Master in Quantum Science and Engineering

Nicolas Macris

journées des masters spécialisés
EPFL, 2 Mars 2023
A cross-faculty master program!
of the three schools
Basic Sciences, Engineering, and
Computer and Communication Sciences

Section de Science et Ingénierie Quantiques

Director: Prof. Nicolas Macris (IC)
Co-directors: Prof. Edoardo Charbon (STI) and Prof. Giuseppe Carleo (SB)
Section deputy: Hind Klinke
Administrative assistant: Emilie Thévoz

Web sites: SSIQ and go.epfl.ch/master-quantum-science
Contact: siq@epfl.ch
This program aims to train a new generation of “quantum proficient” engineers who will be part of the “second quantum revolution”,

engineers that understand and use the quantum paradigm shifts in:

- Information processing
- Computation
- Simulation
- Metrology and sensing

Diploma and title awarded:

MSc Science et ingénierie quantiques - MSc Quantum science and engineering

Ingénieur en science quantique (ing. quant. dipl. EPF)

- Consecutive master for physicists EPFL
- Others must apply until 15 April
  (minimal admission condition GPA 4.5)
The second quantum revolution: what is it about?

Laws of quantum physics known since the 1930’s have led to our modern understanding of the atomic nature of matter and all solid state phenomena and photonics and much more...

Major role in modern technology of integrated circuits, lasers nanotechnology, microscopy, imaging,...

This has completely reshaped our world

But these devices process information/signals classically \(\rightarrow 011000111001010\) \(\rightarrow\) classical bits

But one can use quantum laws at their heart to process information in radically new ways

(‘Pionners of the 80’s: Benioff, Landauer, Wiesner, Feynman, Deutsch, Bennett, and others)

The concept of quantum bit – the **QUBIT** – is the new unit of information here: \(a|0> + b|1>\)

It behaves radically differently than the classical bit and offers new computational resources!
QSE leads to paradigm shifts and applications many areas:

- **Information Processing**: quantum communication (e.g. teleportation), cryptography, quantum networks, distributed information, error correction, random number generators,...

- **Sensing and Metrology**: photon detectors and counters, gravimeters, accelerometers, cold atom interferometers, magnetometry, atomic and optical clocks,...

- **Computation**: quantum algorithms, optimization, quantum machine learning, sampling, data base search, complexity theory,...

- **Simulation**: dynamics of physical systems, low temperature phases of matter, quantum chemistry, better drug discovery,...
A few examples: from sensing and metrology

Magneto-metry with Nitrogen Vacancy centers in diamond

(source Qzabre)

Measurement of very weak magnetic fields

(SOURCE: Qnami)
Examples cont: from sensing and metrology

Cold atom interferometry:

Path of falling cloud of cold atoms is separated and reunited by light pulses.

Interference of quantum waves gives information on gravitational field.

Applications to measurement of very weak gravitational fields, accelerometers, this may also lead to tests of gravitation laws at small distances and weak fields.
Examples: from computation and simulation

Quantum algorithms and circuits for computation (factoring, linear algebra, data base search, optimization, ML,...)

Simulation of physical systems

e.g., for quantum chemistry. Here the ammonia molecule NH\textsubscript{3}
A few examples: from quantum communications

Quantum Teleportation

Initial state:

\[ |\Phi\rangle_A \otimes |EPR\rangle_{AB} = |\Phi\rangle_A \otimes \frac{|00\rangle_{AB} + |11\rangle_{AB}}{\sqrt{2}} \]

Final state after teleportation protocol:

\[ |EPR\rangle_A \otimes |\Phi\rangle_B \]

Quantum state \( |\Phi\rangle \) has been teleported from Alice to Bob (two classical bits are needed).

source:ICFO
Examples: from quantum communication cont

Quantum Key Distribution for cryptography

Intense efforts are being displayed to develop quantum computing hardware technologies

NISQ devices are small Noisy Intermediate Scale Quantum devices allowing computing with 10’s to 400’s qubits.

Stack of advanced classical and quantum electronic technologies operating from room temperature down to a few milli-Kelvins.
Profiles of a quantum engineers?

- Include skills and knowledge in **Computer Science, Engineering, and Physics / Mathematics / Chemistry**
- Few Master’s programs worldwide offer such a multidisciplinary educational profile
- At EPFL, in **IC, STI, and SB**, there is **today a vast portfolio of research and teachings** relevant to the **QSE domain**

- EPFL **new center for Quantum Science and Eng.** fosters research and collab. among teams
- **EPFL Quantum Computing Association**
  
  [https://www.epfl.ch/campus/associations/list/qc/](https://www.epfl.ch/campus/associations/list/qc/)
Needs of the industry

Basic structure of the master

- **Bloc of core courses**: 18 ECTS
- **Master’s thesis**: 30 ECTS
- **Project in SHS**: 6 ECTS
- **Internship**: 12 ECTS
- **Two semester projects**: $8 + 8 = 16$ ECTS
- **Group of Option courses**: 38 ECTS

Choose one specialization:

- **A**: Quantum information and computation
- **B**: Quantum hardware and engineering

*At least 30 ECTS in chosen specialization and at most 10 in the other*
<table>
<thead>
<tr>
<th>Core courses</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum Physics I</td>
<td>5</td>
</tr>
<tr>
<td>Introduction to Quantum Science, Technology and Applications</td>
<td>5</td>
</tr>
<tr>
<td>Quantum Information Processing</td>
<td>5</td>
</tr>
<tr>
<td>Quantum Computation</td>
<td>5</td>
</tr>
<tr>
<td>Solid State Systems for Quantum Information</td>
<td>4</td>
</tr>
<tr>
<td>semiconductors devices I</td>
<td>4</td>
</tr>
<tr>
<td>Quantum and Nanocomputing</td>
<td>6</td>
</tr>
<tr>
<td>Computational Complexity</td>
<td>6</td>
</tr>
</tbody>
</table>

Carefully choose basic **core courses** depending on your background.

-> Should take if didn’t have equiv class before
-> Mandatory for all students
-> Two intro classes quant info and computation
-> Two intro classes for hardware related courses
-> Intro to the “quantum stack”
-> Theoretical comp science class
<table>
<thead>
<tr>
<th>Specialization A: Quantum Information and computation</th>
<th>Specialization B: Quantum hardware and engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information Theory and Coding</td>
<td>Foundations of Data Science</td>
</tr>
<tr>
<td>Foundations of Data Science</td>
<td>Machine Learning</td>
</tr>
<tr>
<td>Computational Complexity</td>
<td>Advanced Machine Learning</td>
</tr>
<tr>
<td>Advanced Algorithms</td>
<td>Mathematics of Data: From Theory to Computation</td>
</tr>
<tr>
<td>Cryptography and security</td>
<td>Deep Learning</td>
</tr>
<tr>
<td>Advanced cryptography</td>
<td>Advanced logic synthesis and quantum computing</td>
</tr>
<tr>
<td>Machine Learning</td>
<td>Quantum Information and Quantum Computing</td>
</tr>
<tr>
<td>Optimization for Machine Learning</td>
<td>Quantum Transport in Mesoscopic Systems</td>
</tr>
<tr>
<td>Artificial Neural Networks</td>
<td>Semiconductor Physics and Light-Matter Interaction</td>
</tr>
<tr>
<td>Advanced logic synthesis and quantum computing</td>
<td>Nonlinear Optics for Quantum Technologies</td>
</tr>
<tr>
<td>Distributed Algorithms</td>
<td>Quantum Electrodynamics and Quantum Optics</td>
</tr>
<tr>
<td>Low Rank Approximation Techniques</td>
<td>Quantum Optics and Quantum Information</td>
</tr>
<tr>
<td>Machine Learning for Physicists</td>
<td>Statistical Physics IV</td>
</tr>
<tr>
<td>Quantum Information and Quantum Computing</td>
<td>Advanced Topics in Quantum Science and Technology</td>
</tr>
<tr>
<td>Computational Quantum Physics</td>
<td>Statistical mechanics</td>
</tr>
<tr>
<td>Quantum Transport in Mesoscopic Systems</td>
<td>Semiconductor Devices I</td>
</tr>
<tr>
<td>Semiconductor Physics and Light-Matter Interaction</td>
<td>Semiconductor Devices II</td>
</tr>
<tr>
<td>Nonlinear Optics for Quantum Technologies</td>
<td>Nanoelectronics</td>
</tr>
<tr>
<td>Quantum Electrodynamics and Quantum Optics</td>
<td>Lab in Nanoelectronics</td>
</tr>
<tr>
<td>Quantum Optics and Quantum Information</td>
<td>Photonic systems and technology</td>
</tr>
<tr>
<td>Solid State Physics III</td>
<td>Fundamentals of Solid-State Materials</td>
</tr>
<tr>
<td>Statistical Physics IV</td>
<td>Superconducting electronics: A materials perspective</td>
</tr>
<tr>
<td>Advanced Topics in Quantum Science and Technology</td>
<td>Introduction to crystal growth by epitaxy</td>
</tr>
<tr>
<td>Statistical mechanics</td>
<td>Properties of semiconductors and related nanostructures</td>
</tr>
<tr>
<td>Fundamentals of Solid-State Materials</td>
<td>Atomistic and Quantum Simulations of Materials</td>
</tr>
<tr>
<td>Molecular Dynamics and Monte Carlo Simulations</td>
<td>Nanotechnology</td>
</tr>
<tr>
<td>Computational Methods in Molecular Quantum Mechanics</td>
<td>Metrology</td>
</tr>
<tr>
<td>Introduction to Electronic Structure Methods</td>
<td>Molecular Dynamics and Monte Carlo Simulations</td>
</tr>
<tr>
<td>Molecular Quantum Dynamics</td>
<td>Computational Methods in Molecular Quantum Mechanics</td>
</tr>
</tbody>
</table>

**Options**

**38 ECTS**

Strong classical IT component is also needed in industry

The two specializations overlap
WHAT ARE THE PREREQUISITES?

Quantum Physics I (3rd year bachelor in PHYS) Anybody that did not have a proper Quantum Physics class should follow this class in first semester of the master. This is in the core group.

Non-physicists: we recommend you take a Quantum Physics class in your 3rd year

- COM, IN, EE: Quantum Physics I (PHYS-313 fall 5 ECTS) → option COM, IN, and hors plan EE,

- MT: La Science Quantique: une vision singulière (MICRO 3 ECTS) → option for MT

- Chimie: 3 classes in module 3 of 3rd year of Bachelor in "Chimie computationnelle"
  - CH-351 Dynamique moléculaire et simulation Monte-Carlo, 2 ECTS
  - CH-352 Eléments de cheminformatique, 3 ECTS
  - CH-353 Introduction to electronic structure methods, 4 ECTS

Some preparation is also given by: Introduction to Quantum Information Processing (COM 309) but does not fully replace a Quantum Physics class.
Job prospects, examples. A nice read in Quantum Insider

- **Big tech companies** IBM, Microsoft, Google, Intel, NEC, Righetti, Atos, ...

- **Medium sized companies and Startups** -> MIRAEX (photonic sensing) QuantumMachines (qubit control systems) QuiX (photonic computing) Onami, Qzabre (sensing) IDQ (crypto, communications), Pasqal (trapped ion computing), Alice and Bob, SANDBOXAQ (computing, ML)

- **Research centers** -> CSEM, PSI, IBMQ, CERN (Switzerland), ICFO (spain), CQT (singapour), VCG, ESQ, IQOQI (Austria), Quantum Alliance (Germany), ...

- **Academic research** -> PhD in QSE. Many exciting possibilities in Switzerland and worldwide!

*Industry needs engineers at all levels of the classical to quantum stack from “quantum aware” to “quantum proficient”.

The program prepares you well also in the classical IT sector.*
Examples of Companies in QSE domain

IBM Quantum solutions
 PsiQuantum
 QUANTUM MACHINES
 Zurich Instruments
 Orange Quantum Systems
 algorithmiq
 Cambridge Quantum
 qnami
 MIRAEX
 AQT

Microsoft
 Google
 Quantum AI
 rigetti
 Amazon
 Intel
 CERN
 ICFO
 Accenture
 PSI
 Paul Scherrer Institut
 Single Quantum
 Excellence in photon detection

XANADU
 NEC
 HORIZON QUANTUM COMPUTING
 IQM
 IONQ
 ENTROPICA LABS
 ColdQuanta
 RedWave
 PicoQuant
 25 QUANTUM MOTION
 aegiq

CRYPTONEXT SECURITY

ThinkQUANTUM
 nu QUANTUM
 QURECA
 quantum resources & careers

More than the sum of its parts
Quantum effort worldwide

Global effort 2021
$24.4b (estimate)

- Quantum Canada CA$1.36b = $1.1b
- United Kingdom £1b = $1.3b
- Netherlands 765m € = $904m
- Germany 2.6b € = $3.1b
- China $10b
- Russia Р50b = $663m
- South Korea W44.5b = $37m
- Japan ¥50b = $470m
- Taiwan NT$8b = $282m
- Australia AU$130m = $98.5m
- New Zealand $36.75m
- France 1.8b € = $2.2b
- Austria 107m € = $127m
- India ₹73b = $1bn
- Singapore S$150m = $109m
- US National Quantum Initiative $1.2b
- European Quantum Flagship 1b € = $1.1b

Source: QURECA quantum resources & careers

©2021 QURECA Ltd – Confidential and Proprietary
Important deadlines and informations

• Application deadline 15 April on EPFL master’s page
  https://www.epfl.ch/education/master/programs/quantum-science/
  For non-physicists necessary requirement for admission is GPA of 4.5

• For Physics EPFL students the master is consecutive

• Anybody applying for a bourse d’excellence must submit his application to SIQ by 15 April deadline (same process for all sections)

• We offer a MINOR

• For any info contact siq@epfl.ch
THANK YOU FOR YOUR ATTENTION
WE HOPE TO SEE MANY OF YOU NEXT SEPTEMBER!

Edoardo Charbon (STI)
Giuseppe Carléo (SB)
Nicolas Macris (IC)
Hind Klinke (section deputy)
Emilie Thévoz (section admin)

More info on Section website https://www.epfl.ch/schools/sections/quantum-science-and-engineering/
EPFL website and for applications https://www.epfl.ch/education/master/programs/quantum-science/
Examples of menu for a specialization A on quantum information and computing:

Bloc courses - example 1 - 18 ECTS and average GPA at least 4
- Quantum Physics I (PHYS-313), Fall, 5 ECTS
- Introduction to Quantum Science, Technology and Applications, Fall 5 ECTS
- Introduction to Quantum Information Processing (COM-309), Fall 5 ECTS
- Introduction to Quantum Computation (CS-308), Spring 5 ECTS

Bloc courses - example 2 - 18 ECTS average GPA at least 4
- Introduction to Quantum Science, Technology and Applications, instructors from various schools, Fall 5 ECTS
- Introduction to Quantum Computation (CS-308), Spring 5 ECTS
- Solid State Systems for Quantum Information (PHYS-464), Spring 4 ECTS
- Semiconductors devices I (EE-557) Fall, 4 ECTS
Group option courses 38 ECTS (specialization A). Examples:

- *Information Theory and Coding* (COM-404), Fall, 8 ECTS
- *Advanced algorithms* (CS-450), Spring, 8 ECTS OR *Cryptography and security* (COM-401), Fall, 8 ECTS
- *Optimization for machine learning* (CS-439), Fall, 5 ECTS OR *Machine learning* (CS-433), Fall, 8 ECTS
- *Quantum Information Theory* (PHYS-550), Spring, 4 ECTS
- *Computational Quantum Physics* (PHYS-463), Spring, 4 ECTS
- *Quantum optics and quantum information* (PHYS-454), Spring, 6 ECTS OR *Quantum Electrodynamics and Quantum Optics* (PHYS 453) 6 ECTS
- *Computational Methods in Molecular Quantum Mechanics* (CH-452), Fall, 4 ECTS OR *Molecular quantum dynamics* (CH-453) Spring 3 ECTS

OR choose two classes from hardware track, for example:

- *Photonic systems and technology* (EE-440), Spring 4 ECTS
- *Fundamentals of solid state materials* (MSE-423) Fall, 4 ECTS
Example study plan for a specialisation B on quantum hardware engineering:

**Bloc courses - example 1** – 18 ECTS and average GPA > 4

- *Introduction to Quantum Science, Technology and Applications*, Fall, 5 ECTS
- *Semiconductors devices I* (EE-557), Fall, 4 ECTS
- *Introduction to Quantum Computation* (CS-308), Spring, 5 ECTS
- *Solid State Systems for Quantum Information* (PHYS-464), Spring, 4 ECTS

**Bloc courses - example 2** – 18 ECTS and average GPA > 4

- *Quantum Physics I* (PHYS-313), Fall, 5 ECTS
- *Introduction to Quantum Science, Technology and Applications*, Fall, 5 ECTS
- *Quantum and Nanocomputing* (MICRO-435), Fall, 6 ECTS
- *Solid State Systems for Quantum Information* (PHYS-464), Spring, 4 ECTS
Group option courses 38 ECTS (specialization B). Example:

- *Deep Learning*, (EE-559), Spring, 4 ECTS
- *Semiconductor Devices II (EE-567)*, Spring, 4 ECTS
- *Photonic systems and technology (EE-440)*, Spring 4 ECTS
- *Metrology (MICRO-428)*, Spring, 3 ECTS
- *Metrology practicals (MICRO-429)*, Spring, 2 ECTS
- *Fundamentals of Solid-State Materials (MSE-423)*, Fall, 4 ECTS
- *Quantum Transport in Mesoscopic Systems (PHYS-462)*, Fall, 4 ECTS
- *Nonlinear Optics for Quantum Technologies (PHYS-470)*, Fall, 4 ECTS
- *Semiconductor Physics and Light-Matter Interaction (PHYS-433)*, Fall, 4 ECTS
- *Nanotechnology (MICRO-530)*, Spring 3 ECTS
- *Nanoelectronics (EE-535)*, Fall 2 ECTS