Computers in Science Education

A new way to teach science?

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Summary

In the last decades we have witnessed an incredible development of both computer hardware and software. Scientific problems that were previously solved on large special-purpose machines with special-purpose software can now be easily handled in general-purpose, interactive environments on standard PCs with the bonus of immediate visualization of the results.

A fundamental challenge to our undergraduate programmes is how to incorporate and exploit efficiently these advances within the standard curriculum in mathematics and the natural sciences, without detracting the attention from the classical topics. This brings with it the major organizational challenge of how to get university professors in a variety of different fields and departments to work together towards such a reform. Furthermore, if students are trained to use such tools from the earliest stages in their education, do such tools really enhance and improve the learning environment? In additionAnd, perhaps even more importantly, does it lead to better understanding and insight?

It is too early to attempt to answer these questions, but here we present one possible approach to the reform: Computational topics are gradually introduced in the undergraduate curriculum in several bachelor of science programmes at the University of Oslo, as an integral supplement to the classical scientific syllabus.

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Introduction

How does a scientist work?

Computer simulations have become an integral part of contemporary basic and applied research in science,[5] and an indispensable tool in industry. Computation is as important as theory and experiment, and the ability "to compute" is part of the standard repertoire of research scientists. As a result, several new research fields have emerged and strengthened their positions in recent years, such as computational materials science, bioinformatics, computational mathematics and mechanics, computational chemistry and physics, just to mention a few. Progress and new insights are frequently obtained from large-scale simulation of problems that have no closed-form answers. In essence we conduct science by solving broad, open-ended and often self-discovered problems, using a combination of analytic, numerical and experimental tools.

How do we teach science?

On the other hand, the way we teach our basic introductory courses in the sciences has not changed much over the past three or four decades. A typical setting is to focus on problems that can be solved in closed form, with what is often mischievously dubbed 'exact' answers. Such problems are in many cases based on severe limitations and assumptions about the system under study. This frequently leads to inexact and unrealistic models whose main aim is simply to provide a so-called 'exact' answer. Such an approach also undermines a deeper understanding of how scientific research is performed.

A typical situation for a scientist entails work with models that are tested and modified based on our understanding of specific physical laws. Simple models often hide this process and the students are left with the impression that there is not much more to discover about the basic laws that govern a system.

Reformed science teaching

New wrapping?

Over the past thirty years, there has been an increasing emphasis on various digital aids in teaching mathematics and science (and other subjects). The wide

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[5] Science here includes mathematics, informatics, and the natural sciences (Physical sciences, earth, space and life sciences).

range of aids include tools as diverse as the pocket calculator and digital communication platforms, as well as software packages that can automate much of the calculations in classical mathematics. It is therefore possible to reduce a considerable part of the calculations in the elementary maths and science classes to pressing the right buttons or issuing the right commands in a program.

Although these tools in themselves are useful, the fundamental flaw in this approach is that the students are led to believe that the programs can solve all problems and they become dependent on the tools without understanding how they work. To equip a student for a forty-year career in science and mathematics, the students must be able to adapt to new tools that will undoubtedly emerge in the future, and they must be able to extend the tools to solve their special problem that is not covered by the standard software. Most importantly, they must have an understanding of how the tools work, otherwise they will be unable to judge the quality of the answers produced by the programs.

Change the contents, not just the wrapping

This means that it is necessary to change the content of our courses, not just the tools we use to do the calculations. The change involves two main ingredients:

- We must introduce realistic examples that make full use of the powerful software methods available. This has the important bonus of making the students aware of the applicability of the theory to real-life problems. However, the most fundamental reason is negative: The classical examples are more or less trivial with modern software at hand, so they make mathematics and science look like a boring game where there is little need for creativity and new ideas other than learning to use the right tools.
- The students must learn about iterative methods. Computers really only have one game-changing ability: They can do many billions of simple arithmetic operations every second. This means that solution methods that are dependent on repeating some simple task many times work extremely well on a computer. Such methods have been known in mathematics for a long time, but they have not been taught in elementary classes.

From this point of view, our project represents a simple, but rather radical revision of the content of many science courses. It goes beyond a mere introduction of new technologies and additional course material. The aim is to bring our teaching closer to the way we do science as researchers, and also closer to the methods applied in the knowledge-based industry.

To study a given physical system, the students need to get an understanding of both the physical laws that govern a system, and the mathematical and physical approximations that are made. Only then can they critically compare their results with experimental data. It therefore seems obvious that university students in mathematics and the natural sciences should receive an education that coherently reflects how computers are used to solve problems in basic and applied research, as well as in industry.

Such an education combines knowledge from several different subjects, such as mathematics, numerical analysis, programming, as well as some basic knowledge of computer technology. These topics are, almost as a rule of thumb, taught in different, and we would like to add, disconnected courses and departments.

The use of computers for solving problems in fields like physics or chemistry is often postponed until the last year of the bachelor's programme or even to the level of master's or doctoral programmes. Only then is the student confronted with the synthesis of all these subjects. At this time, the knowledge from the first programming course, often taught with little relevance to problems in mathematics and the natural sciences, is normally forgotten.

Computations from day one

In order to better prepare our students for their future careers and studies, we firmly believe that computational topics should be incorporated from the beginning of the bachelor's programme. This background should then be exploited in most other undergraduate courses, with the final aim of furnishing the students with a broad repertoire and understanding in numerical analysis and numerical methods applied to scientific problems. In addition to the technical knowledge gained, this also makes it possible to introduce examples and problems from the research frontier at a much earlier stage on the educational ladder.

Don’t throw away everything!

We must emphasize that classical mathematics is at least as important as before. Algebraic fluency is essential in order to solve simplified problems by hand, prepare more general problems for computer solutions in order to analyse the errors in approximations, etc. A thorough understanding of fundamental mathematical and scientific concepts become more important than before, because there are fewer routine calculations.

Computations require student/teacher interaction

Solving problems with computers is an inherently interactive activity that should partly be done with a teacher present to answer questions. For this reason, the introduction of numerical exercises will often improve the learning environment and strengthen a central, but often forgotten aim of the Bologna process, namely instruction-based teaching.

The Computers in Science Education project

Goals and content

The major aim of the Computers in Science Education (CSE) project is to include and integrate a computational perspective in the basic science education at the University of Oslo. To achieve this we have developed a strategy that coordinates the use of computational exercises and numerical tools in many undergraduate courses that are common to six bachelor’s degree programmes in science. The basic idea is to provide an education that combines a mixture of mathematics, numerical computation, informatics, as well as topics from specific sciences such as physics, chemistry, electronics, materials science and geology, in a uniform and well-structured way. In addition, we want to give the students realistic examples from relevant research, even at the beginning of their undergraduate studies.

The computational perspective is introduced as early as the first semester in the elementary programming course with scientific examples, and a course on numerical methods and basic digital knowledge. The computational perspective is strengthened in the other basic maths courses on linear algebra and multivariate analysis. With this solid basis, the students have the necessary background to make use of relatively advanced computational techniques in later courses. We are already seeing the effects of this in many of the science courses. An added bonus is that this also provides the necessary foundation for a professional work experience that is continuously changing, focusing thereby on fundamental and long-lasting knowledge.

What about the teachers?

Many teachers do not have the necessary technical knowledge to do this kind of teaching, and even if they do, they often lack the time and motivation to undertake such a major reform of their course. For this reason the project depends on funding to support the teachers who are willing to participate in the reform. Some teachers want to learn more about numerical algorithms and programming, others may need an assistant who can help with developing relevant problems, and some need support to buy a new computer.

Boundary conditions

The project is centrally rooted in the strategic plans of the University, several centres of excellence, and several bachelor's degree programmes in science at the Faculty of Mathematics and Natural Sciences.

The Norwegian higher education system underwent a major educational reform in 2003, triggered by the Bologna process. One important ingredient was the introduction of quite broad bachelor programmes. At present there are six major bachelor's degree programs in mathematics and the mathematical sciences that share a number of courses in mathematics, informatics and science.

At the same time (2003), the first centres of excellence were established in Norway. At present there are at least five centres of excellence at the University with a strong emphasis on different types/flavours of computations. These centres play an important role in catalysing cross-disciplinary research and educational projects.

Financial support

The CSE project has received considerable financial support from several sources, amongst these the Initiative for Flexible Learning at the University of Oslo during the period 2004-2007, from the Ministry of Education and Research in 2007, from the Norwegian centre of excellence 'Centre of Mathematics for Applications' (CMA), the Faculty of Mathematics and Natural Sciences, and the departments of Geology, Informatics, Mathematics and Physics. The CMA and the Faculty of Mathematics and Natural Sciences together act as the coordinating unit. This financial support has allowed the project to support many teachers who have expressed wishes to reform their courses.

Student assistants

A considerable part of the funding has been used to hire student assistants in summer jobs. These excellent students have contributed in various ways, especially by developing a large body of exercises, and by writing software to support the project. This has several interesting aspects. Firstly, many of the students were more knowledgeable on software matters than many university teachers. They quickly came up with a number of valuable contributions, ranging from new exercises to interesting input to the syllabus of a given course.

Secondly, the summer jobs have an important educational aspect in that the students gain overall insight into several undergraduate courses close to their own fields of study. It is our expressed hope that the summer jobs may have inspired these students to develop a sense of ownership both for the courses, and the whole CSE project. This may prove to be much more significant than the exercises and software they developed, as several of these students may well end up as the next generation of university teachers.

CSE requires cross-disciplinary cooperation

The cross-disciplinary nature of the CSE project, with many departments and centres of excellence involved, provides a unique opportunity for a coordinated effort towards revising the way we teach science. It is rather uncommon that so many university teachers collaborate across disciplines; the opposite is normally what happens. Colleagues from other universities have often commented: *This all sounds great, but how have you been able to collaborate across departments without conflicts?*

One of the unique aspects of this project is the simple fact that there is a group of people from different departments interested in reforming our undergraduate curriculum. Within this group, everybody is deeply involved in research that involves computations. The presence of several centres of excellence that focus on computations has created meeting places for cross-disciplinary projects, as well as many discussions of educational matters.

The first semester

Four of our bachelor's degree programmes (Mathematics, Information theory and Technology; Electronics, Physics, Astronomy and Meteorology; and Mathematics and Economics), which together recruit about 300 students every year, have a common first semester that consists of three courses:

- INF1100: Introduction to programming with scientific applications
- MAT-INF1100: Modelling and computations
- MAT1100: Calculus and analysis

The coordination between MAT-INF1100 and INF1100 is crucial to the CSE project. MAT-INF1100 includes a number of mathematical topics as well as numerical algorithms for performing standard mathematical operations like differentiation and integration, equation solving and solving differential equations. The algorithms derived in MAT-INF1100 are coded and discussed in INF1100, which gives an introduction to computer programming using Python as the programming language, with special emphasis on applications in physics, statistics/probability, biology, medicine and economics.

A simple example is differentiation, which is defined formally and discussed from the classical point of view in the calculus course MAT1100. Algorithms to compute the derivative numerically are discussed in MAT-INF1100, together with error analyses based on Taylor's formula. These algorithms are then implemented and used in particular applications in the programming course INF1100.

The future

The courses MAT1100, MAT-INF1100 and INF1100 have a number of other examples and topics in common, amongst these ordinary differential equations. Differential equations are in turn used widely in other courses in a bachelor's degree. For example, the second-semester mechanics course FYS-MEK1100 uses numerical algorithms for solving differential equations to study topics from the classical pendulum to realistic rocket launching. The central mathematics courses MEK1100, MAT1110 and MAT1120 further develop numerical exercises and problems, in the standard directions of linear algebra and multivariate calculus. The research groups in Meteorology and Oceanography provide another example of the integration of computations in more advanced bachelor courses. These two research groups are responsible for one of the scientific branches of the Physics, Astronomy and Meteorology bachelor's programme. This bachelor's programme typically receives 80–100 new students every year, and in the first year of study, five (out) of six courses include a computational perspective, as indicated above. In the third semester the students may attend the first course in astrophysics or meteorology. Both courses have been reformed via the CSE project and have computational exercises to deepen and illustrate the theory that is taught. Meteorology and oceanography are computationally intensive research fields. Aligning the advanced bachelor's courses with the CSE project therefore allows these groups to introduce fascinating and stimulating research topics into their undergraduate teaching. In this way the students are exposed to programming topics and numerical exercises in a number of bachelor's degree courses during their first three years of study, and this stretches out the computational learning threshold over time and in different courses.

Summary, conclusion and challenges

Main contribution

The bottom line of the CSE initiative is that the students obtain a uniform background in computational skills which allows them to solve realistic problems in their first science courses instead of the simplified problems that are a necessity when the computational power is restricted to pencil, paper and a calculator. The mechanics course is a good example. Typical topics which have been included are rocket launching with realistic parameters, how to kick a football and model its trajectory, and studies of planet motion and the position of planets. Realistic studies of these problems require serious computations. Moreover, since the computational aspects have been taught in the mathematics and informatics classes, there is no need to spend extra time on this in the science classes.

The pivotal point of the CSE project is the first semester, with the recently achieved coordination between the three fundamental mathematics and informatics courses. This has allowed seamless integration of a computational perspective on the teaching of science in later semesters. The coordination between the first semester and the mathematics courses in the second and the third semesters strengthens this perspective and introduces many additional algorithms and their pertinent implementations. This provides the students with a bag of tools that can be used in many other courses.

Extending the CSE project

The coordination introduced by the CSE programme is tailored to the mathematically intensive programmes, such as the programmes in Physics, Astronomy and Meteorology; Mathematics, Information Science and Technology; and so forth. Other bachelor programmes such as Chemistry or Geology have a syllabus with less emphasis on mathematics and computations. One of the challenges is to develop tailor-made mathematics and scientific computing courses for these students as well, in order to gain from the momentum achieved within the mathematically intensive bachelor programmes. This is already taking place in the form of a new course on scientific programming for geology freshmen (first semester).

Further support for teachers

Another major challenge is the attitude of the university teachers towards the introduction of a computational programme, particularly since many teachers are not fully familiar and/or comfortable with such an approach. To this end we have recently, with support from the Flexible Learning Initiative, created a new pedagogical module that introduces the CSE project. This module is used as part of the compulsory pedagogical background every university teacher must attend in order to receive tenure. Further work on this module, with a build-up of a body of relevant exercises and examples, and the possibility of obtaining pedagogical assistance for university teachers who wish to take part in the CSE project, is part of our future plans.

Tenured teachers who want to teach according to the CSE principles, but lack the sufficient technical background, may benefit from web-based modules developed with a life-long learning perspective. These modules will also be available for teachers from other educational institutions and will contribute to a more coherent national education in science.

Integration, not addition

Initially we tried to introduce a computational perspective on our courses by supplementing traditional textbooks with additional material on computations. After a few years of experience, we have learned that this is not a particularly good solution. The reasons are twofold: The first is that computations then remain an addition to the classical material, at least regarding teaching materials. This hinders the important mental process of integrating computations with the classical material. The second reason is that computations inevitably take up more space when added to the classical material. A much better solution is to integrate a computational perspective in the standard teaching material, as computations can then also be used to develop the theory where this is natural. In this way the total volume of the teaching material may be reduced.

Need for new material

The conclusion is that there is a need for new textbooks and related material with an integrated computational profile. In particular new exercises and projects must be developed. This is a challenging task to undertake in subjects where the teaching material and exercises in some cases have been finely honed for hundreds of years.

On the other hand, we believe this is a rare opportunity to participate in a major, paradigmatic shift in science teaching, and a number of new textbooks are being developed within the CSE framework, with considerable interest from a major international publisher.

CSE on a national scale

The CSE project gives our students a broad background in computational techniques of relevance for exploration and problem-solving in the sciences. This kind of background is not at all common for students from other universities. A challenging consequence of the CSE project is therefore that both foreign exchange students and students from other Norwegian universities often find it difficult to attend courses in Oslo that have undergone a CSE revision. In all humility, we do believe the solution to be that CSE-like revisions also take place at the other higher educational institutions.

In this perspective, we view the CSE initiative at the University of Oslo as a national pilot project, and it is our hope that the experience and knowledge we have gained and developed locally can be transferred to other universities and regional colleges. That would be a true service to our science community.