Bachelor of Science program in Computational Physics and Quantum Technologies at Department of Physics, UiO

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Bachelor of Science program in Computational Physics and Quantum Technologies

We would like to propose a new Bachelor of Science program at the Department of Physics of the University of Oslo. This program is called **Computational Physics and Quantum Technologies**, with acronym **CPQT**. Tentative start fall semester 2024.

Possible collaboration with:

- Department of Chemistry

- Department of Informatics

- Department of Mathematics

The program will be administrated by the Department of Physics.

Strategic importance

Computational physics, computational science and data science play a central role in scientific investigations and are central to innovation in most domains of our lives. These fields underpin the majority of today's technological, economic and societal feats. We have entered an era in which huge amounts of data offer enormous opportunities, but only to those who are able to harness them. The 3rd industrial revolution will alter significantly the demands on the workforce. In

particular, the developments taking place in quantum technologies and quantum information systems (QIS) together with artificial intelligence (AI) and machine learning (ML) are expected to play a significant role in technology developments and innovations, and for fundamental discoveries in physics.

AI and machine learning

Artificial intelligence is built upon integrated machine learning algorithms, which in turn are fundamentally rooted in optimization and statistical learning.

AI and ML in Physics

Artificial intelligence (AI) and Machine learning (ML) techniques have in the last years gained considerable traction in scientific discovery. In particular, applications and techniques for so-called **fast ML**, that is high-performance ML methods applied to real time experimental data processing, hold great promise for enhancing scientific discoveries in many different disciplines. These developments cover a broad mix of rapidly evolving fields, from the development of ML techniques to computer and hardware architectures.

Physics based Machine Learning

An important and emerging field is what has been dubbed as scientific ML, see the article by Deiana et al Applications and Techniques for Fast Machine Learning in Science, arXiv:2110.13041

The authors discuss applications and techniques for fast machine learning (ML) in science – the concept of integrating power ML methods into the real-time experimental data processing loop to accelerate scientific discovery. The report covers three main areas

1. applications for fast ML across a number of scientific domains;

2. techniques for training and implementing performant and resource-efficient ML algorithms;

3. and computing architectures, platforms, and technologies for deploying these algorithms.

Many new research directions

For our research in for example particle and nuclear physics, fields which cover a huge range of energy and length scales, spanning from our smallest constituents to the physics of dense astronomical objects like supernovae and neutron stars, AI and ML techniques offer possibilities for new discoveries and deeper insights about the physics of atomic nuclei, elementary particles and

dense matter. Similarly, ML algorithms are widely applied in condensed matter physics, materials science and nanotechnology, in molecular dynamics simulations of complex systems in neuroscience and in many other fields in natural science.

Examples of applications in subatomic physics.

- **Artificial Intelligence and Machine Learning in Nuclear Physics**, Amber Boehnlein et al., arXiv:2112.02309 and Reviews of Modern Physics, 2022, in press

- **Predicting Solid State Material Platforms for Quantum Technologies**, Hebnes et al,. arXiv:2203.16203

- Mehta et al. and Physics Reports (2019).

- Machine Learning and the Physical Sciences by Carleo et al

- Particle Data Group summary on ML methods

Quantum Information Technologies (QIT)

Recent developments in quantum information systems and technologies offer the possibility to address some of the most challenging large-scale problems, whether they are represented by complicated interacting quantum mechanical systems or classical systems. Originally proposed by Feynman, the efficient simulation of for example quantum systems by other, more controllable quantum systems formed the basis for modern constructions of quantum computations. Many algorithmic and theoretical advances have followed since the initial work in this area and with recent developments in quantum computing hardware there is an additional drive to identify early practical problems on which these devices might demonstrate an advantage.

More on QIT

In addition to theoretical activities conducted at the Department of Physics (mainly at the Center for Computing in Science Education (CCSE) and the condensed matter group and other groups), there is a growing interest to study candidate systems for making quantum hardware. In particular, so-called point defects in semiconductors are pursued by experimenters at the center for Materials Science. With this broad list of activities at the department of physics, there is a huge potential to prepare the ground for educating physicists with the theoretical and experimental background needed for the 21st century. There is also a great interest in candidates with such a background, knowledge, skills and competences in industry and the public sector.

Why such a program?

Establishing such an educational program will be unique in Norway and has the potential to attract excellent students. The popularity of the Computational Science and in particular the Computational Physics and Computational Materials Science study direction are clear indicattors that these are fields with the potential to attract new students.

Furthermore, Oslo Metropolitan university has recently acquired two quantum quantum computers, see `https://kommunikasjon.ntb.no/pressemelding/oslomet-avduker-norges-forst` `publisherId=15678779&releaseId=17917781` and is now establishing research and educational initiatives in quantum information systems. There are thus several interesting avenues for joint collaborations in quantum information systems and quantum technologies as well as developing joint educational programs.

More on motivation

Computational physics plays a central role in the above mentioned developments. Computations are simply indispensable. At the department of physics of the university of Oslo this is reflected in the extremely popular study direction Computational Physics of the master of science (MSc) program Computational Science. This program has over the last two decades recruited many excellent students, resulting in highly attractive candidates in academia and in industry and the public sector. A large fraction of these students have specialized either in artificial intelligence and machine learning and/or in quantum information systems. The large majority of the these students have job offers at least one year before completing their MSc theses. The program has also become one of the most selective master programs at the University of Oslo, requiring a grade average of 4.7 for entry in 2021. Furthermore, with recent advances in quantum technologies, there is a strong potential for new developments in the fields of nanotechnology and materials science, with the possibilities to develop new experimental activities.

Rationale

The rationale behind proposing a new bachelor of science (BSc) program in computational physics and quantum technologies (QT) is:

1. To attract at an earlier stage new students with an explicit interest in QIS, QT and AI and ML in physics.

2. To enhance the recruitment to fields in physics which are in high demand for students and candidates with an expertise in computations, QIS, QT, AI and ML. We expect high demands from both the private sector and the public sector for candidates with these competences, insights and skills.

3. Candidates with such a background will be of great importance for new scientific discoveries and technological innovations. At the department

of physics of the university of Oslo there are several research directions whose scientific activities will benefit at large from candidates with such a background, spanning from fast ML for new discoveries to the development of QTs.

Structure of Program and Courses

In developing such a program the Center for Computing in Science Education (CCSE) at the university of Oslo (UiO) could be the entity which provides the pedagogical research resources. It has the needed research experience on how to design curricula so that students develop deep knowledge that is connected and useful.

The figure here, inspired by the QuSTEAM project in the USA `https://qusteam.org` shows how one can link educational developments by involving various stakeholders from academia, industry research laboratories.
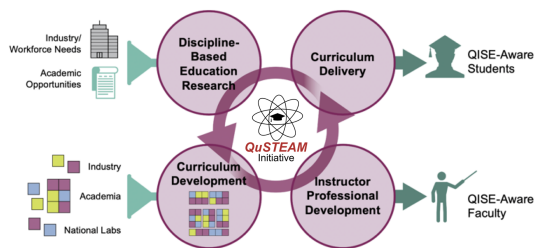
Using recent advances in pedagogical research and defining potentially new research directions in education rsearch

The reason why we believe the CCSE should be involved in planning this BSc program is that it has the necessary expertise to address several issues, such as

1. Lots of conceptual learning: superposition, entanglement, QIS and QT, etc.

2. Connecting statistics and mathematics with ML methods

3. Linking ML algorithms with quantum ML.

4. Coding is indispensable. This is a central reason why the CCSE should be involved.

5. Experience with teamwork, project management, and communication are important and highly valued.

6. Experience with engagement with industry, public sector and priority to diversity through the Computational Science program and other activities at the CCSE.

7. Mentorship should begin the moment students enroll. The experiences with the Computational Science program developed at the CCSE will be of great value, as the activities of the KURT center.

Societal needs

The program aims at addressing future societal needs, such as the needs for specialized candidates (,Master of SciencePhDs, postdocs), but also the needs of people with a broad overview of what is possible in QIS and QT. There are not enough potential employees in AI, ML, QIS and QT. There is a clear supply gap.

A BSc degree with specialization is thus a good place to start. Linking this with the Computational Science program and the study directions Computational physics and Computational materials science, will offer our various research fields top candidates as well as pointing to new research directions.

And what about AI/ML and quantum technologies towards high-school?

Paths in the BSc program

The program has three possible directions

1. Quantum information systems and quantum technologies

2. Artificial intelligence and machine learning in physics

3. Computational Physics

The students specialize in these directions in their last year of the BSc program.

Structure and courses

There are several existing courses which can be included in this program. There are also courses which need to be established. At the CCSE we have the research and educational expertise to establish two to three new courses in these directions. Most likely there are potential teachers from other groups.

A separate application for establishing these courses follows. The additional courses we propose are (these are suggestions and codes are tentative) listed here. Note that we propose these courses as cloned courses. We may consider extensions of these codes in order to offer PhD variants as well.

The list here is tentative. Two of the courses, FYS4446 and FYS4447 have been taught as special topics since 2018 and we have already a large body of material. This list is a mere suggestion.

1. Classical and quantum laboratory, needs to be established, perhaps by researchers at the Center of Materials Science (LENS group), FYS2440

2. Quantum computing and software, needs to be established. This can be organized together with OsloMet and Simula Research lab.

3. Quantum hardware, needs to be established, this can be organized together with OsloMet and Simula Research lab.

4. Quantum computing and quantum machine learning, FYS3446/FYS4446 (cloned course, already developed by CCSE)

5. Advanced machine learning and data analysis for the physical sciences, FYS3447/FYS4447 (already developed by CCSE)

The last three courses are elective ones for the last semester of study. Some of these courses can also be split into modules a 5 ECTS or 7.5 ECTS. There are obviously other course alternatives. The first year is identical with the BSc program **Physics and Astronomy**.

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
6th semester	Elective	Elective	Elective
5th semester	FYS2160	FYS3110	Elective/FYS-STK3155
4th semester	FYS2130	FYS2140	STK2100/FYS2440
3rd semester	MAT1120	FYS1120	FYS3150
2nd semester	MAT1110	FYS12XX	FYS13XX
1st semester	MAT1100	IN1900	FYS11XX

Description of Study directions

The basic structure of the study directions could be

- Description of study directions with potential projects

- Admission criteria

- Learning outcomes

- Program structure

- Semester abroad

- Career prospects

- Teaching and examinations

What follows are text proposals for these items.

Description of learning outcomes

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.

The learning outcomes are subdivided in three general categories, knowledge, skills and general competence.

Study abroad and international collaborators

Students at the University of Oslo may choose to take parts 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 job 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.

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.

The many questions and how do we proceed

1. Do we need a new BSc program in Physics? Could these educational paths be defined as study directions under the Physics program?

2. Potential, Strengths, possibilities and weaknesses of such a program

3. A possible path, if there is interest in this is:

   - The education committee of the department of Physics (studie og undervisningsutvalget) initiates the process by establishing a working group with the mandate to explore these possibilities, not later than May/June 2022 with the aim to have a final report by October 2022.