional courses.
- Parallel separate tracks for conventional and computational physics majors.
- Completely restructured, fully integrated curricula.

The first of these is the least radical and disruptive way to introduce computation into the curriculum. One devoted faculty member can support such a structure, but it is not effective for curriculum-wide integration. Currently most computational reforms conform to this pattern.

A separate degree program in computational physics or computational science operating in parallel with the standard physics major is more radical but not too disruptive. These programs operate under the aegis of the physics department or in a few cases in a computational science consortium. They typically share some courses with the standard program, but have a distinctive, hybrid set of requirements. These programs require two or more faculty to support them.

In cases where computational science is the program purview, faculty may come from several departments, which may be advantageous or problematic for staffing.

The third of these is both radical and disruptive. Ideally, this change would coherently integrate computation across an entirely transformed curriculum. A few current programs can be said to approach this ideal. We conclude that the goal of comprehensive computational integration awaits some new, yet to be conceived paradigm and base this claim by analogy to certain past successful curricular reforms (*c.f.* Microcomputer-Based Laboratories and Workshop Physics).

(5) Implementation. What implementation strategies serve computational integration?²³ There are two strategic areas that particularly affect the shape and speed of integrated computational implementation. One area is cooperation and collaboration where the strategy is for identifying stakeholders in one's own institution who are willing to join planning and creation processes and for dealing with them. Past examples indicate that dedication to the cause by a one or two physics faculty members, although proven to work for making incremental reforms, is inadequate for comprehensive computational integration. For computation to enter every physics course requires that all departmental faculty be amenable to including algorithmic formulations. Such accord will be possible when algorithmic representations of physical laws become as universally accepted as calculus or graphical representations are today.

The other area is setting priorities where the strategy is deciding what courses to address and in what order. Advanced courses, most especially the dedicated course, are the easiest targets for reform, but reach the fewest students. The largest student populations are in the introductory service courses. Some cost/benefit analyses at the planning stage would be helpful for fixing strategies and drawing a good implementation plan.

(6) Materials. Our workshop allowed us to evaluate various module development tactics and roughly calibrate materials development costs.²⁴ The module produced by the typical workgroup included both the computational physics and the scientific computation approaches. Although the balance between the two approaches varied widely among workgroups, their joint incorporation reflects the belief that both are essential in any computational integration into physics. The typical development effort required was two person-weeks to create a preliminary version of a single concept module for student use as an assignment. Other considerations, for example validation and testing issues and archiving facilities, surfaced in workgroup plenary discussions, but could not be explored within the scope of the workshop.

(7) Faculty development. The question of faculty development is important and daunting.²⁵ A significant finding of the survey was a contradictory divergence between individual respondents' attitudes toward numerical computation in the curriculum and the aggregate attitudes of their departments. Figure 2 depicts the distribution of individual respondents' attitudes. Compare this distribution to that of the fraction of faculty in each respondent's department who require computation in their courses as a portion of a student's grade. We count such a requirement as a faculty member's commitment to computation in the department's curriculum and show in Fig. 3 the distribution of departmental commitment at institutions responding to the survey. Our interpretation of this distribution is that a small fraction of faculty currently does most of the computational work in a typical department. We

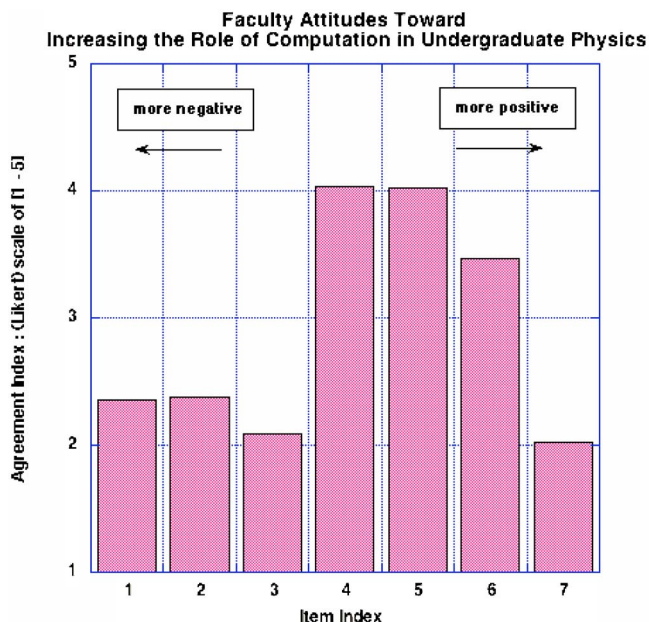


Fig. 2. Average Likert rating by 187 individual faculty evaluating their attitudes on importance of computation in undergraduate physics (Items 1–3, do not favor significant role; Items 4–6, favor significant role; Item 7, favor exclusive role.) Likert scale: 3 indicates neutral attitude, <3 indicates disagreement, >3 indicates agreement, referring in each case to the survey item.

conclude that there are many faculty minds to change, not just faculty skills to train. No program to integrate computation into undergraduate physics can succeed without an effort to do so.

Some factors likely to confront any faculty development effort include changing faculty ways of thinking about how

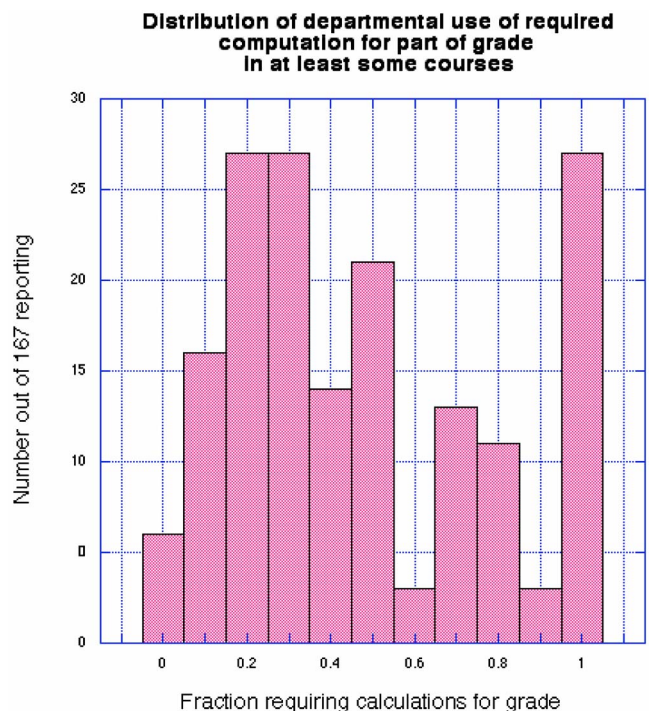


Fig. 3. Number of departments reporting versus fraction of departmental faculty requiring computation work in course grade.

numerical computation fits into both physics and the many other disciplines that physics graduates support, finding a balance between being a computer system expert and a computer Luddite, and recognizing the power of social arrangements to facilitate faculty learning, especially if the new knowledge is radically different.

(8) Support and sustainability. One of the most surprising and interesting outcomes was the expressed need to sustain any computational integration agenda beyond generating materials and developing initial faculty interest in using them. This need was succinctly put by a participant asking “What’s the business model?”²⁶ The discussions that ensued might be an interesting case study for comparison, but did not lead to any consensus and only emphasized the complexity and urgency of creating a business model. Like the question of how to discover a new paradigm for radically restructuring physics curricula, this challenge is open.

V. CONCLUSIONS AND RECOMMENDATIONS

The vision that has emerged from the survey is that all students of physics will have computational physics as an integral part of their education, including students who are physics majors and any student who takes a physics course.

Projects to develop and support the integration of computation into undergraduate physics need guidelines that are both coherent in content and adaptive in applicability to a wide variety of reformative approaches. We offer the following guidelines for critique, debate, and revision:

- (1) Both computational physics and scientific computation are important approaches to computational work, and the education of physicists should offer an understanding of both.
- (2) Both analytic and algorithmic methods of formulating models of physical phenomena are important in science and engineering and, hence, physics education should treat both of these methods and connections between them.
- (3) The use of scientific software is important to all the sciences and engineering. All physics students should be able to write and validate at least simple programs in at least one third-generation language and be capable of learning on their own to use at least the rudiments of scientific software tools.
- (4) Complicated systems, for example those containing chemical, geological, and biological subsystems like nuclear waste disposal, require numerical methods for representing intersystem interactions. The materials, methods, and content of physics courses should embody elements of numerical modeling that emulate its capability to relate interactions across disciplinary boundaries.
- (5) There are many algorithms that are important in modeling and some of these are particularly well used in physics. Any development project should include algorithms on the basis of their transportability within the body of physics phenomena and their vertical extensibility from simple to sophisticated applications.
- (6) The proliferation of computing platforms and technologies is a permanent feature of the technological landscape. Development projects should seek the most universal implementation formats for materials they create.
- (7) Thinking computationally is a matter of acculturation to which most physics faculty members have not yet sub-

scribed. Development projects should acculturate new acolytes by stressing accessible technologies such as visualization as a tool for discovery and the spreadsheet as a useful tool for effectively initially learning to model numerically.

- (8) The comprehensive integration of computation into undergraduate physics curricula will require a supportive social network linking developers and users, including pioneers, early adopters, willing followers, and holdouts. Any development project should outline ways in which the capabilities of developers will be harnessed to the needs of various users.

Our specific recommendations for early actions include the following:

- Jump-start large-scale engagement of faculty imaginations with the concept of computational integration by developing computational exercises keyed to popular texts at all levels.
- Develop a provisional taxonomy, if not a detailed set of relations, connecting physics concepts to computational skills and methodologies.
- Include high performance computing as a high priority for incorporation into undergraduate curricula.
- Under the auspices of an appropriate professional society, develop a commonly accepted set of standard outcomes (for example, ABET engineering accreditation criteria) that any physics curriculum having integrated computation, however implemented, should have.²⁷

We invite the physics community to scrutinize, test, and debate our vision and guidelines. We recognize that we failed to identify many active or interested educators who may be interested in contributing to this discussion or joining this effort. We invite interested readers to share their departments’ experiences with computation by adding these to the survey database,²⁸ or you may convey your interest in becoming an active part of this developing community and/or in sharing your computational materials.^{29,30}

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Education Committee. Davidson College was the host in July 2007 of a topical conference on computational physics for upper level courses.³¹ Several members of PICUP participated in this conference. A summary of the results of our efforts appeared in the opening talk.³² The plenary talks and open discussions provided additional material for this paper, for which we are grateful.

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¹R. Ivie and K. Stowe, *The Early Careers of Physics Bachelors* (American Institute of Physics, College Park, MD, 2002), AIP Pub. R-433.

²See EPAPS Document No. E-AJPIAS-76-002804 for all reports and data related to the results. This document can be reached through a direct link in the online article's HTML reference section or via the EPAPS homepage (<http://www.aip.org/pubservs/epaps.html>).

³Survey questionnaire for uses of computation in undergraduate physics, (www.computer.org/cipcs).

⁴R. G. Fuller, "Numerical computations in U.S. undergraduate physics courses," *Comput. Sci. Eng.* **8**(5), 16–21 (2006).

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⁸R. Landau, "Computational physics: A better model for physics education?," *Comput. Sci. Eng.* **8**(5), 22–31 (2006).

⁹Special issue on "Computation in undergraduate physics courses," *Comput. Sci. Eng.* **8**(5) (2006).

¹⁰Notes from the computational physics dinner discussion at the Syracuse AAPT July 2006 meeting, edited by David Winch. Reference 2, item #2.

¹¹Partnership for Integration of Computation into Undergraduate Physics (PICUP) membership list. Reference 2, item #3.

¹²The Shodor Education Foundation home page (www.shodor.org/).

¹³Supercomputing 2007 Education Committee home page (sc07.supercomputing.org/?pg=education.html).

¹⁴The TeraGrid Project home page (www.teragrid.org/about/).

¹⁵Computing in Science and Engineering home page (www.computer.org/portal/site/cise/).

¹⁶Notes from the Seattle AAPT/AAS January 2007 meeting on "High-performance computing in undergraduate physics and astronomy," edited by Norman Chonacky. Ref. 2, item #4.

¹⁷Description of organization and operation of Argonne workshop (<http://compphysed.shodor.org/>).

¹⁸Argonne workshop - overview, structure, and functions. Reference 2, item #5.

¹⁹Workshop findings from the technology perspective. Reference 2, item #6.

²⁰Workshop findings from the content perspective. Reference 2, item #7.

²¹Workshop findings from the pedagogical perspective. Reference 2, item #8.

²²Workshop findings from the strategic perspective of rethinking curricular structures. Reference 2, item #9.

²³Workshop findings from the strategic perspective of implementation. Reference 2, item #10.

²⁴Workshop findings from the tactical perspective of materials development. Reference 2, item #11.

²⁵Workshop findings from the tactical perspective of faculty development. Reference 2, item #12.

²⁶Findings from the business model perspective. Reference 2, item #13.

²⁷Current criteria for accreditation of various types of engineering-related programs. Accreditation Board for Engineering and Technology (ABET) website (www.abet.org/forms.shtml).

²⁸For adding your department's experiences with computation in its courses, fill out the survey of uses of computation in undergraduate physics: (www.computer.org/cipcs).

²⁹To convey your interest in affiliating with PICUP for future development work, please contact Norman Chonacky, norman.chonacky@yale.edu.

³⁰To express interest in sharing your instructional materials for computational applications to physics with Compadre contact David Winch at winch@kzoo.edu.

³¹Davidson Conference on Computation in the Upper Division Physics, Davidson College, July 2007 (www.opensourcephysics.org/CPC/).

³²N. Chonacky, "Computational applications to physics, other sciences, and engineering," slides from presentation at the Davidson Conference. Ref. 2, item #14.