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COMPUTATIONAL SCIENCE AND ENGINEERING EDUCATION: SIAM'S PERSPECTIVE

By Hans-Joachim Bungartz, Donald Estep, Ulrich Rüde, and Peter Turner

This year's SIAM CSE conference featured a structured program on education that sought to attract attention to and sustained interest in this essential topic.

No question, the story of computational science and engineering (CSE) is one of success. Today, research in almost every field of science or engineering critically depends on a systematic approach to computations or simulations. However, compared to its research maturity, CSE's academic education and career path is still somewhat muddled. On the one hand, for example, we have specialized "Computational *X*" programs and courses; on the other, scientists claim that merely adding "some computing flavor" to established curricula suffices—and actually might be the best approach. Also, researchers who want to create a CSE study program at their universities have no guidelines, skeletons, or even professional societies to guide them. Rather, they face considerable (and organized) "disciplinary" resistance. Hence, the typical outcome will be some mixture of the initiating group's ideas and their institution's available resources and restrictions; the result is not necessarily bad, just inappropriate. Many colleagues active in CSE research or education are aware of this situation, and at least some kind of an education-related event has become a quasi-standard in CSE meetings or conferences. Nevertheless, there's still a somewhat astonishing lack of both organization and convergence.

Many members of the Society for Industrial and Applied Mathematics are closely involved with CSE education and research, and SIAM conferences have included numerous CSE-related educational activities and talks. However, the program committee for SIAM's 2009 CSE conference held 2–6 March in Miami decided to put together a more structured CSE educational program by bundling educational activities and events with the goal of attracting more attention to this important topic, as well as obtaining increased sustainability. Because the presentations and discussions during and after that meeting are relevant for everyone in CSE or computing, we present here a summary of them for *CiSE* readers. We also discuss our PhD student paper competition; its impressively high level shows that at least the upper end of the CSE education pipeline already is in rather good shape.

Undergraduate Education: Program Highlights

The 2009 SIAM CSE conference reflected the growing interest in undergraduate CSE activities. Mini symposia were devoted to new study programs in computational applied mathematics, enhancing the awareness of programs and student opportunities and showcasing selected undergraduate research projects. To some extent, all such issues have been addressed at previous CSE meetings. However, the growth of interest and participation over time clearly reflects an increasing demand for continuing discussions.

Tuesday morning featured the "Innovative Programs in Undergraduate Computational Mathematics" session organized by Eric Kostelich (Arizona State University). This mini symposium comprised presentations on four intensive CSE summer research programs at four very different schools. Each program fosters curricular initiatives and features short courses on various application topics. Several of the programs are funded through the US National Science Foundation's Computational Science Training for Undergraduates in the Mathematical Sciences (CMUMS) initiative (www.nsf.gov/funding/pgm_summ.jsp?pims_id=13655).

Such programs well illustrate the range of mathematical topics and application areas appropriate for undergraduate student research activities and involvement. A common program theme is the immersion approach to early CS instruction. At Brigham Young University, for example, students must attend a "boot camp" that covers the mathematical, statistical, and computational foundations they need to pursue independent research projects. Those same fundamentals,

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often enhanced by other topics for particular programs or applications, can form the basis of student research across diverse applications. At Arizona State University, for example, this common background prepares students for further CSE research in such diverse areas as cancer dynamics, atmospheric science, fluid dynamics, or mathematical finance. In another presentation, participants described a new CS undergraduate program at The New Jersey Institute of Technology that comprises many of the same fundamental course topics and application areas. Finally, presenters described George Mason University's program, which has two tracks; once students have completed them, they have the opportunity to join an NSF CSUMS program, which offers a yearlong CSE research experience.

Thursday was a busy day! Angela Shiflet (Wofford College) organized a mini symposium on "Spreading the Word" about CSE undergraduate education. In one of the featured presentations, the Shodor Foundation's Bob Panoff gave a remote presentation (via cellular phone and computer speakers) on petascale computing and how to incorporate high-performance computing into the undergraduate experience. Shiflet—joined by her partner, George Shiflet—discussed their course at Wofford, which brings the power of, and interest in, CSE to biology labs by modeling the spread of disease.

The final presentations focused on publicizing and publishing CSE undergraduate research and pedagogical work in a better and more visible way. Steve Gordon (Regula School of Computational Science) discussed the new peer-reviewed *Journal of Computational Science Education*. The journal provides a much-needed new outlet for developments in CSE education including lesson plans, projects, and assessment or evaluation pieces. Peter Turner talked about the new SIAM publication, *Undergraduate Research Online* (SIURO), which is devoted to publishing some of the best undergraduate research in computational and applied mathematics (www.siam.org/students/siuro). In addition, the SIAM Web site offers its initial working group report on *Undergraduate Computational Science and Engineering Education* (www.siam.org/about/pdf/CSE_Report.pdf).

The growing interest and participation clearly reflects an increasing demand for undergraduate programs and research opportunities.

Two further sessions on Thursday afternoon were devoted to student presentations; the quality was outstanding, which has been typical of both undergraduate and graduate student presentations. Clarity, preparation, and time-keeping were three hallmarks here that were often lost on more experienced presenters. The sessions included a total of 11 presentations with broad topical and geographical range. Six different institutions were represented, including one from India. Much of the research had resulted from internships and experiences in widely dispersed locations, including Hong Kong, Europe, and around the US.

On Friday afternoon, the undergraduate educational theme was revisited in "Computational Mathematics Topics for Collaborative Curriculum Development," organized by Wright State University's Ronald Taylor. Unfortunately, we were unable to attend what looked to be a very interesting discussion on interinstitutional cooperation and how to introduce CSE to the liberal arts curriculum.

Graduate Education: Structure for the Zoo?

Teaching CSE graduate students is an important activity for many of us. People involved with CSE programs often hold strong feelings about what content is suitable, relevant, and essential for graduate CSE curricula. At the same time, our programs are trapped and hindered by existing university structures. Many institutions have created what are essentially CSE programs that might go by various names and that together present a wide spectrum of solutions to the problem of creating new interdisciplinary programs in a rigid university structure. Providing an overview of this zoo-like collection of programs—while also trying to identify differences and similarities—led the organizers of this year's SIAM conference on CSE to include several sessions on graduate education in CSE.

In the first of a two-part mini symposium, Donald Estep (Colorado State University), Celeste Sagui (North Carolina State University), Lennart Edsberg (Royal Institute of Technology, Stockholm), and Michael Schäfer (Darmstadt University of Technology) offered an overview of existing programs and activities worldwide, with a special focus on the US, Europe, and Germany. In the second part, Chris Johnson

(University of Utah), David Keyes (Columbia University and King Abdullah University of Science and Technology), Marek Behr (RWTH Aachen), and Max Gunzburger (Florida State University) addressed issues important to programs everywhere, such as the handling of students with heterogeneous backgrounds; the ingredients of CSE programs, including specific, tailored modules (beyond "a bit from here and a bit from there"); and last but not least, SIAM's potential role as a promoter of CSE education.

Perhaps in keeping with some hidden rule about all conferences including a panel discussion, we reconvened for one following a brief break. Sometimes, such discussions suffer from a rather obvious lack of interest; in many cases, the organizers' goal shrinks to simply having more people in the audience than on the panel. With this in mind, we were a bit concerned. However, our education panel's members—which included six speakers and organizers from the mini symposia, along with Ulrich Rüde (University of Erlangen) and Misha Kilmer (Tufts University)—were far outnumbered by the audience. Donald Estep acted as moderator and guided the panel and audience through a discussion focused on three main questions:

- What are the characteristics and main ingredients of CSE graduate programs?
- How can SIAM (better) support graduate education in CSE?
- What trends, needs, and threats lie in store for CSE programs and graduates?

Given the spectrum of topics covered and opinions articulated, it's not easy to summarize this multifaceted "educational afternoon." Nevertheless, we now highlight some of the general findings from the presentations and lively discussions.

First, dealing with data and related issues that arise in the simulation context is clearly an important issue in CSE; this CSE research trend will probably increase and our education programs must reflect it. A substantial portion of the SIAM CSE meeting's technical research symposia focused on statistics-related topics, including sensitivity analysis and uncertainty quantification.

Second, the adjectives "interdisciplinary" and "multidisciplinary" have become mandatory vocabulary in most scientific areas, especially (of course) CSE. The still ubiquitous and powerful disciplinary silos, however, frequently turn even the most eloquent statements about the need for interdisciplinary and multidisciplinary programs into lip service.

Third, despite the appearance of an almost astounding number of CSE strategic reports and overviews in the US and elsewhere—which typically address education to some extent—we clearly need a "living" report that we can continuously update. This could define another possible role for SIAM.

Fourth, politics frequently drives the desire to rename things—and thus the urge is probably inevitable—but to some extent, this complicates the actual need to establish a "CSE field" as distinct from the dominant existing programs, such as mathematics or physics. No one at the graduate education sessions, for example, could really articulate the differences between "CSE" and the more recent "simulation-based science and engineering" label; some considered the first as the broader term, while others found the second to be more encompassing.

Fifth, although classical, lecture-based courses will probably remain a core component of CSE graduate programs, there's a tendency to include substantial research-, project-, and team-oriented modules.

Sixth, CSE program development requires both a top-down push (from executive boards, deans, and so on) and a bottom-up push (from experts in the field). Without either of the two, the risk of failure is high.

Dealing with data and related issues that arise in the simulation context is clearly an important issue in CSE.

Finally, establishing dedicated new schools or departments might be the most difficult path initially, but the payoffs will come later—with the hiring and support of new faculty with interests in CSE, for example. This was emphasized by both Max Gunzburger, who chairs Florida State University's Department of Scientific Computing, and David Keyes, who heads King Abdullah University of Science and Technology's Department of Applied Mathematics and Computational Sciences. The latter department's heavy CSE emphasis is definitely one of the world's most exciting academic developments at this time.

The discussions also gave rise to several suggestions for SIAM's role in CSE developments. As we noted earlier, one issue that SIAM could or

Observatoire Landau

Does Broadening Participation in Computing (BPC) = PC?

By Rubin Landau, Department Editor

Last April, I attended the 2009 Richard Tapia Celebration of Diversity in Computing Conference in Portland, Oregon, at which I tried to act my part as mentor to under-represented students. The conference aims to broaden participation in computing (BPC) and provide "a supportive networking environment for under-represented groups across the broad range of computing and information technology, from science to business to the arts to infrastructure." It rained and was cold on the first day, but was bright and warmer at the end. Although I've been familiar with this event since its inception in 2001, this was the first time I attended (only 100 miles away). Many students came to the celebration, and—as expected—they came in various colors, shades, and shapes. What I didn't expect, but was delighted to find, was how bright, well-spoken, socially skilled, and well dressed were the students compared to the physics and CS students I'm familiar with (who tend to possess brightness, but few of the other attributes). In fact, as the days of the conference passed, I became even more convinced that these students were real winners by any standards and should be successful in their various fields.

As if reading my thoughts, the conference ended with Richard Tapia himself addressing the students in a fatherly way and telling them (as I recall) that they should "think of themselves as minority professionals in their respective fields and not as professional minorities." This particularly rang a bell with me. I've spent years in faculty governance, where I've seen "diversity" grow into an industry at our university and have listened to faculty complain about the imposition of politically correct (PC) social programs into their academic specialties. The Tapia Celebration led me to wonder how diversity in computing might especially impact computational science.

Playing my role as a professor type, I did some homework and came up with some data that shows both the problem that CS diversity efforts seek to address and a possible, if partial, solution. According to surveys and reports, the total number of students now in computing is inadequate to meet future (post-recession) needs in the US (see, for example, www.nitrd.gov/pitac/reports/20050609_computational/computational.pdf, www.nitrd.gov/pitac/report, and www.nsf.gov/od/oci/reports/toc.jsp). Other surveys indicate that there are disproportionally few minorities, women, and persons with disabilities in computing (see, for example, www.nsf.gov/statistics/wmpd/pdf/tabc-4.pdf). The data in Table 1 exemplifies this in relation to female students.

As the table shows, in 2004, women earned 21 percent of the bachelor's degrees in CS. That same year, women earned 56 percent of bachelor's degrees in all sciences (42 percent in the physical sciences and 62 percent in the biological sciences). Furthermore, the number of women in CS in 2004 was 8 percent less than that in 1997. So, not only is the percentage of CS degrees given to women lower than that in all disciplines except engineering, the percentage is also decreasing at present. Although I don't have this same measure for other groups, as Table 2 shows, I did find data showing the fields that college freshman intend to major in according to race, ethnicity, and gender (see www.nsf.gov/statistics/wmpd/pdf/tabb-8.pdf).

As Table 2 shows, students enter college with only half to one-thirtieth the interest in computing as they have in other sciences. Given this handicap, higher education can't do much to fix the ultimate underrepresentation.

I do see a positive aspect in these tables, however: because the percentage of underrepresented students in other sciences is significantly higher than that in CS, it seems that we can significantly increase the number of

should take care of is tracking worldwide developments in CSE education. Another closely related idea also emerged from the discussions: What about guidelines for implementing programs in "Computational *X*"? In many countries, professional organizations or university department associations are doing this in other disciplines. For accreditation, for example, a program's design often must follow established recommendations or at least rough frameworks. However, things that are quite natural for physics, computer science, or electrical engineering don't seem to apply to CSE so far. Although there was a broad consensus that program differences—arising from local boundary conditions, topical ancestors, or specific strongholds—shouldn't be overly constrained or regulated, some guidance would clearly be helpful. And what groups would be better suited to tackle this than the SIAM or *CiSE* communities?

Together, the Miami sessions made it obvious that educational issues of all kinds are a hot topic in CSE. Although we identified many problems, the story has an encouraging side, too: The excellent quality of the student paper competition's entries clearly showed that CSE graduate education is on a good path.

Table 1. Percentage of bachelor's degrees given to female students by science field.

Year	All science and engineering	Agriculture	Biology	Computing	Earth	Physical	Social	Engineering
1997	55.7	46.4	58.5	28.0	40.0	41.1	54.2	20.5
2004	55.7	51.5	61.7	20.5	41.2	42.4	53.7	19.5

Table 2. Percentage of freshman intending to major in various fields by race, ethnicity, and gender (2006).

Race, ethnicity, and gender	All science and engineering	Biology and agriculture	Computing	Engineering	Physical	Social and behavioral
White (female)	24.2	8.1	0.3	2.2	1.9	11.0
Black (female)	32.1	11.0	1.1	2.3	1.6	15.7
Hispanic (male/female)	35.9	9.8	1.2	6.4	2.1	15.5
American Indian (male/female)	34.4	10.0	1.6	7.5	2.7	12.2

students educated in computation, and broaden participation in computing by bringing CS-level computation into more of the sciences. So, rather than trying to bring diverse students into CS, we can bring computation to where the students are. This is exactly what many of us in CSE education have been trying to do in our own particular ways for some time (for an example, see the Computing Research Association's program on Women in Computing Research at www.cra.org/Activities/craw/projects/best_practices.php). Furthermore, other surveys have found that students not currently attracted to CS's hardware and software aspects become more interested in computing after they learn how essential it is to solving many societal problems.[1]

Although I know of no data to substantiate it, broadening participation in computing is not only a socially responsible thing to do, it should benefit computational science as well. As the US National Science Foundation states, "the under participation of these groups causes a loss of opportunity for individuals, a loss of talent to the workforce, and a loss of diverse perspectives and creativity that are needed to shape the future of technology." Furthermore, because "diverse" students will be incorporating computation into diverse fields, we should see an increase in the need for original, creative, and challenging applications of computing. This, in turn, should bring new challenges and advances into CS (which in my view has turned inward and away from applications in recent times).

So, the CSE community has much to gain here. By teaching and incorporating computation in fields other than CS, we'll help meet the nation's need for well-educated IT workers, correct some social wrongs of the past, better use computation to solve societal problems, and bring new ideas into CS. We'll also meet some very interesting people. And, if it helps sell some more of my books, well that's okay, too.

Reference

1. J. Cuny and W. Aspray, *Recruitment and Retention of Women Graduate Students in Computer Science and Engineering,* report, Computing Research Assoc. Committee on Status of Women in Computing Research, 2001; www.cra.org/reports/r&rwomen.pdf.

The 2nd Biannual BGCE Student Prize

Following a successful debut two years ago, the SIAM Conference on CSE once again hosted a thriving student paper competition, sponsored by the Bavarian Graduate School of Computational Engineering (BGCE). The BGCE is a consortium run by two Bavarian universities—Technische Universität München and University of Erlangen Nuremberg—that offer a joint international master's program with an honors track for the best and most motivated CSE students. The biannual competition, which is open to both undergraduate and graduate students worldwide who haven't yet completed their PhDs, aims to promote both excellence and the CSE-typical breadth by recognizing outstanding student work. The competition's prize is a one-week trip to Bavaria as a guest of the BGCE.

This year, 14 students from seven countries submitted entries consisting of a four-page short paper or extended abstract describing their work. Based on these contributions, BGCE selected finalists from five countries, who were invited to present their work in two mini symposia at the SIAM conference. Figure 1 shows the eight finalists:

- Julianne Chung (Emory University): "Numerical Algorithms for

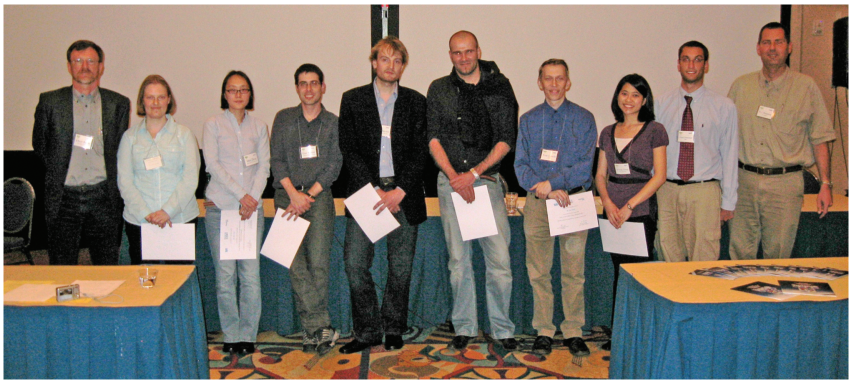

Figure 1. The eight finalists for the second biannual Bavarian Graduate School of Computational Engineering student paper competition flanked by two BGCE representatives. From left: Ulrich Rüde (BGCE), Gisela Widmer, Min Zhou, Eran Treister, Mike Nicolai, Christoph Mack, Toni Lassila, Julianne Chung, Chad Lieberman, and Hans-Joachim Bungartz (BGCE).

Polyenergetic Digital Breast Tomosynthesis Reconstruction";

- Chad Lieberman (Massachusetts Institute of Technology): "Parameter and State Model Reduction for Uncertainty Quantification in Large-Scale Statistical Inverse Problems";
- Christoph Mack (French National Centre for Scientific Research/Ecole Polytechnique): "Global Hydrodynamic Stability Analysis of Large-Scale Compressible Flows Using Krylov Techniques";
- Gisela Widmer (Swiss Federal Institute of Technology Zurich): "Adaptive Sparse Finite Elements for Radiative Transfer";
- Min Zhou (Rensselaer Polytechnic Institute): "Local Partition Modification for Improved Parallel Finite Element Computations";
- Toni Lassila (Swiss Federal Institute of Technology Lausanne): "How to Get in Better Shape (Mathematically)";
- Mike Nicolai (RWTH Aachen): "Towards Shape Optimization for Fluids Involving Complex Shape Parameterization"; and
- Eran Treister (Technion): "Square and Stretch Multigrid for Stochastic Matrix Eigenproblems."

The student talks were, as always, simply superb. Moreover, the talks highlighted many of the central issues of CSE research. Clearly, CSE graduate education is in fairly good shape at the fundamental level. In addressing important problems from various application areas—such as medical imaging and low-temperature physics—the presentations also highlighted the underlying mathematical and informatics principles that lead to effective and efficient computational tools. Moreover, the finalists all gave clear and well-organized presentations, leaving the judges with a very difficult task.

The international prize committee, consisting of Esmond Ng, Peter Turner, Carol Woodward, Kirk Jordan, Padma Raghavan, Scott MacLachlan, Hans Petter Langtangen, Hans-Joachim Bungartz, and Ulrich Rüde, ranked the students on their work's technical merit and the presentation quality (including both the submitted papers and the mini symposia talks). The presentations' uniform excellence, however, resulted in a statistically insignificant difference between the finalists' average scores. On behalf of the entire prize committee, we once again congratulate all of the finalists for their impressive performances.

After two hours of truly difficult deliberation, the committee agreed to award the prize to Gisela Widmer from the Swiss Federal Institute of Technology Zurich for her paper, "Adaptive Sparse Finite Elements for Radiative Transfer." Her work nicely highlights CSE's research path: motivated by the real-life problem of modeling energy transport in plasma arcs, she developed an accurate and efficient computational technique based on a sparse tensor-product discretization and a preconditioned Krylov method solver. Widmer also managed another astonishing feat: she visited Bavaria outside Bavaria. That is, as her prize, she joined BGCE in September for a two-week summer school in the Northern Italian Alps—a joint endeavor of the two BGCE universities that's now in its 26th year.

Because of the presentations' excellent quality, the committee decided to deviate from its original plan and award a second prize—also an invitation to Bavaria—to Chad Lieberman from the Massachusetts Institute of Technology for his contribution, "Parameter and State Model Reduction for Uncertainty Quantification in Large-Scale Statistical Inverse Problems." Lieberman actually made it to Bavaria—in June, where he gave lectures in Erlangen and Munich and enjoyed Bavarian summer (even without drinking beer).

One of the most interesting points that arose from the presentations and discussions is that there are several viable approaches to CSE education and strong opinions about each approach's benefits and pitfalls. We can divide the approaches into two general categories: one that focuses first and foremost on developing a general or methodological CSE educational program and one that's more application-oriented, focusing on training and preparing students to work in multidisciplinary CSE teams. The lively exchanges between proponents of the two approaches gradually revealed that they're not mutually exclusive. Rather, there's significant overlap in the educational components of both, and ultimately, they might simply converge into programs with a common core of training, followed by specialization, that simultaneously instruct students in the skills needed for team-based multidisciplinary research.

Finally, one argument frequently mentioned against all types of CSE training programs is the oft-heard "students get trained a bit in many things, but learn nothing in a profound way." If any refutation—as mathematicians, we'd even dare use the word *proof* here—is still required on this point, the student presentations unanimously showed that there's no intrinsic contradiction between breadth and depth. CSE education at all stages can and must take the challenging, but nevertheless viable route of creating understanding in and enthusiasm for *both* simulation applications from science and engineering *and* simulation methodology from mathematics and computer science, as well as training students to work in multidisciplinary groups. This also means, of course, that we need new educational concepts and modules; this year's SIAM CSE conference offered much insight and inspiration as to how we can achieve them. That said, things are still evolving—so stay tuned! CiSE

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