Including Quantum Technologies and AI/ML in educational programs at the Department of Physics, UiO

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Planned start: Fall 2024 for new study direction (first point below)

Establishing new study directions in the Physics and Astronomy BSc program and Master of Science in Physics

We would like to propose

1. A new study direction under the Physics and Astronomy (PA) BSc program called
   - **Quantum technologies and AI/ML** (name to be discussed)
   - Planned start fall 2024 for the new study direction

2. At a later stage, a possible name change of the PA BSc program to for example
   - Physics, Astronomy and Quantum Technologies

3. Similarly, the Physics MSc program changes name to
   - Physics and Quantum Technologies
   - With a study direction in Quantum Technologies/Science
   - and a study direction Computational Physics and AI/ML for the Physical Sciences

Possible collaboration 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.

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 change?

Establishing such educational directions 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 indicators that these are fields with the potential to attract new students.

Oslo Metropolitan university has recently acquired two quantum quantum computers 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 such new study directions 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.

Societal needs

The new study direction 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 to our various research fields top candidates as well as pointing to new research directions.

Paths in the BSc program

The study direction we propose is

- **Quantum technologies and AI/ML in the physical sciences** (name to be discussed)

Structure and courses

There are several existing courses which can be included in this program. There are also courses which need to be established. We would like to propose three new courses (see tentative course contents below) for the new BSc study direction.

1. FYS1xxx Introduction to Quantum Technologies, third semester
2. FYS2xxx Quantum Materials, fifth semester
3. FYS3xxx Quantum Computing, sixth semester

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 study direction in quantum technologies and computational physics and AI/ML.

	10 ECTS	10 ECTS	10 ECTS
6th semester	Elective/ExPhil	Elective/ML courses	FYS3XXX Quantum Computing, new
5th semester	FYS2160	FYS3110	FYS3XXX Quantum Materials, new
4th semester	FYS2130	FYS2140	FYS3150/FYS2150
3rd semester	MAT1120	FYS1120	FYS1XXX Introduction to Quantum Technol
2nd semester	MAT1110	STK-FYS1100	FYS1105
1st semester	MAT1100	IN1900	FYS1100

Description of new courses for BSc study direction

First course: Introduction to quantum technologies, third semester, 10 ECTS.

Content:

1. Motivasjon
2. Basic quantum physics/ QT at a glance
3. Quantum bits versus classical bits
4. Materials and actual realizations/quantum platforms
5. Quantum sensors
6. Quantum communication and quantum cryptography
7. Quantum computing

Learning goals. Main objectives: general introduction to quantum technology that provides an overview of the entire field Understand the difference between qubits and classical bits.

Second course: Quantum materials, fifth semester, 10 ECTS.

First part: Condensed matter physics.

1. Introduction
2. Crystal bonding
3. Lattices
4. Reciprocal space
5. Crystals
6. Bragg diffraction
7. Brillouin zones
8. XRD/TEM lab
9. Phonons
10. Vibration in atomic chains
11. Dispersion relation
12. Periodic boundary conditions
13. Phonons and heat
14. Free electron gas
15. Transport properties of electrons
16. Electrons in the solid state
17. Origin of band gap
18. Bloch functions
19. Kronig penny model
20. Effective mass model

Second part: Quantum materials.

1. Trapped ions
2. Manipulating single atoms
3. Applications for QT, memory and computing maybe
4. BCS theory
5. Meissner effect and energy gap

6. Type 1 og type 2 Superconductors
7. Josephson junctions
8. SQUID
9. Quantum dots and point defects
10. Magnetic field sensing
11. Quantum computing
12. Construction of a quantum computer

Learning goals. **TBA**

Third course: Quantum Computing, sixth semester, 10 ECTS.

Content.

1. Tensor products of Hilbert Spaces and definitions of Computational basis sets
2. Simple Hamiltonians and other operators
3. Unitary transformations, gates and quantum circuits
4. States and Observables for Composite systems
5. Quantum operations
6. Spectral decomposition and measurements
7. Density matrices
8. Schmidt decomposition
9. Entanglement and Entropy
10. Quantum State Preparation
    - Single qubit state preparation
    - Two-qubit state preparation
    - Two-qubit gate preparation
    - Four qubit state preparation
11. Quantum gates and operations
12. Central quantum algorithms

13. Quantum Fourier Transforms
14. Quantum Phase estimation algorithm
15. VQE, Variational Quantum Eigensolver
16. Simulating Hamiltonians on NISQ quantum computers
17. Jordan-Wigner transformations
18. Suzuki-Trotter approximation
19. Running computations on IBM's machines with Qiskit
20. Quantum Partition Function
21. Quantum Tomography
22. Quantum Error Correction

Learning goals. After completing this course, you are able to:

1. apply quantum computing algorithms to selected quantum-mechanical many-particle systems.
2. describe the differences between quantum and classical computation of quantum mechanical many-particle systems.
3. discern potential performance gains of quantum vs. classical algorithms.
4. implement and design quantum circuits for studies of quantum mechanical systems.
5. run these algorithms on existing quantum computers.
6. understand the role of noise in quantum computing.