Master in Quantum Science and Engineering

Nicolas Macris – IC

journées des masters spécialisés
EPFL, 9 Mars 2022

École polytechnique fédérale de Lausanne

A cross-faculty master program!
of the three schools
Basic Sciences, Engineering, and
Computer and Communication Sciences

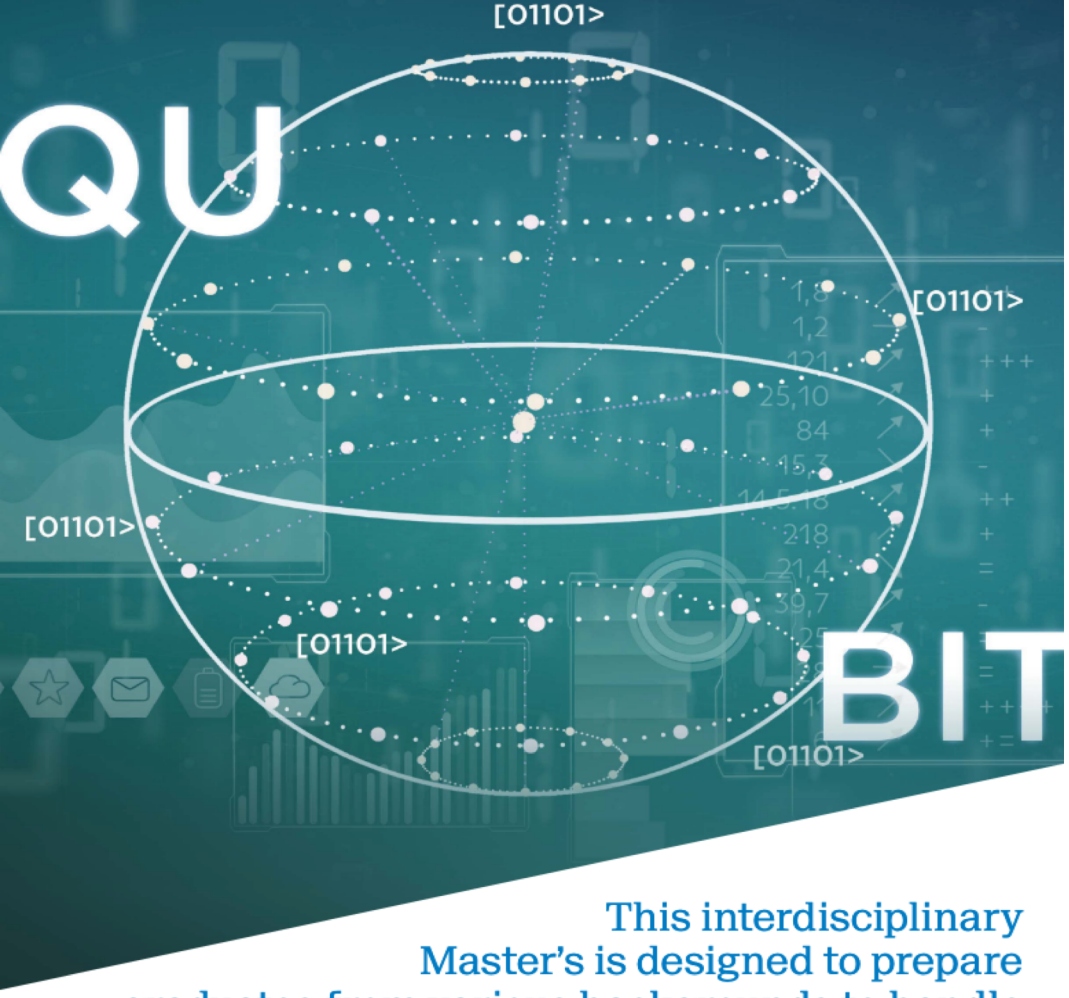
Section de Science et Ingénierie Quantiques
SSIQ

Director: Prof. Nicolas Macris (IC)

Co-directors: Prof. Edoardo Charbon (STI) and
Prof. Giuseppe Carleo (SB)

SSIQ also offers a minor

go.epfl.ch/master-quantum-science
Contact: nicolas.macris@epfl.ch



This interdisciplinary Master's is designed to prepare graduates from various backgrounds to handle the new paradigm shift brought by Quantum science and technology in the way we treat data, communicate, measure and compute. Thanks to their broad vision of diverse aspects of the field, they will have the ability to thrive in this new technology frontier which has the disruptive potential to revolutionize our society.

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 (communication, storage, encryption)
- Computation and simulation
- Metrology and sensing

Diploma and title awarded:

MSc Science et ingénierie quantiques - MSc Quantum science and engineering

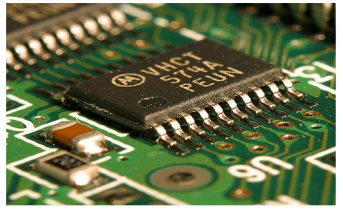
Ingénieur en science quantique (ing. quant. dipl. EPF)

- Consecutive master for physicists EPFL
- Others must apply until 15 April
  (minimal admission condition GPA 4.5)

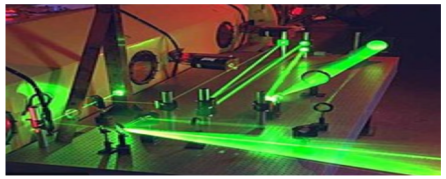
The second quantum revolution: what is it about ?

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…

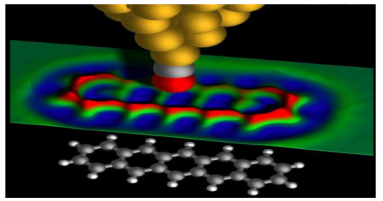
→ **Major role in modern technology. For example transistors and integrated circuits,**



lasers



and tunnel effect microscopes



This has completely reshaped our world. But with these devices information is processed classically.

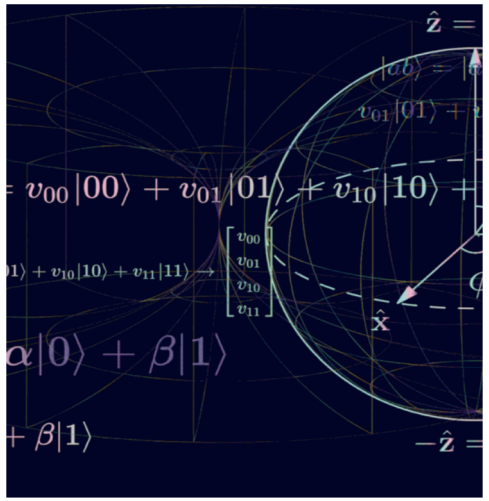
In the 1970's – 1990's it was realized that one could use quantum laws to process information in radically new ways (*Benioff, Landauer, Wiesner, Feynman, Deutsch, Bennett,…*)

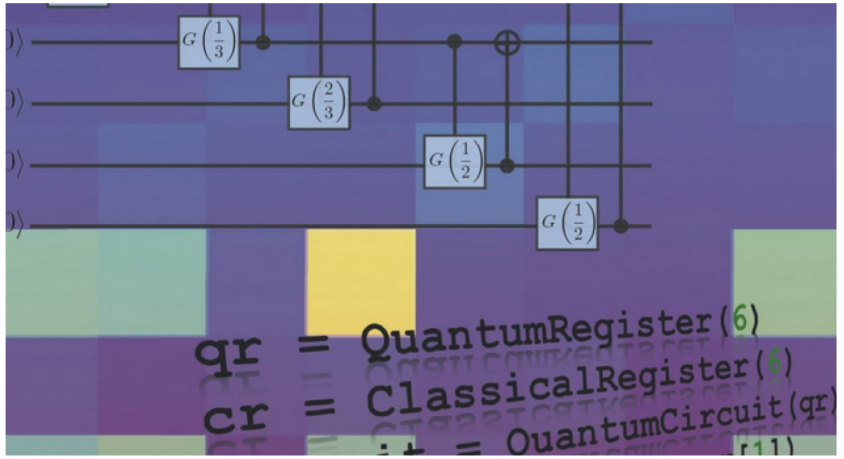
The concept of quantum bit – the QUBIT – is the new unit of information here. It behaves radically differently than the classical bit and offers new computational resources !

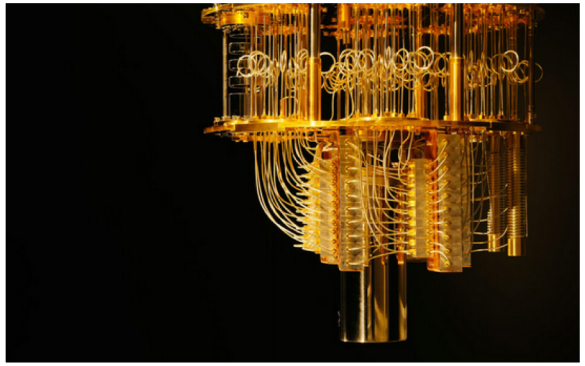
Currently massive investments are done in QSE worldwide.

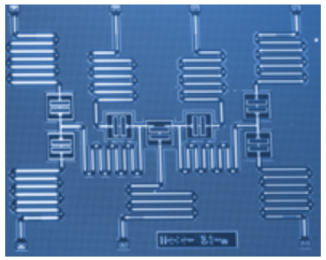
Primitive principles of qubits:

- superposition
- entanglement
- measurement
- unitary evolution

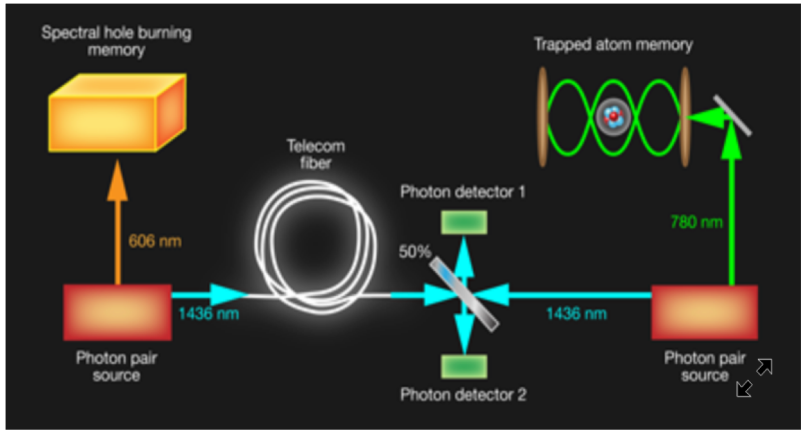




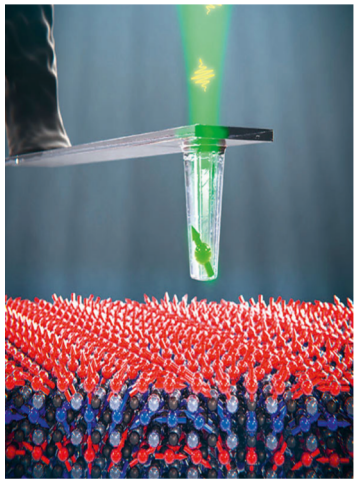




NISQ devices



entangling memories ICFO 2021

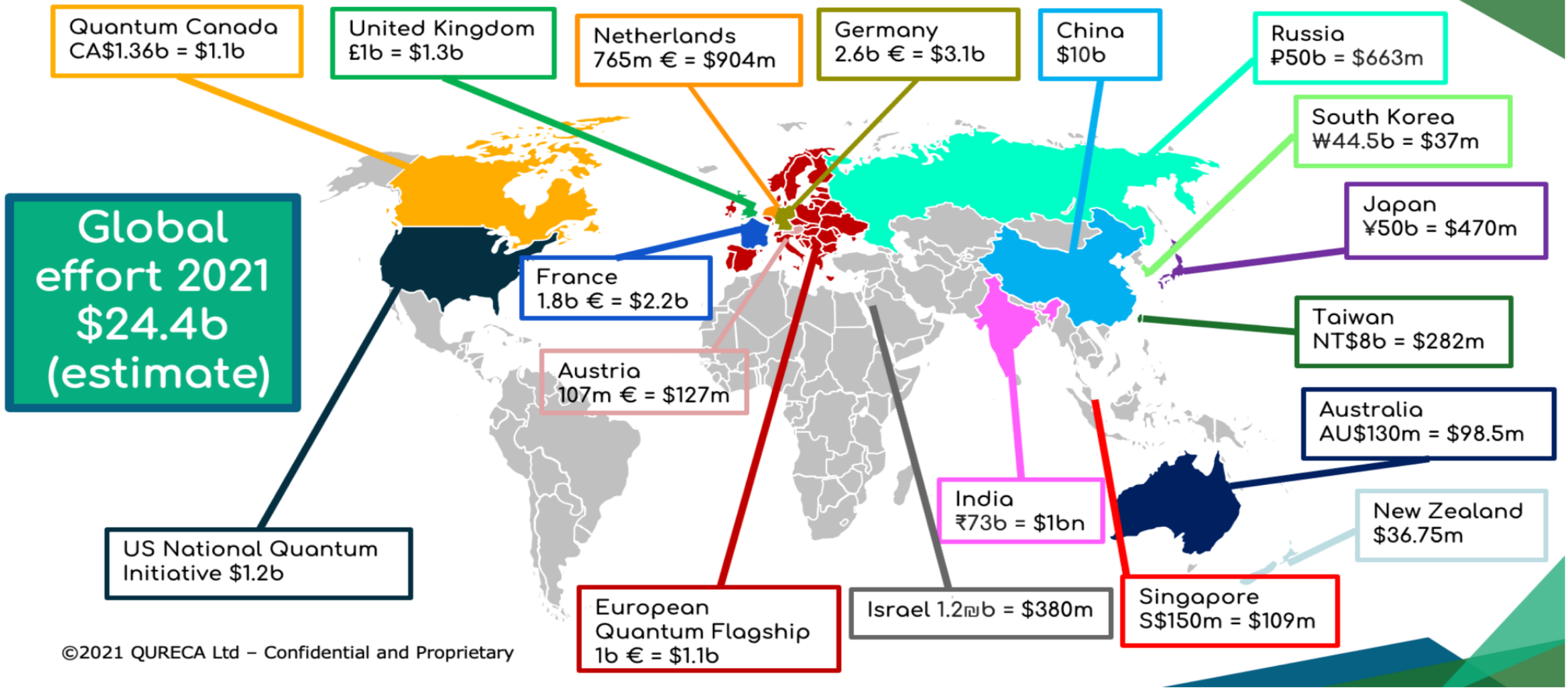


@Univ Basel

Paradigm shifts and applications in:

- Efficient algorithms e.g., factoring,…
- Complexity theory
- Quantum machine learning
- *Optimization algorithms*
- *Quantum chemistry*
- Quantum key distribution
- Random number generators
- Error correction
- *Distributed information in networks*
- *Metrology, Sensing*

Quantum effort worldwide

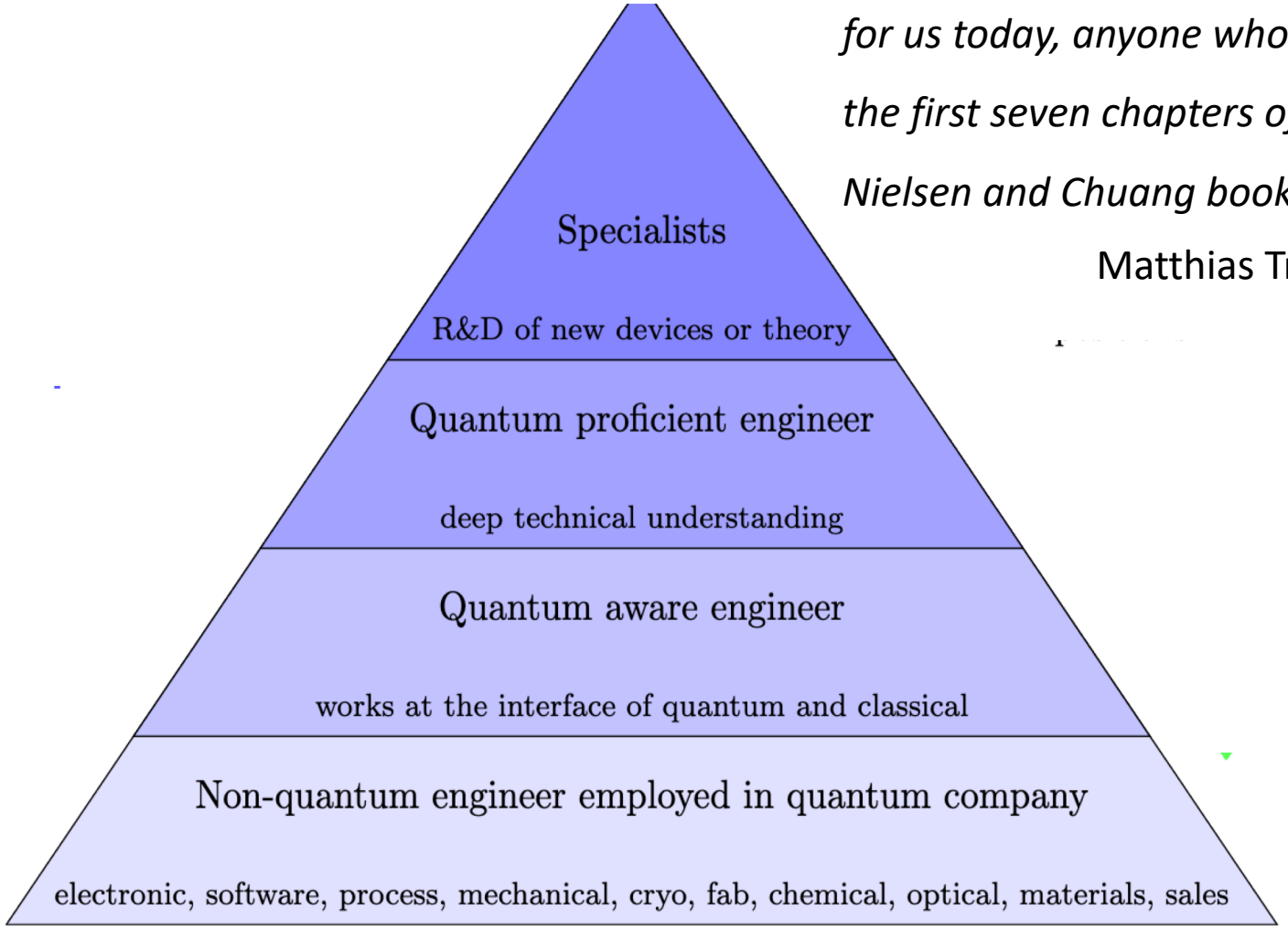


Source: QURECA quantum resources & careers

Needs of the industry

"There are so few Quantum Software Engineers that, for us today, anyone who can code and has read the first seven chapters of the Nielsen and Chuang book qualifies"

Matthias Troyer, Microsoft (~ 3 years ago)

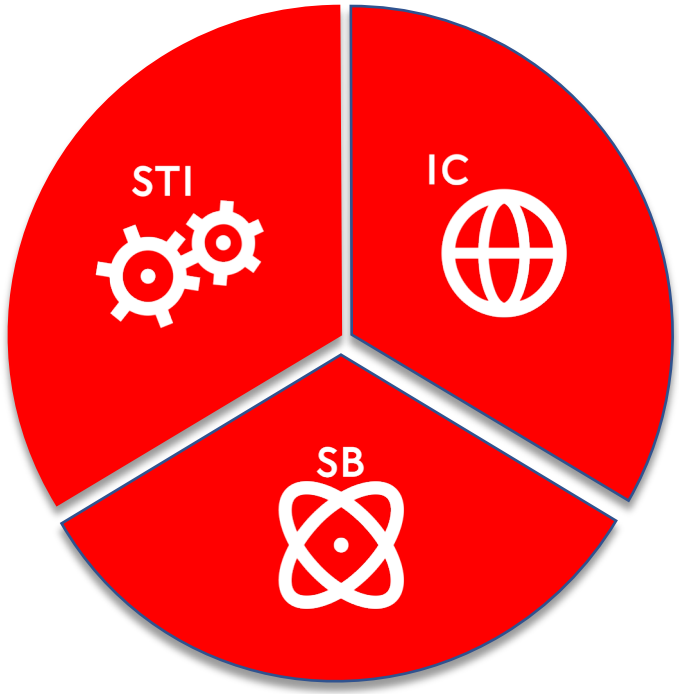


Source: *Building a Quantum Engineering Undergraduate Program* by Abraham Asfaw et al arXiv: 2108.01311 [physics.ed-ph]

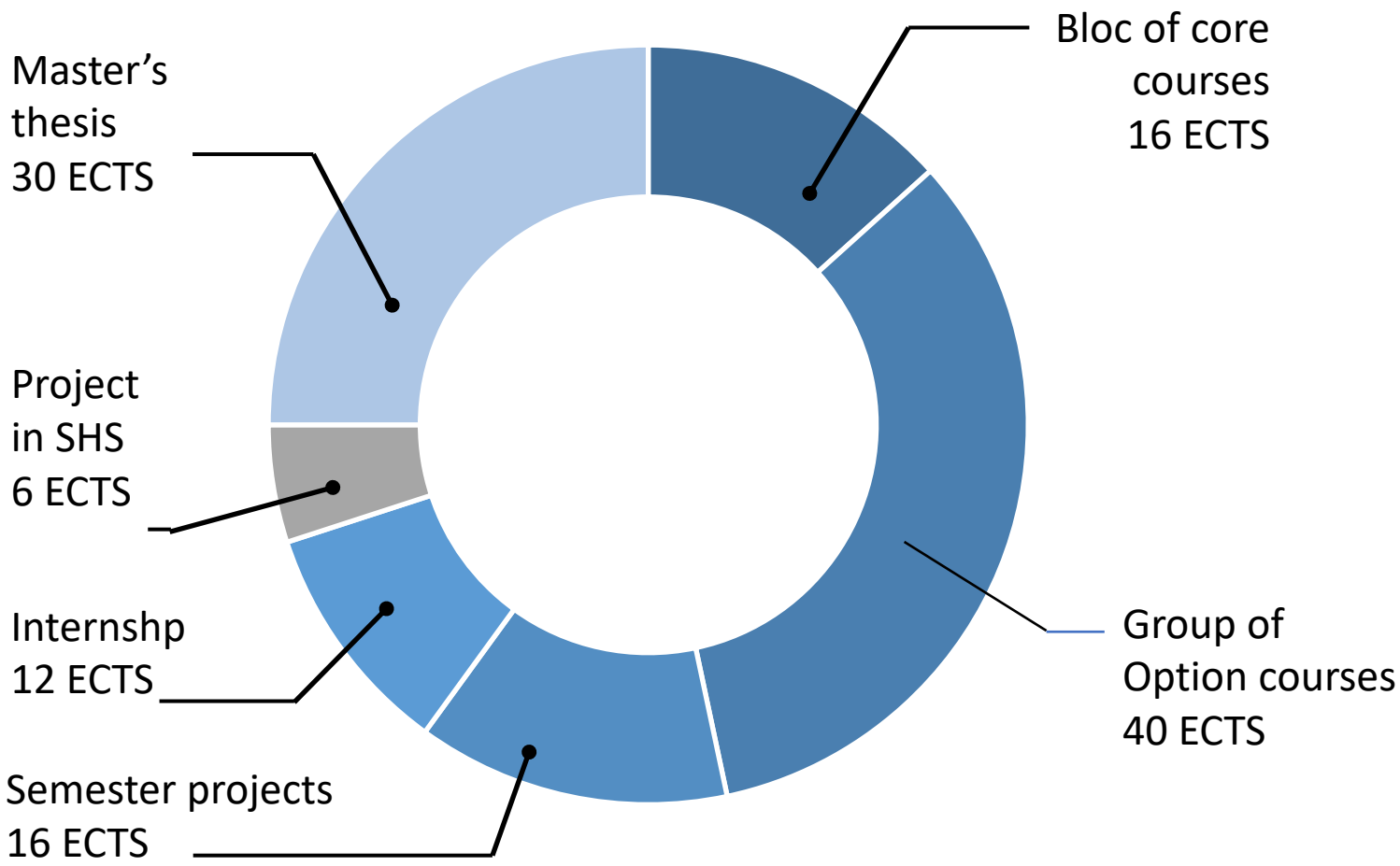
Profile of a quantum engineer ?

- Must 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/



Basic structure of the master



Course requirements

- **Bloc of core courses** 16 ECTS + average GPA ≧ 4.

- **Group of option courses** 40 ECTS. Pass each class separately (≧ 4). Choose one **specialization**:

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

  At least 30 credits in the specialization. Possible to choose 10 credits in other specialization. (conseillers d'études will help students compose the study plan matching their ambitions)

- **Two semester projects** 8 ECTS each. In SB, STI, IC labs.

- **SHS** Courses & projets 6 + 6 =12 ECTS (colleges of humanities and management).

- **Internship** of min 8 weeks, 12 ECTS.

- **Master thesis** 30 ECTS. In EPFL research lab 17 weeks, in industry 25 weeks.

	Credits
Core courses	**16**
Quantum Physics I	5
Introduction to Quantum Science, Technology and Applications	5
Quantum Information Processing	4
Quantum Computation	4
Solid State Systems for Quantum Information	4
Physics of semiconductors devices	4
Quantum and Nanocomputing	6

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

-> Mandatory for non-physicist

-> Mandatory for all students

-> Two introductory classes quant info and computation

-> Two introductory classes for hardware related courses

-> Intro to the “quantum stack”

Quantum Physics I (3rd year bachelor in PHYS - instructor G. Carléo) 5 ECTS

Anybody that did not have a real quantum physics class must follow this class. This is BASIC.

Introduction to quantum science technology and applications
(with instructors from PHYS, STI, IC) 5 ECTS

Will give a broad vision of the QSE domain. 3 modules with introductions on

- Information processing and computer science aspects (IC)
- Physics and algorithms, qubit platforms (SB)
- Hardware, metrology (STI)

Recommended prerequisites for non-physicists in next editions of the master:

- Quantum Physics I (PHYS-313) or other quantum physics class on campus (planned in STI)
- One of Quantum Information Processing (COM-309) or Quantum computation (CS-308)

Specialization A: Quantum Information and computation	
Information Theory and Coding	8
Foundations of Data Science	8
Computational Complexity	4
Advanced Algorithms	8
Cryptography and security	8
Advanced cryptography	4
Machine Learning	8
Optimization for Machine Learning	5
Artificial Neural Networks	5
Advanced logic synthesis and quantum computing	2
Distributed Algorithms	6
Low Rank Approximation Techniques	5
Machine Learning for Physicists	4
Quantum Information and Quantum Computing	4
Computational Quantum Physics	4
Quantum Transport in Mesoscopic Systems	4
Semiconductor Physics and Light-Matter Interaction	4
Nonlinear Optics for Quantum Technologies	4
Quantum Electrodynamics and Quantum Optics	6
Quantum Optics and Quantum Information	6
Solid State Physics III	6
Statistical Physics IV	6
Advanced Topics in Quantum Science and Technology	4
Statistical mechanics	4
Fundamentals of Solid-State Materials	4
Molecular Dynamics and Monte Carlo Simulations	2
Computational Methods in Molecular Quantum Mechanics	4
Introduction to Electronic Structure Methods	4
Molecular Quantum Dynamics	3

Specialization B: Quantum hardware and engineering	
Foundations of Data Science	8
Machine Learning	8
Advanced Machine Learning	4
Mathematics of Data: From Theory to Computation	6
Deep Learning	4
Advanced logic synthesis and quantum computing	2
Quantum Information and Quantum Computing	4
Quantum Transport in Mesoscopic Systems	4
Semiconductor Physics and Light-Matter Interaction	4
Nonlinear Optics for Quantum Technologies	4
Quantum Electrodynamics and Quantum Optics	6
Quantum Optics and Quantum Information	6
Statistical Physics IV	6
Advanced Topics in Quantum Science and Technology	4
Statistical mechanics	4
Semiconductor Devices I	4
Semiconductor Devices II	4
Nanoelectronics	2
Lab in Nanoelectronics	4
Photonic systems and technology	4
Fundamentals of Solid-State Materials	4
Superconducting electronics: A materials perspective	3
Introduction to crystal growth by epitaxy	2
Properties of semiconductors and related nanostructures	5
Atomistic and Quantum Simulations of Materials	4
Nanotechnology	3
Metrology	3
Molecular Dynamics and Monte Carlo Simulations	2
Computational Methods in Molecular Quantum Mechanics	4
Introduction to Electronic Structure Methods	4
Molecular Quantum Dynamics	3

Options
40 ECTS

Strong classical IT component is also needed in industry

The two specializations overlap

Examples of menu for a specialization on quantum information and computing:

Bloc courses - example 1 - 16 ECTS and average GPA at least 4

- *Quantum Physics I (PHYS*-313), Giuseppe Carleo, Fall, 5 ECTS
- **To be created 2022.** *Introduction to Quantum Science, Technology and Applications*, instructors from various schools Fall, 5 ECTS
- *Quantum Information Processing* (COM-309), Nicolas Macris, Fall, 4 ECTS
- *Quantum Computation* (CS-308), Nicolas Macris, Spring, 4 ECTS

Bloc courses - example 2 - 16 ECTS average GPA at least 4

- **To be created 2022.** *Introduction to Quantum Science, Technology and Applications*, instructors from various schools, Fall, 4 ECTS
- *Quantum Computation* (CS-308), Nicolas Macris, Spring, 4 ECTS
- *Solid State Systems for Quantum Information* (PHYS-464), Pasquale Scarlino, Spring, 4 ECTS
- *Physics of semiconductors devices* (MICRO-312), Pierre-André Besse, Fall, 4 ECTS

Group option courses 40 ECTS

- *Information Theory and Coding* (COM-404), Emre Telatar, Fall, 8 ECTS
- *Cryptography and security* (COM-401), Serge Vaudenay, Fall, 8 ECTS
- *Machine Learning* (CS-433), Martin Jaggi, Nicolas Flammarion, Fall, 8 ECTS
- *Quantum Information and Quantum Computing, (PHYS-641),* Vincenzo Savona, Spring, 4 ECTS
- *Computational Quantum Physics* (PHYS-463), Giuseppe Carleo, Spring, 4 ECTS
- *Computational Methods in Molecular Quantum Mechanics (CH-452*), Sara Bonella, Fall, 4 ECTS
- *Statistical physics IV* (MSE-436), Tobias Kippenberg, Spring, 6 ECTS

Or for example replace COM 401 by:

- *Computational Complexity* (CS-524), Mikka Göös, Fall, 4 ECTS
- Statistical mechanics (MSE 421), Michelle Ceriotti, Spring, 4 ECTS

Example study plan for a specialisation on quantum hardware engineering:

Bloc courses - example 1 – 16 ECTS and average GPA > 4

- *Quantum Physics I (PHYS*-313), Giuseppe Carleo, Fall, 5 ECTS
- **To be created 2022.** *Introduction to Quantum Science, Technology and Applications*, instructors from various schools Fall, 5 ECTS
- *Physics of semiconductors devices* (MICRO-312), Pierre-André Besse, Fall, 4 ECTS
- *Quantum Computation* (CS-308), Nicolas Macris, Spring, 4 ECTS

Bloc courses - example 2 – 16 ECTS and average GPA > 4

- *Quantum Physics I (PHYS*-313), Giuseppe Carleo, Fall, 5 ECTS
- **To be created 2022.** *Introduction to Quantum Science, Technology and Applications*, instructors from various schools, Fall, 5 ECTS
- *Quantum and Nanocomputing* (MICRO-435), Edoardo Charbon, Fall, 6 ECTS
- *Solid State Systems for Quantum Information* (PHYS-464), Pasquale Scarlino, Spring, 4 ECTS

Group option courses 40 ECTS

- *Deep Learning,* Francois Fleuret (EE-559), Spring, 4 ECTS
- *Semiconductor Devices I* (EE-557), Elison Matioli, Fall, 4 ECTS
- *Semiconductor Devices II (EE-567),* Adrian Ionescu, Andras Kis, Spring*, 4 ECTS*
- *Photonic systems and technology* (EE-440), Camille Brès, Spring 4 ECTS
- *Metrology* (MICRO-428), Claudio Bruschini, Edoardo Charbon, Georg Fantner, Spring, 3 ECTS
- *Metrology practicals* (MICRO-429), Claudio Bruschini, Edoardo Charbon, Georg Fantner, Spring, 2 ECTS
- *Fundamentals of Solid-State Materials* (MSE-423), Nicola Marzari, Fall, 4 ECTS
- *Superconducting electronics: A materials perspective* (MSE-438), Philip Moll, Johannes Walter, Spring, 3 ECTS
- *Quantum Transport in Mesoscopic Systems* (PHYS-462), Mitali Banerjee, Fall, 4 ECTS
- *Nonlinear Optics for Quantum Technologies* (PHYS-470), Christophe Galland, Fall, 4 ECTS
- *Semiconductor Physics and Light-Matter Interaction* (PHYS-433), Raphaël Butté, Fall, 4 ECTS

Companies in QSE domain - internships and master thesis in industry

csem
PAUL SCHERRER INSTITUT PSI
amazon
intel
CERN
ICFO
Microsoft
Google Quantum AI
rigetti
Baidu Research
Atos
QUANTINUUM
IBM Quantum solutions
XANADU
Type Private
Industry Quantum Computing
Founded 2016
Founder Christian Weedbrook, CEO
Headquarters Toronto, Canada
Website xanadu.ai
NEC
HORIZON QUANTUM COMPUTING
accenture
IQM
PsiQuantum
QUIX QUANTUM
IONQ
ENTROPICA LABS
SINGLE QUANTUM
Excellence in photon detection
QUANTUM MACHINES
Zurich Instruments
RedWave Labs
25 years PicoQuant
seeqc
ColdQuanta
QUANTUM MOTION
Orange Quantum Systems
Algorithmiq
parityqc
IDQ
QUANTUM DICE
aegiq
CRYPTONEXT SECURITY
Cambridge Quantum
Entangled Networks
more than the sum of its parts
ThinkQUANTUM
nu QUANTUM
KETS
nami
MIRAEX
AQT
VECTOR PHOTONICS
QURECA
quantum resources & careers

Job prospects, examples:

- **Academic research** → PhD in QSE. Many exciting possibilities in Switzerland and worldwide !
- **Research centers** → CSEM, PSI, IBMQ, CERN (Switzerland), ICFO (spain), CQT (singapour), VCQ, ESQ, IQOQI (Austria), Quantum Alliance (Germany),……
- **Startups and medium sized companies** -> MIRAEX (photonic sensing) QuantumMachines (qubit control systems) QuiX (photonic computing) Qnami (sensing) IDQ (crypto, communications).....
- **Big tech companies** IBM, Microsoft, Google, Intel, NEC, Righetti, Atos, ……

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.

Important deadlines and informations

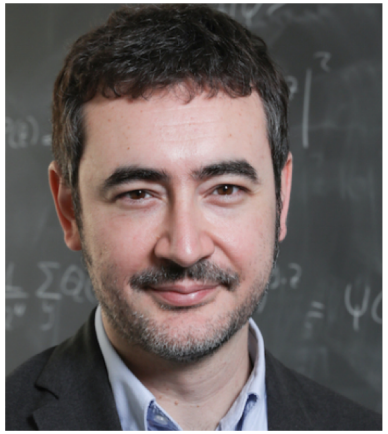
- Application deadline 15 April on EPFL master's page
  https://www.epfl.ch/education/master/programs/quantum-science/
  For non-physicists necessary requirement for admission is GPA of 4.5
- For Physics EPFL students the master is consecutive
- Anybody applying for a bourse d'excellence must submit his application by 15 April deadline (same process for internal, external, physics EPFL, other sections etc)
- We offer a MINOR. This can be a good deal if you hesitate changing section.
- For any info contact nicolas.macris@epfl.ch (prog. dir IC)
  or edoardo.charbon@epfl.ch (STI) giuseppe.carleo@epfl.ch (SB)
- List and syllabus of courses of master and minor (subject to change).
  New section website: to be created…

THANK YOU FOR YOUR ATTENTION

WE HOPE TO SEE MANY OF YOU NEXT SEPTEMBER!

https://www.epfl.ch/education/master/programs/quantum-science/

Edoardo Charbon (STI)



Giuseppe Carléo (SB)

Nicolas Macris (IC)