Computational Science and Engineering Programs in the United States

Donald Estep

Department of Mathematics
Department of Statistics
Center for Interdisciplinary Mathematics and Statistics
Program for Interdisciplinary Mathematics, Ecology, and Statistics
Colorado State University

CS&E Programs in the U.S.

Listing these programs invokes some controversy

- Many programs (self-indentified) have started over the last few years
- This begs the question: “What is a CS&E program?”
- Proponents of different approaches to CS&E programs can be fairly militant
- Some applied mathematicians feel they have been doing CS&E for decades: How do traditional applied mathematics programs fit into CS&E ?

The SIAM Report on CS&E

Appeared in SIAM Review in 2001

The SIAM Report on CS&E

Graduate Education for Computational Science and Engineering

SIAM Working Group on CSE Education

Linda Petzold (Chair); Uri Ascher; H. Thomas Banks; James Crowley; Walter Gander; Leslie Greengard; Michael Heath; Andrew Lumsdaine; Cleve Moler; Tinsley Oden; Robert Schnabel; Kris Stewart; Anne Trefethen

http://www.siam.org/students/resources/report.php

This presents the emerging state of CS&E in the U.S. in 2000

Defining CS&E

"CSE is a broad multidisciplinary area that encompasses applications in science/engineering, applied mathematics, numerical analysis, and computer science."

"CSE focuses on the development of problem-solving methodologies and robust tools for the solution of scientific and engineering problems."

"Going from application area to computational results requires domain expertise, mathematical modeling, numerical analysis, algorithm development, software implementation, program execution, analysis, validation and visualization of results. CSE involves all of this."

Defining CS&E

"Although it includes elements from computer science, applied mathematics, engineering and science, CSE focuses on the integration of knowledge and methodologies from all of these disciplines, and as such is a subject which is distinct from any of them. "

"It differs from mathematics or computer science in that analysis and methodologies are directed specifically at the solution of problem classes from science and engineering, and will generally require a detailed knowledge or substantial collaboration from those disciplines."

Applications Mentioned in the Report

Existing

- Weather and climate prediction
- Combustion
- Nuclear stockpile stewardship
- Simulation, design, and control of vehicles
- Aircraft design
- Electronic design automation

Emerging

- Biology
- Chemistry
- Materials
- Bioengineering

Educational Objectives in CS&E

Quoting:

- ... a CSE graduate must have a thorough education in an application area
- The ... mathematical knowledge will be sufficient to model technological and scientific problems
- Knowledge of computer science, and in particular numerical algorithms, software design and visualization, enable the CSE graduate to make efficient use of computers
- A graduate knows how to find and exploit software ...
- A CSE student performs interdisciplinary work ...
- A CSE graduate is trained to communicate with ... an engineer or physicist and/or a computer scientist or mathematician ...

Core Training in CS&E

Identified core areas in a CS&E curriculum

- Numerical analysis (linear algebra, optimization, differential equations)
- Applied mathematics (modeling in engineering and science, dynamical systems, differential equations)
- Computer science (languages, operating systems, networking, parallel and distributed computing)
- Data analysis (visualization, statistical methods)
- Application areas (working knowledge of an application)

Core Training in CS&E

Identified core areas in a CS&E curriculum

- “It is absolutely essential that interdisciplinary collaboration be an integral part of the curriculum and the thesis research. ”

Ways this is to be achieved:

- Courses should include multidisciplinary projects and presentations whenever possible.
- Participation in a multidisciplinary research team.
- Internship at a National Laboratory or in industry.

Comments on Core Training in CS&E

A couple of (controversial?) issues:

- There is no mention of probability and stochastic modeling, which have come to play an increasingly important role
- There is no mention of training students in the use of solution techniques to carry out scientific investigation and engineering design, e.g. sensitivity analysis, inverse problems, optimization, error estimation, uncertainty quantification
- The training in “interdisciplinary collaboration” is not spelled out in great detail
  - There is little mention of the fact that much of CS&E research is team-based
  - Does taking courses in another department constitute effective interdisciplinary/multidisciplinary training?

Types of Programs in CS&E

Quoting

Two general models for the organization of CSE graduate degree programs have emerged.

- In the first model, a graduate degree is awarded in the new discipline of CSE. Often in this model the CSE program resides within an existing department, usually mathematics or computer science.
- In the second model, graduate degrees are awarded in the traditional disciplines of mathematics, computer science, science and engineering, with an area of specialization of CSE. The CSE programs ... usually share a core curriculum and a basic set of standards

Types of Programs in CS&E

Report observations on the different approaches:

- The degree in CSE may allow a more focused and cohesive program, since this program is often implemented within a single department such as mathematics or computer science, or within a separate academic unit.
- On the other hand it may be difficult to achieve depth within this type of program, especially for the application areas, or to distinguish this program from applied mathematics.

These are certainly controversial statements

Programs Highlighted in the Report

- Scientific Computing and Computational Mathematics Program, Stanford University
- Computational and Applied Mathematics (CAM) at University of Texas, Austin
- CSE Option at University of Illinois, Urbana-Champaign
- Computational Sciences and Computational Engineering, Purdue University

Two Observations about the Report

- The training discussion is largely focused on course work
- The research and output discussion is largely focused on the multidisciplinary and integrative nature of CS&E research

A More Recent List

Putting Together an Updated List of Programs

In 2006, I put together an updated list of CS&E programs

I started with the lists in the SIAM CSE Report, the Krell Institute, and from Michael Heath

Several people performed web searches for CS&E programs, also accepted self nominations

We made no attempt to filter

CS&E Programs in 2006

- Arizona State University, Computational Biosciences
- Boston University, Center for Computational Science
- Brown University, Division of Applied Mathematics
- California Institute of Technology, Applied and Computational Mathematics
- Carnegie Mellon University, Algorithms, Combinatorics and Optimization
- Carnegie Mellon University, Computational Biology and Chemistry
- Carnegie Mellon University, Computational Molecular Biology
- Carnegie Mellon University, MS in Computational Finance
- Catholic University of America, Institute for Astrophysics and Computational Sciences
- Clark University, Computational Science
- College of William and Mary, Computational Science Cluster

CS&E Programs in 2006

- Colorado State University, Master of Science Degree in Mathematics with Specialization in Applied and Computational Mathematics
- Colorado State University, Program for Interdisciplinary Mathematics, Ecology, and Statistics
- Columbia University, Applied Physics and Applied Mathematics
- Cornell University, Center for Applied Mathematics
- Cornell University, Computational Science and Engineering
- Duke University, Center for Computational Science, Engineering and Medicine
- Duke University, Statistical and Applied Mathematical Sciences Institute
- Emory University, Mathematics and Computer Science Department Ph.D. Track in Computational Mathematics

CS&E Programs in 2006

- Florida State University, School of Computational Science
- Florida State University, Department of Mathematics: Applied and Computational Mathematics Program
- George Mason University, School of Computational Sciences
- Georgia Institute of Technology, Computational Science and Engineering Division
- Georgia State University, M.S. Concentration in Scientific Computing
- Harvard University, Engineering and Applied Sciences
- Illinois Institute of Technology, Department of Applied Mathematics: Concentration in Computational Mathematics
- Indiana University, Scientific Computing
- Iowa State University, Bioinformatics and Computational Biology
- Kent State University, Institute for Computational Mathematics

CS&E Programs in 2006

- Louisiana State University, Center for Computation & Technology
- Louisiana State University, Physics and Computer Science Dual Degree
- Louisiana Tech University, Computational Analysis and Modeling
- Loyola University, Scientific/Technical Computing
- Massachusetts Institute of Technology, Computational Engineering
- Massachusetts Institute of Technology, Applied Mathematics
- Michigan State University, Masters in Industrial Mathematics
- Michigan Technological University, Computational Science and Engineering Ph.D. program
- Mississippi State University, Computational Engineering
- New York University, Courant Institute of Mathematical Sciences

CS&E Programs in 2006

- New York University, Masters Degree Program in Scientific Computing
- North Carolina A&T State University, Computational Science and Engineering
- North Carolina State University, Center for Research in Scientific Computation
- North Carolina State University, Numerical Analysis
- Northwestern University, Department of Engineering Sciences and Applied Mathematics
- Ohio (Statewide Program), Ohio Computational Science Initiative
- Ohio University, M.S. in Mathematics - Computational Track
- Old Dominion University, Center for Computational Sciences
- Old Dominion University, Certificate in Computational Science & Engineering
- Oregon State University, Computational Physics

CS&E Programs in 2006

- Pennsylvania State University, Institute for Computational Science
- Princeton University, Princeton Institute for Computational Science and Engineering
- Princeton University, Program in Applied and Computational Mathematics
- Purdue University, Computational Finance Program
- Purdue University, Computational Science & Engineering
- Rensselaer Polytechnic Institute, Computational Science and Engineering Program
- Rice University, Center for Computational Geophysics
- Rice University, Computational and Applied Mathematics
- Salve Regina University, Computational Sciences
- San Diego State University, Computational Science Research Center

CS&E Programs in 2006

- Southern Methodist University, Center for Scientific Computation
- Stanford University, Institute for Computational and Mathematical Engineering
- State University of New York at Brockport, Computational Science
- State University of New York at Buffalo, Center for Computational Research
- State University of New York at Buffalo, Computational Science
- State University of New York at Stony Brook, Department of Applied Mathematics and Statistics
- Syracuse University, Computational Science Program
- Temple University, Interdisciplinary Program in Mathematics and Physics
- Texas A&M University, Institute for Scientific Computation
- University of Arizona, Computational Science & Engineering

CS&E Programs in 2006

- University of Arizona, Interdisciplinary Program in Applied Mathematics
- University of California, Berkeley, Computational Engineering Science Program
- University of California, Davis, Center for Computational Science and Engineering
- University of California, Davis, Department of Applied Science
- University of California, Los Angeles, Computational and Applied Mathematics
- University of California, Los Angeles, Institute for Digital Research and Education
- University of California, San Diego, Computational and Applied Math
- University of California, San Diego, Computational Science, Mathematics, and Engineering

CS&E Programs in 2006

- University of California, Santa Barbara, Computational Science and Engineering
- University of California, Santa Barbara, Institute for Computational Earth System Science
- University of Chicago, Computational and Applied Mathematics
- University of Colorado at Boulder, Applied Mathematics
- University of Colorado at Denver, Center for Computational Mathematics
- University of Delaware, Graduate Program in Scientific Computation
- University of Delaware, Numerical Analysis and Scientific Computing
- University of Houston, Computational Science Initiative

CS&E Programs in 2006

- University of Illinois at Chicago, Applied Mathematics and Computational Science
- University of Illinois at Urbana-Champaign, Computational Science and Engineering Graduate Option Program
- University of Illinois at Urbana-Champaign, Scientific Computing
- University of Iowa Numerical Analysis,
- University of Iowa, Program in Applied Mathematical and Computational Sciences
- University of Kansas, Numerical Analysis
- University of Kentucky, Center for Computational Sciences
- University of Kentucky, Numerical Analysis and Scientific Computing
- University of Maryland, Institute for Advanced Computer Studies

CS&E Programs in 2006

- University of Maryland, College Park, Applied Mathematics and Scientific Computation Program
- University of Maryland, College Park, Center for Scientific Computation and Mathematical Modeling
- University of Maryland, College Park, Mathematics of Advanced Industrial Technology
- University of Massachusetts - Lowell, D.Sc. in Computational Mathematics
- University of Massachusetts - Lowell, M.S. in Scientific Computation
- University of Michigan, Doctoral Program in Scientific Computing
- University of Michigan, Applied and Interdisciplinary Mathematics

CS&E Programs in 2006

- University of Michigan - Dearborn, Applied and Computational Mathematics
- University of Minnesota - Duluth, Applied and Computational Mathematics
- University of Minnesota - Twin Cities, Program in Applied, Computational & Industrial Mathematics
- University of Minnesota - Twin Cities, Scientific Computation
- University of New Mexico, Center for High Performance Computing
- University of New Mexico, Scientific Computation
- University of Oregon, Computational Science
- University of Pittsburgh, Scientific Computing
- University of Southern Mississippi, Computational Sciences
- University of Tennessee at Chattanooga, Computational Engineering

CS&E Programs in 2006

- University of Tennessee at Knoxville, Computational Science Program
- University of Tennessee at Knoxville, MS Concentration in Applied Math
- University of Tennessee at Knoxville, Joint Institute for Computational Sciences
- University of Texas at Austin, Center for Numerical Analysis
- University of Texas at Austin, Computational and Applied Mathematics
- University of Texas at Austin, Institute for Computational Engineering and Sciences
- University of Texas at Dallas, Master of Science in Bioinformatics and Computational Biology

CS&E Programs in 2006

- University of Utah, Computational Engineering & Science Graduate Program
- University of Utah, Scientific Computing and Imaging Institute
- University of Utah, Ph.D. Track in Scientific Computing
- University of Washington, Applied and Computational Mathematical Sciences
- University of Washington, Department of Applied Mathematics
- Virginia Tech, High Performance Computing and Communications
- Virginia Tech, Interdisciplinary Center for Applied Mathematics
- Western Michigan University, Applied and Computational Mathematics

Comments on this List

The list can be downloaded from

http://www.math.colostate.edu/∼estep/education/cse/cselisting.html

Comments:

- Most assuredly, a number of new programs have started since we compiled this list
- Also assuredly, a number of programs on this list have withered or have changed directions significantly

Some Highlighted Programs

Classification of Programs

In the 2005 Annual SIAM Meeting, David Levermore expanded the ways to set up applied mathematics, statistics, or computation programs

- within an existing disciplinary department;
- within a new distinct tenure and degree granting department;
- as an interdisciplinary program that involves existing disciplinary departments;
- as an interdisciplinary program housed within an existing interdisciplinary institute;
- as an interdisciplinary program housed within a new interdisciplinary institute;
- as some combination of the last three.

Programs Useful as Role Models

- Department of Scientific Computing, Florida State University
- Computational Science, Engineering and Mathematics (formerly CAM), University of Texas at Austin
- Computational Science and Engineering Graduate Option Program, University of Illinois at Urbana-Champaign
- Computational Engineering and Science Certificate Program, University of Utah
- Computational Science and Engineering, Georgia Tech
- Computational Science and Engineering and Computational Life Science programs, Purdue University
- Computational Science and Engineering Emphasis, University of California, Santa Barbara
- Computational Science and Engineering, Rice University

Programs Useful as Role Models

- Institute for Computational and Mathematical Engineering, Stanford University
- Applied Mathematics & Statistics, and Scientific Computation, University of Maryland, College Park*
- Computational Science and Engineering, Michigan Technological University†
- Program in Computational Science, Mathematics, and Engineering, University of California at San Diego♣

* a very interdisciplinary applied mathematics program

† Web pages include some interesting and useful explanations of CS&E for the "lay person"

♣ Proposal for the program is based on a lot of research into existing and past CS&E programs

Separate Programs or Not?

Rationale for Separate Programs

In the 2005 Annual SIAM Meeting, Max Gunzburger gave a talk examining the creation of separate programs

This can be downloaded (starting Friday)

http://www.math.colostate.edu/∼estep/education/cse/max-siam-am05.pdf

My Thoughts

I find compelling arguments for both distinct and degree-plus programs

It is likely that the optimal approach is highly dependent on the institution and the partners

Both approaches struggle with problems and barriers arising from common issues

- The need to train students to work in multidisciplinary teams and to provide the necessary interdisciplinary foundation
- The need to recognize the importance and value of multidisciplinary research in discipline-oriented universities

Perhaps those are the issues that require a community focus