

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

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Planned start: Fall 2024 (?)

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. The program will be administrated by the Department of Physics.

Possible collaborations (to be discussed) with:

- Department of Chemistry
- Department of Informatics
- Department of Mathematics

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.

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.

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.

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 physics (largely subatomic physics)

1. **Artificial Intelligence and Machine Learning in Nuclear Physics**, Amber Boehnlein et al., [arXiv:2112.02309](#) and Reviews of Modern Physics, 2022, in press
2. **Predicting Solid State Material Platforms for Quantum Technologies**, Hebnes et al., [arXiv:2203.16203](#), Nature Materials Communications, submitted.
3. [Mehta et al. and Physics Reports \(2019\)](#).
4. [Machine Learning and the Physical Sciences](#) by Carleo et al
5. [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.

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 theory group), 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 clear 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.

Establishing such a program, could also lay the foundations for theoretical and experimental activities in quantum technologies.

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 indicates that these are fields with the potential to attract new students.

We may also consider adding a new study direction (or changing the name of Physics and Materials Science to Computational Physics and Quantum Technologies) for the CS master of science program.

Furthermore, Oslo Metropolitan university has recently acquired two quantum quantum computers, see <https://kommunikasjon.ntb.no/pressemelding/oslomet-avduker-norges-forste-quantum-computer> 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.

Links of interest to other (mainly MSc and PhD level) programs

There are many universities around the world offering quantum computing as a graduate program, allowing a bridge to form between research and industry. This is especially beneficial for students looking to transition from academia into

a quantum computing job. The list here shows some of the top 20 quantum computing graduate programs (master of science and PhD programs) in 2022

In addition to the above list, see also

1. University of Copenhagen
2. EPFL Lausanne
3. University of Barcelona
4. ETH Zurich
5. Quantum Technology Open Master
6. European Master Certificate in Quantum Science and Technology
7. Educational programs of EU's QC flagship

And potential projects with industry.

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 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:

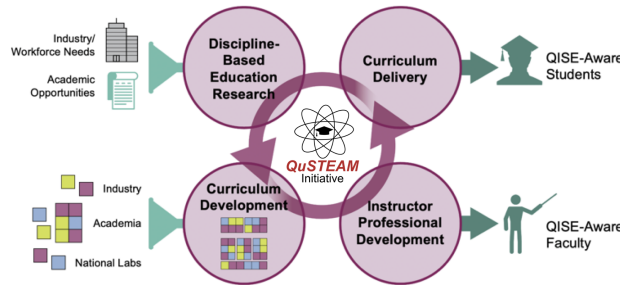
1. To attract at an earlier stage new students with an explicit interest in QIS, QT and AI and ML in physics.
2. To enhance the recruitment to fields in physics which are in high demand for students and candidates with an expertise in computations, QIS, QT, AI and ML. We expect high demands from both 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. Together with colleagues and interested teachers from other research groups, one can establish an educational team which oversees the development of courses in these topics and lays the foundation for an innovative educational program.

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.



To base the development of courses and educational programs on established research in physics education has several important aspects. In particular, quantum mechanics is a highly non-trivial topic to teach and there are several topics which deserve the attention of physics education research, 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 could (or should) be involved.

5. Machine learning and artificial intelligence in physics involve also many computational aspects which fit well with data analysis and statistics.
6. Experience with teamwork, project management, and communication are important and highly valued.
7. Experience with engagement with industry, public sector and priority to diversity through the Computational Science program and other activities at the CCSE.
8. Mentorship should begin the moment students enroll. The experiences with the Computational Science program developed at the CCSE will be of great value. Similarly, the activities of the KURT center are highly relevant (with important ramifications to high school education).

Societal needs

The program aims at addressing future societal needs, such as the needs for specialized candidates (Master of Science, PhDs, 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 Physics MSc program and 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.

Study specializations in the BSc program

The program could offer 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.

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. Similarly, we expect potential teachers from both the theory group and the condensed matter group.

Researchers at the CCSE have for more than twenty years been deeply involved in the establishment and development of courses in computational physics, data analysis and machine learning (FYS3150/4150 established in 1999 and FYS-STK3155/4155 established in 2018). Furthermore, the same group offers

advanced courses in computational physics (FYS4411/9411 and FYS4460/9460 since early 2000) and two new courses on quantum computing and advanced data analysis and machine learning for the physical sciences (FYS5419/FYS9419 and FYS5429/FYS9429, start spring 2023).

Education

1. Incorporate elements of statistical data analysis and Machine Learning in undergraduate programs
2. Develop courses on Machine Learning and statistical data analysis
3. Build up a series of courses in QIS, inspiration
 - s) initiative from USA
 - (a) Modifying contents of present Physics programs or a new program on Computational Physics and Quantum Technologies
 - i. study direction/option in **quantum technologies**
 - ii. study direction/option in **Artificial Intelligence and Machine Learning**
 - iii. study direction on Computational Physics
 - (b) Master of Science/PhD programs in Computational Science and Data Science
 - i. UiO has already MSc programs in CS and DS
 - ii. Many other universities are developing or have similar programs

Possible courses

Topics in a Bachelor of Science/Master of Science.

- (a) General university course on quantum mech and quantum technologies
- (b) Information Systems
- (c) From Classical Information theory to Quantum Information theory
- (d) Classical and quantum laboratory, needs to be established, perhaps by researchers at the Center of Materials Science (LENS group), FYS2440
- (e) Quantum computing and software, needs to be established. This can be organized together with OsloMet and Simula Research lab.
- (f) Quantum hardware, needs to be established, this can be organized together with OsloMet and Simula Research lab.
- (g) Quantum computing and quantum machine learning (FYS5429)

- (h) Advanced machine learning and data analysis for the physical sciences (FYS5419)

The first year is identical with the BSc program **Physics and Astronomy**.

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**.

The table here is an example of a suggested path a BSc degree.

	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 (revised version)
2nd semester	MAT1110	FYS12XX	FYS13XX
1st semester	MAT1100	IN1900	FYS11XX

Important Issues to think of

- (a) How to include concepts from statistical data analysis and machine learning
- (b) Lots of conceptual learning: superposition, entanglement, QIS applications, etc.
- (c) Coding is indispensable.
- (d) Teamwork, project management, and communication are important and highly valued
- (e) Active learning
- (f) Engagement with industry: guest lectures, virtual tours, co-ops, and/or internships.
- (g) Mentorship could 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.

Many interesting physics education research topics (CCSE).

Observations

- (a) Students do not really know what QIS is.
- (b) ML/AI seen as black boxes/magic!
- (c) Students perceive that a graduate degree is necessary to work in QIS. A BSc will help.

Future Needs/Problems

- (a) There are already great needs for specialized people (Ph. D. s, post-docs), but also needs of people with a broad overview of what is possible in ML/AI and/or QIS.
- (b) There are not enough potential employees in AI/ML and QIS . It is a supply gap, not a skills gap.
- (c) A BSc with specialization is a good place to start
- (d) It is tremendously important to get everyone speaking the same language. Facility with the vernacular of quantum mechanics is a big plus.

The many questions

- (a) Do we need a new BSc program in Physics? Could these educational paths be defined as study directions under the Physics program?
- (b) Potential, Strengths, possibilities and weaknesses of such a program
- (c) and more