# Master program in Computational Physics, Mathematics and Life Science

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## Master program in Computational Physics, Mathematics and Life Science

We propose a new Master of Science program at the Faculty of Mathematics and Natural Sciences of the University of Oslo. This program is called **Computational Physics, Mathematics and Life Science**, with acronym **CPMLS**

The program is a collaboration between five departments and classical disciplines:

- Department of Biosciences
- Department of Chemistry

- Department of Informatics
- Department of Mathematics
- Department of Physics

The program will be administrated by the Department of Physics. The program is based on the highly successful Computational Physics direction under the present Master program in physics at the University of Oslo.

The program is multidisciplinary and all students who have completed undergraduate studies in science and engineering, with a sufficient quantitative background, are eligible. The language of instruction is English.

## Strategic importance

The program will educate the next generation of cross-disciplinary science students with the knowledge, skills, and values needed to pose and solve current and new scientific, technological and societal challenges. The program will lay the foundation for cross-disciplinary educational, research and innovation activities at the Faculty. The program will contribute to building a common cross-disciplinary approach to the key strategic initiatives at the Faculty: Energy, Materials, Life Science, and Enabling Technologies.

A particular strength of physics students is their ability to pose and solve problems that combine physical insights with mathematical tools and now also computational skills. This provides a unique combination of applied and theoretical knowledge and skills. These features are invaluable for the development of multi-disciplinary educational and research programs. In this program we build on and refine this philosophy. The main focus is not to educate computer specialists, but to educate students with a solid understanding in basic science as well as an integrated knowledge on how to use essential methods from computational science. This requires an education that covers both the specific disciplines like physics, biology, geoscience, mathematics etc with a strong background in computational science.

## Scientific and educational motivation

**Applications of simulation.** Numerical simulations of various systems in science are central to our basic understanding of nature and technlogy. The increase in computational power, improved algorithms for solving problems in science as well as access to high-performance facilities, allow researchers nowadays to study complicated systems across many length and energy scales. Applications span from studying quantum physical systems in nanotechnology and the characteristics of new materials or subamotic physics at its smallest length scale, to simulating galaxies and the evolution of the universe. In between, simulations are key to understanding cancer treatment and how the brain works, predicting climate changes and this week's weather, simulating natural disasters, semi-conductor devices, quantum computers, as well as assessing risk in the insurance and financial industry. These are just a few topics already well covered at the University of Oslo and that can be topics for coming thesis projects as well as research directions.

**Job market.** A large number of the candidates from the four involved departments get jobs where numerical simulations are central and essential. The proposed program will raise the educational quality in this area, because our candidates need a broader understanding of the possibilities and limitations of computation-based problem solving.

## Multiscale modeling is the big open research question

Today's problems, unlike traditional science and engineering, involve complex systems with many distinct physical processes. The wide open research topic of this century, both in industry and at universities, is how to effectively couple processes across different length and energy scales. Progress will rely on a multi-disciplinary approach and therefore a need for a multi-disciplinary educational program.

The proposed program will foster candidates with the right multi-disciplinary background and comutational thinking for understanding today's simulation technology and its challenges.

## The new program combines old and new initiatives

This program builds on the strengths and successes of two existing master's programs in Computational Physics (at the Dept. of Physics) and Applied Mathematics and Mechanics (at the Dept. of Mathematics).

A new master's program in Computational Life must anyway be developed to meet coming needs of the scientific community. If successful, it will position the University of Oslo as the leading institution nationally in computational life science. We belive this new program is best developed in close collaboration with already successful computational science programs.

The program in Computational Life Sciences will have a strong link to the Norwegian University of Life Sciences. Further links to NTNU will be developed.

## Computational Physics at UiO has been a great success

This initiative has its roots in the highly successful direction called Computational Physics under the Master program in Physics at the University of Oslo.

This program has educated almost 60 Master of Science students during the last ten years. Over 50% of these students have continued with PhD studies in Physics, Chemistry, Mathematics and now recently Biology connected with the CINPLA project.

## The new program will also host the CSE project

The new proposed program will also take a leading responsibility in further developments of the highly successful Computing in Science Education initiative at UiO. Master of science thesis projects linked up to the CSE project will be offered.

If the program becomes successful, it will naturally lead to new cross-disciplinary research and a need for a new department in computational science.

## Computing competence

Computing means solving scientific problems using computers. It covers numerical as well as symbolic computing. Computing is also about developing an understanding of the scientific process by enhancing the algorithmic thinking when solving problems. Computing competence has always been a central part of the science and engineering education.

Computing competence is about

- derivation, verification, and implementation of algorithms
- understanding what can go wrong with algorithms
- overview of important, known algorithms
- understanding how algorithms are used to solve mathematical problems
- reproducible science and ethics
- algorithmic thinking for gaining deeper insights about scientific problems

## Key elememts in computing competence

The power of the scientific method lies in identifying a given problem as a special case of an abstract class of problems, identifying general solution methods for this class of problems, and applying a general method to the specific problem (applying means, in the case of computing, calculations by pen and paper, symbolic computing, or numerical computing by ready-made and/or self-written software). This generic view on problems and methods is particularly important for understanding how to apply available, generic software to solve a particular problem.

Computing competence represents a central element in scientific problem solving, from basic education and research to essentially almost all advanced problems in modern societies. Computing competence is simply central to further progress. It enlarges the body of tools available to students and scientists beyond classical tools and allows for a more generic handling of problems. Focusing on algorithmic aspects results in deeper insights about scientific problems.

Today's projects in science and industry tend to involve larger teams. Tools for reliable collaboration must therefore be mastered (e.g., version control systems, automated computer experiments for reproducibility, software and method documentation).

## Learning outcomes

Students of this program learn to use the computer as a laboratory for solving problems in science and engineering. The program offers exciting thesis projects from many disciplines: biology and life science, chemistry, mathematics, informatics, physics, geophysics, mechanics, geology, computational finance, digital signal processing and image analysis – the students choose their field according to their own interests.

A Master's degree from this program gives the student a methodical training in planning, conducting, and reporting large research projects, often together with other students and university teachers. Projects usually emphasise finding practical solutions, developing an intuitive understanding of the science and the scientific methods needed to solve complicated problems, use of many tools, and not least developing your own creativity and independent thinking. The thesis work is a scientific project where the students learn to tackle a scientific problem in a professional manner.

## Specific skills

The students learns to understand and develop insights in high-level scientific problems, involving a fundamental understanding of the methods and tools which are necessary and to present these results orally and in written form as scientific reports. In addition, students learn to get

- Deep knowledge of the most fundamental algorithms involved, how optimizatize these and statistical uncertainty quantification.
- Overview of advanced algorithms and how they can be accessed in available software.
- Knowledge of high-performance computing elements: memory usage, vectorized and parallel algorithms.
- Understanding of approximation errors.
- Knowledge of at least one computer algebra system and how it is applied to perform classical mathematics (calculus, linear algebra, differential equations - with verification).
- Extensive experience with programming in a high-level language (MATLAB, Python, R). Experience with programming in a compiled language (Fortran, C, C++).
- Experience with implementing and applying numerical algorithms in reusable software that acknowledges the generic nature of the mathematical algorithms.

- Experience with debugging software, e.g., as part of implementing comprehensive tests.
- Experience with programming of testing procedures.
- Experience with different visualization techniques for different types of computed data.
- Experience with presenting computed results in scientific reports and oral presentations.
- Critical evaluation of results and errors
- Be able to develop software and algorithms for solving complicated scientific problems independently and/or in collaboration with other students.

## Structure and courses

The table here is an example of a suggested path for a Master of Science project, with course work the first year and thesis work the last year.

| | 10 ECTS | 10 ECTS | 10 ECTS |
|---|---|---|---|
| 4th semester | Master thesis | Master Thesis | Master Thesis |
| 3rd semester | Master thesis | Master Thesis | Master Thesis |
| 2nd semester | Master courses | Master courses | Master courses |
| 1st semester | Master courses | Master courses | Master courses |

The program is very flexible in its structure and students may opt for starting with their thesis work from the first semester and scatter the respective course load across all four semesters.

Depending on interests and specializations, there are many courses on computational science which can make up the required curriculum of course work. Furthermore, courses may be broken up in smaller modules, avoding thereby the limitation of 10 ECTS per course only. Some of these courses are listed below.

## Structure

Here follows a list of suggested courses that students may include in their required course load.

- FYS4150 Computational Physics I
- FYS4411 Computational Physics II
- FYS4460 Computational Physics III
- INF5620 Numerical Methods for Partial Differential Equations
- INF5631 Project on Numerical Methods for Partial Differential Equations

- FYS388 Computational Neuroscience
- STK4520 Laboratory for Finance and Insurance Mathematics
- STK4021 Applied Bayesian Analysis and Numerical Methods
- MAT-INF4130 Numerical Linear Algebra
- MAT-INF4110 Mathematical Optimization
- ECON4240 Equilibrium, welfare and information
- MEK4470 Computational Fluid Mechanics
- MEK4250 Finite Element Methods in Computational Mechanics

The program plans to develop other courses in computational science and its applications, ranging from life science to materials science.

## Admission

The following higher education entrance qualifications are needed

- A completed bachelor's degree (undergraduate) comparable to a Norwegian bachelor's degree in one of the following disciplines

  1. Biology, molecular biology, biochemistry or any life science degree
  2. Physics, astrophysics, astronomy, geophysics and meteorology
  3. Mathematics, mechanics, statistics and computational mathematics
  4. Computer science and electronics
  5. Chemistry
  6. Materials Science and nanotechnology
  7. Any undergraduate degree in engineering
  8. Mathematical finance and economy

- The language of instruction is English. An internationally recognised English language proficiency test is required.

## The program opens up for flexible backgrounds

While discipline-based master's programs tend to introduce very strict requirements to courses, we believe in adapting a computational thesis topic to the student's background, thereby opening up for students with a wide range of bachelor's degrees. A very heterogeneous student community is thought to be a strength and unique feature of the new program.

## Study abroad and international collaborators

Students at the University of Oslo may choose to take part of their degrees at a university abroad.

Students in this program have a number of interesting international exchange possibilities. The involved researchers have extensive collaborations with other researchers worldwide. These exchange possibility range from top universities in the USA, Asia and Europe as well as leading National Laboratories in the USA.

## Career prospects

Candidates who are capable of modeling and understanding complicated systems in natural science, are in short supply in society. The computational methods and approaches to scientific problems students learn when working on their thesis projects are very similar to the methods they will use in later stages of their careers. To handle large numerical projects demands structured thinking and good analytical skills and a thorough understanding of the problems to be solved. This knowledge makes the students unique on the labor market.

Career opportunities are many, from research institutes, universities and university colleges and a multitude of companies. Examples include IBM, Hydro, Statoil, and Telenor. The program gives an excellent background for further studies, with a PhD as one possible goal.

The program has also a strong international element which allows students to gain important experience from international collaborations in science, with the opportunity to spend parts of the time spent on thesis work at research institutions abroad.