Keeping CS&E Curricula Focussed and Balanced

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Overview

- What is CS&E
- What should a C&E curriculum include
- Who should host CS&E
- Dangers to CS&E programs
- Structural requirements
- Conclusions
The Two Principles of Science

Three

Theory
Mathematical Models, Differential Equations, Newton

Experiments
Observation and prototypes empirical Sciences

Computational Science
Simulation, Optimization (quantitative) virtual Reality
Computational Science & Engineering

Science
Engineering

Theory

Computation
Computer simulation

Virtual experiments
Virtual prototypes
Virtual reality

Observation
Experiment
Building
prototypes

Computer models in physics,
chemistry, electrical engineering
mechanical engineering
material sciences
chemical engineering, …
What is it called?

- Mathematics
- Applied Mathematics
- Techno-Mathematics
- Computer Science
- Computational Science
- Scientific Computing
- Numerical Analysis
- (Numerical) Simulation
- Computer Engineering
- Computational Engineering
- Computational Physics
- Industrial Mathematics
- ...

There is no generally accepted definition what is what.

(and this sometimes creates problems)
From the call for papers of the SIAM J. Scientific Computing Special Issue on Computational Science & Engineering (Chris Johnson, David Keyes, Ulrich Ruede eds.)

... Many CS&E problems can be characterized by a "pipeline" that includes Modeling techniques (mathematical and geometric), Simulation techniques (discretizations, algorithms, data structures, software frameworks, and problem solving environments), and Analysis techniques (data mining, data management, visualization, and error, sensitivity, stability, and uncertainty analyses). The guest editors are seeking papers that tackle problems from the real world, describe several aspects of the CS&E pipeline involved in solving the problem, and make a research contribution in one or more of the techniques of CS&E. Papers should illustrate new and useful techniques and tools for solving realistic problems, which often have complicated three-dimensional geometries, multiple scales, heterogeneities, anisotropies, and multi-physical or biological descriptions. Though such problem domains often thwart proofs of accuracy or efficiency, papers should address validation and verification through reduction to analyzable cases and convergence studies, as applicable, and comparisons with alternative approaches.
Current main stream programs do not educate students in CS&E

- **CS&E is not** (a specialization within) Computer Science
- **CS&E is not** (a specialization within) (applied) Mathematics
- **CS&E is not** part of or specialization within any other Science or Engineering Discipline
- **CS&E is the science of methods using computation for understanding and solving problems in science and engineering**
- **CS&E uses computation to**
  - understand
  - predict
  - and optimize
- objects of scientific study
- Any CS&E program must be **interdisciplinary**
- **CS&E education requires more than just offering its components**
  It is not enough to offer only a mix of existing courses from CS, Math, and target discipline. It is expecting too much from students to believe that things grow together by themselves.
CSE Education (2)

- CS&E education must include
  - methods and techniques coming from
    - mathematics
    - computer science
    - one (or more) target discipline
  - examples how CS&E methods are applied
  - project experience
  - practical experience with the full CS&E pipeline (not just parts of it).
  - communication skills with colleagues from other disciplines
CSE Education (3)

- CS&E is a science of **methods and techniques**
- CS&E is not a part of the science where these methods are applied (target discipline)
  - students must be made aware that many methods are applicable in more than just one discipline.
  - students should learn that methods that come from seemingly unrelated disciplines may be useful in other contexts
    - example: fluid mechanics and computational finance
- CSE is not just a „specialization“ within an existing discipline but reaches beyond conventional disciplines - students should be trained accordingly
CSE Education (4)

We need

- Co-Teaching of classes
  - involving faculty from different disciplines
  - methods development driven by the target science

- Projects in teams
  - Students must learn that most serious CS&E research cannot be done by a single individual

- Communication with other disciplines
  - CSE students must be able to quickly learn the language of a new application discipline
Differences between US undergraduate and Bolgogna-style (German) undergraduate programs

US undergraduate education aims at a general education
- mix of courses from many fields
- often many electives
- mix of courses

German undergraduate programs are topically focussed from day one
- other courses („soft skills“, as required by the Bologna agreement) are kept to a minimum
- aim at providing also the „theoretical foundation“ of the field (though there is of course a trend to make them more practically/industry/job oriented)
Computational Engineering at Erlangen

- started as International Master program in 1997
- Master program taught in English
- undergraduate program since 1999
- organized from within Computer Science
- offers specializations in
  - Sensorics/ Mechatronics
  - Information Technology
  - Control
  - Micro Electronics
  - Material Sciences
  - Fluid Dynamics
  - Applied Chemistry
- Students must choose an application field right from the beginning (and then stay with it)
Bavarian Graduate School of Computational Engineering (BGCE)

- Consortium of TU Munich and FAU Erlangen-Nürnberg
- Offerers add-on to curriculum for our best students
- Awards „Master with Honours“
- Extra Courses/Offeres include
  - Summer and Winter academies (Italy, Russia, India, ...)
  - Participation in conferences
  - Compact courses by guest lecturers, e.g.
    - Multigrid
    - Stochastic DE
    - ...
  - Joint (block) seminar between universities
  - Project team work (ref. H. Bungartz)
  - Special courses like
    - Leading yourself and others
    - Supervised Teaching
    - Scientific Publishing
Interdisciplinary example courses from Erlangen: Numerical Simulation of Fluids

- co-taught by dept. of fluid mechanics and CS
- integrated concept including the full CS&E pipeline: each student develops an incompressible NS-solver from scratch
- project oriented: Based on the core solver, student teams tackle "more complex application projects", e.g.
  - simulating a mixer
  - simulating auto exhaust in a tunnel
Student project: Karman vortex street
Other interdisciplinary example courses from Erlangen CE

- Numerical Computation of Electromagnetic Fields
  - co-taught by EE and CS
  - Maxwell's equations, weak formulation, FE discretization, solver, software development: the CS&E pipeline

- Numerical Methods for Particle Technology
  - co-taught by Chemical Engineering and CS
  - development of a multi-particle solver (molecular dynamics), including parallelization, long range potentials, from theory to running simulator plus visualization
  - some trouble with heterogeneous audience (chemical engineers/ material scientists and computational engineers)
Critical Points

- Student interest and non-CS&E faculty drive the curriculum away from CS&E core:
  - requirement to take math classes has been replaced by „math-oriented“ classes (that is: basically any engineering class)
  - „Numerical methods“ has been replaced by „Numerical methods for Engineers“
  - More than half of the (Master) graduates avoid to take „Numerics of PDE/ advanced numerics“
- It is notoriously difficult to market the program and to recruit students
- We require students to select the „application field“ (target discipline) right away
  - Curricula (plural!) determined by specific needs of the various target disciplines rather than „universal methods“
  - Essentially the program is fragmented into five rather different ones
  - Students after the second year take disjoint sets of courses (depending on target discipline)
  - We have drop-out rates of 50-70% (undergraduate)
Fitting CSE into the university structure

Where should a CSE program be hosted?
- in a CS department (as in Erlangen)
- a Math department (probably the majority of existing programs)
- an engineering department ("Computational Mechanics")
- a physics department ("Computational Physics")
- ...

Any of these brings the danger that
- the program is considered as just a "variant of the main field" offered by the department. This may be acceptable for application-centered programs, such as computational mechanics, likely less so for CS or Math.
- conflicts occur in
  - funding decisions
  - hiring decisions
- recruiting of students for the CS&E program is handicapped

It has the advantage that
- the program can profit from existing administrative structures
- students may have more flexibility to switch between different programs
When CS&E programs are hosted by a classical department, this discipline tends to dominate the program:

- it may be difficulty to integrate courses from other departments and to influence their contents
- „political“ arguments may affect which courses are included in the curriculum
- the development of the program may depend on only few core people - if they leave the whole program may be in danger
- CS&E curriculum may depend on too many inputs (form other departments) creating the continuous need for changes and adaption

It is a continuous battle to keep CS&E from drifting to become a CS or a math, or a discipline-specific program:

- pressure from colleagues in the collaborating departments
- pressure from students
CS&E Structure

Should we have CS&E departments?
- how would they interface with math, cs & target disciplines?
- who would finance them?

Should we have “Interdisciplinary CS&E Institutes” at our universities?
- Responsible for CS&E administration
- Coordinate (and define) „imports“ form math, cs, target disciplines
- Offer „glue“ courses to connect the educational building blocks from the different departments
- Coordinate team teaching courses
- These CS&E institutes need control over their ressources
- How to influence hiring decisions? It may not be enough to have a minority CS&E representative in a CS&E-related hiring committee

CS&E can only be successful at a university if it
- is run with a long term strategy
- is backed by administration (dean, rector, vice chancellor, ...) and these understand CS&E
- is run by a sufficiently large „CS&E faculty“
International Status of Graduate CSE Education

- Relatively little activity outside the US and Europe
- European graduate CS&E programs
  - currently focussed on the Master level, but PhD programs to come
  - diverse models
  - often internationally oriented (taught in English)
  - Trend to form trans-institutional consortia and double degree programs
    • EU-funded networks (Erasmus Mundus - joint degree)
    • Bavarian Graduate School in Computational Engineering
- US graduate CS&E education sometimes „only“ as an add-on to degree in existing field
International Status of Undergraduate CSE Education

- Undergraduate CS&E programs are less common both in the US and Europe
- In Europe the situation is currently strongly affected by the Bologna process
- German (European?) undergraduate programs are
  - more oriented towards providing a solid foundation (in theory) rather than a broad education
  - start right away focussed on the discipline
  - put more emphasis on theory, leaving applications for later
International Status of Undergraduate CSE Education

Do we need extra CS&E undergraduate programs? Or should we add

- CS&E content to existing degree programs (e.g. as integral part of courses in the target disciplines)
- by offering a „minor“ in CS&E?
- e.g. as electives to better prepare students to do graduate studies in CS&E
Conclusions

- To start a CS&E program is difficult
- To sustain a CS&E program in the long term is even more difficult
- The sustainability of CS&E requires sufficient support and suitable structures
Talk is Over

Questions?