Computing in Science Education (CSE)
A New Way to Teach Science?

Øyvind Ryan + CSE team

Center of Mathematics for Applications
University of Oslo

Katowize, October 13 2011

Main contributors in the CSE project

Scientific staff:

- Hans Petter Langtangen, Computer Science
- Knut Mørken, Computer Science
- Anders Malthe Sørensen and Arnt Inge Vistnes, Physics
- Tom Lindstrøm, Mathematics
- Øyvind Ryan, Mathematics and Computer Science

Administration:

- Annik Myhre, Dean of Education
- Hanne Sølna, Director of studies

+ many others

`http://www.mn.uio.no/english/studies/cse/`

Motivation behind the CSE project

- An integrated introduction of computation in the basic science education.
- Pupils and students hear about the relevance of science and engineering for industry and research, but see little direct evidence of this relevance in school and in the first years at the university.
- See to that mathematics, science, and realistic applications are not seen separately (some think that education uses ONLY pen and pencil, while industry uses ONLY a computer).

Motivation behind the CSE project

- Computers give students new possibilities to be exposed to solution of realistic problems early in the study.
  - Can perform large computations by iteration, which previously were infeasible.
  - Introduces ossibilities for research based teaching early
  - Students can be turned into active users.
- To put the focus on the content of computations, rather than how it is presented.
- Trigger further insights in math and other disciplines

What is computation?

- Something else than the digital teaching environment itself
- More than use of specific tools/programs, calculator, or spreadsheets to solve problems.
- Includes numerical methods and digital representation of information.
- Includes knowledge needed to deduce a numerical method.
- Mastering computations with aid of a computer (basic programming skills combined with classical mathematics)

Tools for introducing computation

It is not obvious from the start what tools to use when introducing computations.

Should we use a tool like Mathematica?

- Students should primarily learn basic programming principles and algorithmic problem solving
- The tools should be pedagogical and simple so that the priciples are clear
- It should be a broad agreement on the choice of tool
- Based on these points, one can argue that one should NOT use a package such as Mathematica!

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How to introduce computation

- May not increase the syllabus, but will certainly change its contents
- Demands new textbooks where computations are integrated with classical mathematics.
- Classical mathematics is just as important as before
- No longer a demand that the differential equation is on a particular form in order to find a solution.

How to introduce computation

- Computations in mathematics courses could be the basis for computations in fields like physics, astrophysics, statistics
- This opens possibilities to study realistic problems in these fields earlier, since one can build on the computational background from the beginning mathematics courses.
- In the second semester students in mechanics can be presented to advanced problems such as simulation of a rocket launch, models for frictions, realistic motion of a football.

History of Computation at UIO

Before 2000 Computation was for the specially interested. Specialized topics in numerical analysis.

2000-2003 A-, B-, C-variants in mathematics. Maple in C-variant, Java in B-variant. A a a pure mathematical variant. Physics and mathematics not synchronized.

2003 Center of Mathematics for Applications (CMA) was established. Mathematicians, numerisists, and some physicians were localized at the same place. Broad bachelor programs with mathematically heavy topics as common block . CSE project was established.

2005 Computations in the education entered the strategic plan of the faculty. Solid anchoring of the CSE project in the leadership of the faculty.

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History of Computation at UIO

2007 Beginning course in programming with applications for natural sciences. Uses Python. More fields join the CSE project

2010-2011 Working group establishes a steering document for introduction of computational perspectives in education in Norway. Uses experience from CSE. http://www.mn.uio.no/english/about/collaboration/cse/national-group/computing-in-science-education.pdf

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Computation at UIO today

- Students get an introduction to computation and programming together with classical mathematics already the first semester.
- Computational perspecive included also in succeeding mathematics courses.
- We will continue to work for a coordinated use of computations also in Chemistry, Molecular Biology, and Biology.
- Fields like statistics, physics, geophysics, astrophysics, geosciences, mathematics, informatics are already represented in the CSE project, but more can be done

My role in the CSE project

- Teaching the beginning courses in mathematica, first three semesters
- Further development of existing course material, with focus on integrating classical mathematics theory with computation
- Preparing new topics for inclusion in the syllabus, which have strong roots both in compuation and classical mathematics: Processing of sound and images, data compression, ranking of webpages.
- Interdisciplinary coordinating role, such as inclusion of parts from computation used in mathematics courses, in a geoscience course.

Example of a first semester math course (MAT-INF1100 - Modelling and computations)

- `http://www.uio.no/studier/emner/matnat/math/MAT-INF1100/h11/`
- Induction, natural and real numbers, difference equations, Taylor polynomials, differential equations
- Numeric differentiation, integration, interpolation, solution of differential equations.
- representation of numbers in computers, text, sound and images. Lossless compression.
- Excellent new textbook by Knut Mørken

Example of a first semester informatics course (INF1100 - Introduction to programming with scientific applications)

- Programming in Python and our first programming course `http://www.uio.no/studier/emner/matnat/ifi/INF1100/h11/`,
- examples from mathematics, science and engineering.
- Matlab-type programming
- objectoriented programming, suclasses and inheritance
- Programming of numerical methods, simple graphics, simple Monte Carlo simulations, vector arithmetics.
- Excellent new textbook by Hans Petter Langtangen

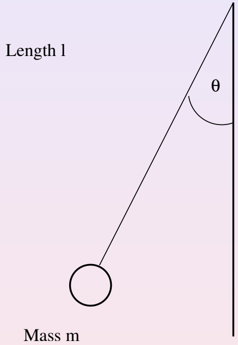
Example of a second semester math course (MAT1110 - Calculus and linear algebra)

- `http://www.uio.no/studier/emner/matnat/math/MAT1110/v11/`
- Functions of several variables, Multiple integrals
- Elementary linear algebra, linear systems of equations, max/min problems
- Contractions and completeness, Newtons method in several variables, power series
- Computations with Matlab or Python.
- Numerical exercises and problems, from linear algebra to multi-dimensional integration.
- Excellent new textbook by Tom Lindstrøm. Focus on classical mathematics, with computational examples with Matlab integrated throughout the book.

Example of a third semester math course (MAT1120 - Linear algebra)

- Abstract vector spaces. Eigenvalues and eigenvectors, Orthogonality and least squares methods, symmetric matrices and quadratic forms
- Markov chains, the power method, simple Fourier analysis, singular value decomposition
- Numerical exercises and problems: Computations with Google pagerank, compression of images, wavelets.

Computational example from a second Semester physics course (FYS-MEK1110 - Mechanics)



Realistic Pendulum

Classical pendulum with damping and external force

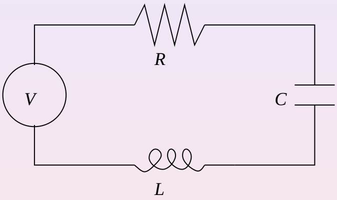
$$ml\frac{d^2\theta}{dt^2} + \nu\frac{d\theta}{dt} + mgsin(\theta) = Asin(\omega t).$$

Easy to solve numerically without classical simplification, and then visualize the solution. Done in first semester!
Same equation for an RLC circuit

$$L\frac{d^2Q}{dt^2} + \frac{Q}{C} + R\frac{dQ}{dt} = V(t).$$

http://www.uio.no/studier/emner/matnat/fys/FYS-MEK1110/v11/

Computational example from a third Semester physics course (FYS1120 - Electromagnetism)



RLC circuit

Same equation as the pendulum for an RLC circuit

$$L\frac{d^2Q}{dt^2} + \frac{Q}{C} + R\frac{dQ}{dt} = V(t).$$

From the numerics, the students found the optimal parameters for studying experimentally chaos in an RLC circuit. Then they did the experiment.

What can we do with the pendulum?

Many interesting problems

- Can study chaos, theoretically, numerically and experimentally, can choose 'best' parameters for experimental setup.
- Can test different algorithms for solving ordinary differential equations, from Euler's to fourth-order Runge Kutta methods. Tight connection with algorithm and physics.
- Can make classes of differential equation solvers.
- Can make a general program that can be applied to other scientific cases in later courses, such as electromagnetism (RLC circuits). Students realize that much of the same mathematics enters many physics cases.

More Examples from Physics Courses, 2-5 semester

- Air resistance in two and three dimensions with quadratic velocity dependence.
- Launching a probe into a tornado
- Rocket launching with realistic parameters, gravity assist
- How to kick a football and model its trajectory.
- Planet motion and position of planets
- Magnetic fields with various geometries based on Biot-Savart's law

More Examples from Physics Courses, 2-5 semester

- Harmonic oscillations and various forms of electromagnetic waves.
- Combined effect of different potentials such as the electrostatic potential and the gravitational potential.
- Simple studies of atoms and molecules, and much more
- Computational Physics I, fifth semester, `http://www.uio.no/studier/emner/matnat/fys/FYS3150/h11/`
- Computational Physics II, eight semester (openCL and GPU programming), `http://www.uio.no/studier/emner/matnat/fys/FYS4411/v11/`

Example: Computations from day one

Differentiation

Three courses the first semester: MAT1100, MAT-INF1100 og INF1100.

- Definition of the derivative in MAT1100 (Calculus and analysis)

$$f'(x) = \lim_{h \to 0} \frac{f(x+h) - f(x)}{h}.$$

- Algorithms to compute the derivative in MAT-INF1100 (Mathematical modelling with computing)

$$f'(x) \approx \frac{f(x+h) - f(x-h)}{2h}.$$

- Implementation and use in applications in the programming course INF1100, with Python as programming language.

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Other Examples

Integration by Trapezoidal Rule

- Definition of integration in MAT1100 (Calculus and analysis).
- The algorithm for computing the integral with the Trapezoidal rule for an interval $x \in [a, b]$

$$\int_a^b (f(x)dx \approx \frac{1}{2}\left[f(a) + 2f(a+h) + \cdots + 2f(b-h) + f(b)\right]$$

  is taught in MAT-INF1100 (Mathematical modelling)
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Coordination

More Examples

- The courses MAT1100, MAT-INF1100 og INF1100 have many common examples and topics, amongst these ordinary differential equations. They solve the pendulum at the end of INF1100.
- Differential equations are in turn used widely in our mechanics course, which comes in the second semester,with examples spanning from the classical pendulum to rocket launching.
- Differential equations (partial and ordinary) are in turn used in many many other courses, from electromagnetism to quantum physics.

Example of bachelor program in Physics, Astronomy and Meteorology

6. semester	Se ønsket studieretning	EXPHIL03 - Examen philosophicum /Valgfritt	Valgfritt
5. semester	Se ønsket studieretning	Se ønsket studieretning	Valgfritt/ EXPHIL03 - Examen philosophicum
4. semester	Se ønsket studieretning	Se ønsket studieretning	Se ønsket studieretning
3. semester	FYS1120 - Elektromagnetisme	AST1100 - Innføring i astrofysikk / GEF1000 - Klimasystemet	MAT1120 - Lineær algebra
2. semester	FYS-MEK1110 - Mekanikk	MEK1100 - Feltteori og vektoranalyse	MAT1110 - Kalkulus og lineær algebra
1. semester	INF1100 - Grunnkurs i programmering for naturvitenskapelige anvendelser	MAT-INF1100 - Modellering og beregninger	MAT1100 - Kalkulus
	10 studiepoeng	10 studiepoeng	10 studiepoeng

- First semester common for several Bachelor programs (Math, Physics, Astrophysics, Meteorology, Materials Science, Nanotechnology, Math and Economy, Electronics, Geology)
- The mathematics courses MAT1100, MAT1110, MAT1120 and MEK1100 are common to many Bachelor programs.

Lessons learnt

- Since computations are incorporated from day one, courses higher up do not need to spend time on computational topics (technicalities), but can focus on the interesting science applications and generic methods.
- New textbooks with an integrated computational perspective take time to mature. It will take a long time to develop a body of good computational exercises of the same quality as the classical ones
- Big need for development of new material. Continuous process.
- The need for coordination across topics

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Lessons learnt 2 (practicalities)

- The need for an administration following up
- The need for meeting places and frequent meetings
- The need for advertisement to a broad audience.

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Lessons learnt 3 (students)

- Computations do not make the study easier for the student. Must work hard
- Not worse results than before.
- Involvement of students in CSE development is crucial. Students can be motivated early in the study to do research.
- Students can get very enthusiastic about the courses, even more than us!
- Can be problematic for students from other universities.

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Current status

- Seminars. Annual christmas seminar
- Lunches for sharing experiences, creating a community.
- Frequent meeting activity, to aid coordination across fields.
- Frequent travel activity, advertising for the CSE cause
- Seminars for collaboration, such as on writing textbooks

Current status

- Writing textbooks with computational perspectives. Books are in fields as diverse as physics, computational physics, statistics, mathematics, numerical methods, informatics, geosciences.
- Evaluating of other topics for CSE-adoption. Calls for funding applicants in other fields, who also would like to intoduce computational perspectives.
- Using clever students. Students get summer projects, for working on a computational perspective for a given topic.

Prerequisites for CSE-type initiatives

- Budget and external funding
- Meeting places for students and researchers.
- An administration which is active behind the curtains:
  - Organizing social events,
  - securing funding from department/government,
  - nominates for prices,
  - maintains documents, websites,
  - contact with industry,
  - contracts with students,
  - takes notes from meetings and makes sure things are followed up

Prerequisites for CSE-type initiatives

- Frequent meetings between main coordinators.
- Interdisciplinary discussions and meeting places.
- Anchoring in strategic plans. Backing by university board and involved departments.
- Minimum of bureaucracy.
- Broad agreement and collaboration for the main goals
- Broad agreement on tools to be used

Need for collaboration

- There is no reason why material from CSE-type projects can not be shared with similar projects elsewhere. Scope should be international.
- Puts demands on coordination and administration, such as making agreements for how material should be shared.
- International development of textbook material should be possible. Should avoid the native language.
- People from different disciplines/different countries should come together, to form material together.

Discussion

- Discussion into our current projects.
- How to secure continuity in CSE? The project depends crucially on a few individuals in a starting phase.
- Challenge: How to reflect computational exercises in grading and final evaluations?
- Can one defend, for industry, NOT introducing CSE perspectives at universities?
- Reward system motivating people to introduce CSE.
- Other aspects important for a successful introduction of CSE? Organizational matters etc.
- Can we identify direct points to follow up for the road ahead?