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

Marianne Etzelmüller Bathen, Morten Hjorth-Jensen, and Lasse Vines

Department of Physics, UiO

Planned start: Fall 2024 (?)

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
   - Computational Physics and AI/ML in the Physical Sciences

Possible collaboration with:

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

The program is 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 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.

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 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.

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.

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 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.

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

Paths 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.

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/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 Techno
2nd semester	MAT1110	STK-FYS1100	FYS1105
1st semester	MAT1100	IN1900	FYS1100

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.

ETH MSc in quantum engineering https://master-qe.ethz.ch/ https://www.nature.com/articles/s41563-021-01080-6.epdf?sharing$_{t}oken = hzaL6bfnmuTfmbxDqAhxkNRgN0jAjWel9jnR3ZoTv0MXCITNgQctn$
$jJRufnLzILslhZSFq_{P}QE{-}o{-}160_{p}aOACFYc2ZoEHSyLdsafCp69C0o6krGYLR8EFa_{M}Ov5lg1Cto7SG4$

Aalto university BSc and MSc in QT https://www.aalto.fi/en/study-options/quantum-technology-bachelor-of-science-technology-master-of-science-technology Qt specific courses Introduction to quantum technology Quantum materials Quantum information Quantum labs https://www.aalto.fi/en/programmes/aalto-bachelors-programme-in-science-and-technology/curriculum-2022-20241-major-studies Quantum circuits BSc thesis Photonics, microscopy, nanotechnology, materials physics, advanced quantum mech, quantum games, practical quantum computing and quantum machine learning are optional

University of Surrey Physics with QT BSc and MSc https://www.surrey.ac.uk/undergraduate/physics-quantum-technologiesstructure Not much QT specific on BSc level

University of Copenhagen MSc in quantum information science https://studies.ku.dk/masters/quantum-information-science/ Three compulsory courses Introduction to Quantum Information Science (UCPH) Introduction to Quantum Computing (UCPH) Applied Quantum Physics: Quantum Information Technology (DTU)

MIT Paper: Building a Quantum Engineering Undergraduate Program https://dspace.mit.edu/bitstream/handle/1721.1/143817/Building$_{aQ}uantum_{E}ngineering_{U}ndergraduate_{P}rogr$
2

West Chester and Uni Delaware https://www.wcupa.edu/communications/newsroom/2023/03.07engineering.a
Combo BSc and MSc

Harvard https://gsas.harvard.edu/program/quantum-science-and-engineering Graduate, so MSc and PhD

Universities Chicago https://chicagoquantum.org/education-and-training/undergraduate-and-graduate-education Mest MSc og PhD

Cornell https://quantum.cornell.edu/education/ San Jose state uni https://www.sjsu.edu/quantum/ MSc in quantum tech

Kursinnhold

Må lage nye kurs om vi skal ha studieretning i kvanteteknologi.

Nye kurs vi må lage

Introduksjon til kvanteteknologier (3 semester) Grunnleggende kurs Krever kun linalg som forkunnskap Kan tas også av andre, e.g. IT og kjemistudenter Marianne, Lasse, Johannes? Innhold Bits Qubits Kvanteteknologier Kvanteinfo Litt om Algoritmer, grover og shor f eks Lab Måle transistor, sammenligne med qubits Qiskit, måle qubits Kanskje se på enkel Grover Shor algoritmer Quantum materials (5 semester) Slags kompo av eksperimentalfysikk, faststoff og kvantehardware Må ha noe om strukturer, kan ha XRD lab Må ha noe om båndstruktur, kan ha UV VIS lab Snakke om bits, qubtis Gjøre litt fabrikasjon, eller spare det til senere? Kvantealgoritmer (6 semester) Algoritmer og kvanteinformasjonsteori Johannes, Morten, Joakim? Har allerede et lignende kurs Blir som å lage et halvt nytt kurs Quantum materials 2? MSc kurs Resten av kondenserte 1 så man kan ta kondenserte 2 Døpe om FysEd? Kombinere med nye MENA9510?

Kurs 1: Introduksjon til kvanteteknologier (Introduction to quantum technologies) Innhold Motivasjon Basic kvantefysikk/ QT at a glance 1st and 2nd quantum Kvantebits vs klassiske bits Materialer og praktiske kvanteplattformer Kvantesensorer Kvantekommunikasjon og kryptering Kvanteberegninger til slutt fordi linalg er parallelt

Læringsmål Hovedmål: generell introduksjon til kvanteteknologi som gir oversikt over hele fagfeltet Forstå forskjellen mellom qubits og klassiske bits

Ukesplan Motivasjon for kvanteteknologi og oppbygging av faget Popvit oversikt over hele kurset Oversikt over kurset Kvanteteknologier; inndeling i sensorer, kommunikasjon og computing Fra klassisk til moderne fysikk Blackbody radiation Fotoelektrisk effect og fotoner UV catastrophe Compton De Broglie Grunnleggende konsepter i kvantefysikk Kvantisering av energinivåer Bølgefunksjon Partikkel i boks Fra enkeltatom til fast stoff First and second quantum revolution Halvleder, transistor, minne Fra det makroskopiske til det mikroskopiske Utnytte de mest eksotiske delene av kvantefysikken Tunnelering Entanglement superposition NMR Tunneleringsdioder Utnyttelse av superposisjon og entanglement; fra ide til virkelighet First and second quantum revolution Halvleder, transistor, minne Fra det makroskopiske til det mikroskopiske Utnytte de mest eksotiske delene av kvantefysikken Tunnelering Entanglement superposition Måling i kvanteteknologi NMR Tunneleringsdioder Utnyttelse av superposisjon og entanglement; fra ide til virkelighet Byggeklosser for klassisk og kvanteteknologi Bits Qubits Krav og egenskaper til qubits Superposisjon og entanglement i praksis Lab; måle transistorer Lab; måle qubits i qiskit Materialplattformer for qubits Superledere Trapped ion Halvleder (quantum dot, point defects) Optisk Andre plattformer? Vapor phase greier Fabrikasjonsteknologier for kvanteteknologi (halvleder, superleder, trapped ion, optisk) Nanoteknologi Renrom Lasere og optikk Kvantesensorer Definisjon og Konsept, meterologi Eksempler Atomic clock NMR LIGO NV i diamant i celler Kvantekommunikasjon Sikkerhet i kommunikasjon med klassik kryptering Måling i kvantefysikk/ measurement of the quantum state QKD Utfordringer: repeaters osv Kvantecomputing; Klassisk vs kvantecomputing Klassiske kretser og logic gates Quantum gates Adiabatisk kvantecomputing Kvantekretser Lab Kvantecomputing; Klassisk vs kvantecomputing Klassiske kretser og logic gates Quantum gates Adiabatisk kvantecomputing Kvantekretser Kvantecomputing; Kvantealgoritmer og quantum information Shor Grover Teste lab, qiskit – Grover Hele informasjonssystemet Kvantecomputing; Status and future Noisy qubits QEC NISQ Quantum machine learning Wrap up Tillegg til forelesninger Undervisningsform: Forelesning, 2 timer per uke? Diskusjonspoppgaver i plenum Menti

Ukesoppgaver: Gruppeoppgaver for diskusjon hver uke Regneoppgaver noen uker – oblig??

Lab: Eksp 1: Målinger av bits; dioder og transistorer MiNa Probe station Eksp 2: Noe material-relatert med høy throughput av studenter Teori 1: qiskit, måling av qubits Teori 2: qiskit, sette opp enkle kvantekretser, Grover

Vurdering: Midtveisvurdering Eksamen Multiple choice? Prosjekt er urealistisk for mange studenter

Pensumlitteratur Lage kompendium?

Kurs 2: Quantum materials

Ressurser fra lignende kurs TU Delft https://ocw.tudelft.nl/course-lectures/1-3-1-quantum-materials/ Quantum materials provide the environment where qubits, the elemental unit of quantum information processing, are defined and live. Precision in material uniformity, chemical composition and electrical properties are crucial for the requirements of having both many qubits and long decoherence times. Chemical Vapour Deposition is an industrial process that uses high purity gases to make high quality materials, with desired physical and electronic properties. Transmission electron microscopy is a process to inspect the fabricated heterostructures with high resolution. Temperature, electric fields and magnetic fields are useful parameters to determine properties of quantum materials such as mobility and electron density.

Uppsala university https://www.uu.se/en/study/course?query=1FA654 MSc level course Learning outcomes On completion of the course, the student should be able to: present and apply theoretical condensed matter models and evaluate their applicability under various conditions classify condensed matter based on their electronic structure apply Dirac formalism to perform quantum mechanical analysis of relevant systems carry out and explain experiments in condensed matter physics Reading list: Sakurai, J. J.; Napolitano, Jim., Modern Quantum Mechanics, Third edition., Cambridge, Cambridge University Press, 2021Compulsory* Kittel, Charles; McEuen, Paul, Introduction to solid state physics, 8. ed., Hoboken, N.J., Wiley, c2005Compulsory* Content: Quantum mechanical formulation of Bloch functions in a periodic crystal. Single particle models for electrons. Descriptions of electrons and quasiparticles with the Schrödinger and Dirac equations. Classification of materials based on their electronic structure. Introductory laboratory experiments in connection to solid state physics. Introduction to emerging phenomena with Dirac materials, conventional and unconventional superconductors, spintronic and topological materials. Short introduction to second quantization.

KTH https://www.kth.se/student/kurser/kurs/SK2904?l=en This course addresses future quantum materials, where control of the electron spin opens possibilities for a new technological era, the "quantum age". Their unique material properties will be described together with a physical description of how such properties occur, and also how these materials have the potential to generate new technological devices and applications for a sustainable society. Furthermore, the course will describe the most important experimental characterization methods used to understand these complex materials down to a subatomic level. Intended learning outcomes After the course, students should be able to: Describe the characteristics of different quantum materials and explain the physical background to these unique characteristics. Explain how these materials can be used in future technical applications. analyze how new quantum materials can affect development towards a sustainable society. Assess which experimental methods are best suited to characterize the properties of quantum materials. Examination • LAB1 - Laboratory work, 2.0 credits, grading scale: P, F • PRO1 - Poject work, 5.5 credits, grading scale: A, B, C, D, E, FX, F Dear participating students of SK2904 "Quantum Materials". The course is given in a mixed format where I will first give a set of general introductory lectures on quantum materials as well as advanced experimental techniques that are utilized to study such materials. There are then a set of topics (see list below) where each student will select one topic to focus on and prepare a presentation about. Topological Insulators vs. Weyl semimetals Two-Dimensional Materials Skyrmions Quantum Magnets Nanostructured semiconductors NV Centers in Diamond Ferroelectrics & Multiferroics High-Temperature Superconductors Heavy Fermions Manganite and Colossal Magnetoresistance Ultra-Cold Atoms Aalto University https://mycourses.aalto.fi/course/view.php?id=33560

Using the links below you should be able to read the course book, Young and Freedman, University Physics (14th Edition), Pearson. Link to the book via Aalto university library https://primo.aalto.fi/permalink/358AALTO$_I$*NST/1rd34t9/alma997819554406526Topa*
basicquantities, waveequation, wavevelocity, energy, reflectionandtransmission, wavesin3D, Snell′slaw, int
photoelectriceffect, X−raygenerationanddiffraction, Comptonscattering, pairproduction, wave−
particleduality, uncertaintyrelationĹWavepropertiesofparticles : Bohrmodelofhydrogenatom, wavenaturec
Schrodingerequation, potentialwells, quantumtunneling, measurement, 3Ddeeppotentialwell, hydrogenatom

Learning Outcomes (from Sisu): After the course, the student 1. knows the basics of wave propagation 2. can explain the formation of intensity distribution in interference and diffraction patterns 3. knows the Heisenberg's uncertainty principle and the wave-particle dualism in quantum mechanics 4. can solve simple quantum mechanical systems using Schr¨odinger's equation 5. can identify properties of atoms and condensed matter based on quantum mechanics

Content (from Sisu): Interference, diffraction, dispersion, group- and phase velocity. Heisenberg's uncertainty principle, wave-particle dualism. Schr¨odinger's equation, statistical nature of quantum mechanics. Quantum numbers, Pauli exclusion principle, spin and periodic table of elements

https://mycourses.aalto.fi/pluginfile.php/1746418/mod$_r$*esource/content/2/mqmat.pdfQuantumMaterials*

Innhold Slags kombinasjon av faststoff, eksperimentalfysikk og quantum hardware Krystallstruktur Båndstruktur Halvlederfysikk (enkel) Superledere

Læringsmål

Ukesplan Part 1: Condensed matter physics Introduksjon Crystal bonding Lattices Reciprocal space Overview of course Crystals Bragg diffraction Brillouin zones XRD/TEM lab Phonons Vibration in atomic chains Dispersion relation Periodic boundary conditions, Born von Karman, DOS Phonons and heat Electrons in the wild Free electron gas DOS i 1D, 2D, 3D Transport properties of electrons Electrons in the solid state Origin of band gap Bloch functions Kronig penny model Effective mass model

Part 2: Quantum materials Trapped ion Bruk som tankeeksperiment Manipulating single atoms Applications for QT, memory and computing maybe Metals – superconductors - 1 Metals og Fermi surfaces BCS teori Meissner effect og energy gap Type 1 og type 2 Superconductors – 2 Josephson junctions SQUID Qubits Applications! Magnetic field sensing Quantum computing Construction of a quantum computer LAB Semiconductors – 1 Band gap Energy bands Doping Semiconductors – 2 Pn junction quickly Heterojunctions in 1, 2 and 3 dimensions Surfaces, interfaces, strain Point defects Single photon emitters Electrical lab, DLTS Application of structures in semicondcutors for QT Quantum wells Quantum dots Point defects P in Si, Kane quantum computer Applications Sensing Communication Computing Lab Application of structures in semiconductors for QT Quantum wells Quantum dots Point defects P in Si, Kane quantum computer Applications Sensing Communication Computing Lab Emission of light from quantum materials Excitons Defects QDs PL-lab Manipulation of photons for QT Squeezed light LIGO SPDC Entanglement Applications for QT, communication Lab Application and wrap up, next coursed

Tillegg til forelesninger

Lab XRD for krystallstruktur Superlederlab Halvleder UV-VIS for båndstruktur Elektrisk lab CV, IV for enkle devices DLTS PL lab Helst en HBT type lab/ squeezed light

DLTS for defekter?? PL?? Ideelt sett klarer vi hBT, HOM Renrom og nanofabrikasjon blir kanskje det mer avanserte kurset?

Pensumlitteratur