

How to read the competence framework

The QTedu CSA of the Quantum Flagship has created a competence framework for Quantum Technologies. It aims to map the landscape of possible competences and skills in Quantum Technologies. In the following pages you will find the beta version of this framework.

The framework has been created in a combined deductive and inductive approach. A key ingredient was the input from the QT community experts who participated in our Delphi study. There will be a final round of the study to evaluate the framework.

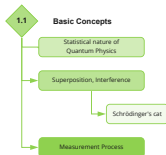
The competence framework consists of seven main areas that structure the field, such as:



Each of these main areas has several sub-areas, e.g.



The overview diagram shows the main areas and the sub-areas. In addition, there is an extra page for each area with more details, e. g.



The background colour of the boxes indicates how often this aspect was mentioned in the Delphi study. Darker background means more mentions. In the example above, "measurement" has been mentioned very often, "statistical nature" has been mentioned less. "Schrödinger's cat" was not mentioned at all, but we believe it should be present (dead or alive).

To illustrate the meaning of the keywords in the boxes, they are supplemented by quotes from the the replies in the Delphi study. An arrow "→" indicates the experts' opinion of what a particular competence is "useful for", e.g.



No single person can have all the competences listed. For each entry, a person can have a proficiency level (from A1 - newcomer to C2 - innovator). One way of using the competence framework is to define the subject areas and the proficiency levels one is aiming at in a particular program.

This is the beta version of the competence framework. We would be very happy to receive your feedback: Did we (and the community experts) miss some important points? Are there redundancies or irrelevant points? Please tell us what would you change. We look forward to your feedback until early January.

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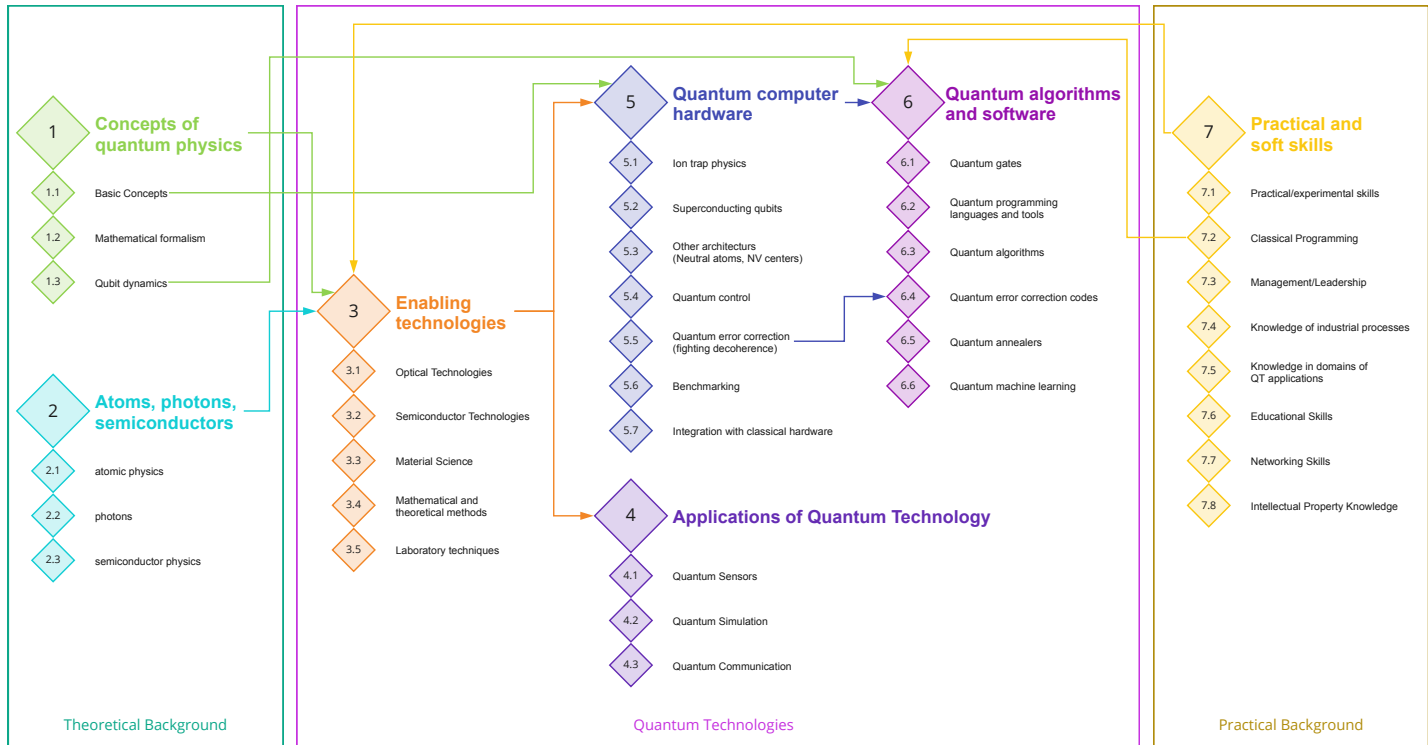


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Quantum Flagship

Competence Framework for Quantum Technologies

Beta version



1

Concepts of quantum physics

1.1

Basic Concepts

Perception of conceptual difference of classical and quantum mechanics. For users: Fundamental principles and formulae, many examples but not too much mathematical derivations.
→ understanding the basic building blocks of electronics

Understanding quantum phenomenology under the sensing principle (squeezing, entanglement, superposition, quantum interference)
→ building a sensor

Basic phenomenological understanding of superposition states, entanglement and decoherence. Need to understand the concepts but not necessarily the mathematical or even physical underpinnings.
→ All engineers working on the field in order to understand the properties they need to develop.

Superposition, entanglement, decoherence. When applying an existing algorithm to a use case, a qualitative understanding should be enough. For developing new algorithms a deeper understanding will be required.
→ understanding the specifics of quantum computing, its advantages and limitations; understanding and implementing quantum algorithms

Understand the difference between classical and quantum randomness and notions of coherence

Understanding of probabilistic character of quantum theory

Statistical nature of Quantum Physics

Superposition, interference

understanding of principles like superposition and decoherence (deeper knowledge to be able to co-simulate classical electronics and qubits together)
→ system design considerations

Schrödinger's cat

Understanding superposition principle (model thinking, linking experimental results to theory)
→ understanding wave nature of matter and interference effects

Measurement Process

Understanding of the process and nature of measurements in quantum physics

uncertainty

Quantum measurement: [Engineers] need to understand the concepts but not necessarily the mathematical or even physical underpinnings.

Unitary evolution

understanding the concept of uncertainty

Schrödinger equation

Predict the evolution of quantum system, extract the state and/or measurable parameters

Bloch/Master equation

tunneling

understanding entanglement, photon interactions
→ designing new sources of entangled photons

Entanglement, non-locality

understanding of the concept of entanglement
→ understanding the complex dynamics of quantum many-body systems, needed to develop / identify potential applications

Bell states

Decoherence

understanding of principles like superposition and decoherence (deeper knowledge to be able to co-simulate classical electronics and qubits together)
→ system design considerations

mechanisms of decoherence

understanding of the concept of decoherence
→ building and improving quantum simulation platforms requires mitigation of noise, which leads to decoherence

1

Concepts of quantum physics II

1.2

Mathematical formalism

State space, wave function

Bra-ket notation

operators, eigenvectors, eigenvalues

energy quantization, bound states

Photon states / QED / Fock space

Quantum many-body systems

Mathematical foundations (linear algebra, statistics, topology, combinatorics)

understanding
Quantum state space
→ quantum control

theoretical description of quantum mechanical
systems (states, density matrices, Hilbert-space)
→ understanding the potential of the quantum
simulation platform

Use linear algebra to calculate and
understand abstract conclusions
following from the postulates of QT

Linear algebra (Hilbert spaces,
vectors/matrices/tensors etc.) Profound
understanding and experience required. This is the
most important competence as without it you will
not understand at all (on a technical level) what
you are doing and will not be able to understand
any literature on the subject.
→ understanding quantum algorithms, mapping
the actual use cases to a quantum formulation

Basic understanding of physical effects like Pauli
principle and Coulomb blockade
→ developing control and readout of qubit states

Many-body phenomena
→ understanding the mappings
expect resulting phenomena

Linear algebra (complex numbers, unitary matrices,
hermitian matrices, tensor products, matrix
diagonalization, eigenvalues and eigenvectors,
finite-dimensional vector spaces, finite fields.)
→ this is the language of quantum information

Statistics: Users need basic knowledge of probability, expectation and
variance. → evaluating quantum measurements; develop deeper
understanding/ a different view of entanglement and mixed quantum states

Combinatorial topology (graphs, lattices, co/
homology to define the codewords, wider
characteristic, topological defects)
→ topological codes

Combinatorics (binomial theorem, proofs
by induction, awareness about ois.org.)

Stabilizer formalism (basic group
theory (Pauli group and abelian
subgroups thereof, elementary
abelian 2-groups, group actions); also
subsystem codes)
→ Understanding of QECCs, efficient
description of many-qubit states

understanding of physical phenomena in qubits
(knowledge of energy levels, Bloch sphere, the ways
how EM field interacts with qubits)
→ controlling quantum gates using electrical signals

understanding of the concept of qubits (knowledge of how a qubit is
physically realized and what the requirements for its operation are)
→ developing control and readout of qubit states

1.3

Qubit dynamics

Bloch sphere

dynamics of qubits

pulses

Bloch sphere picture of qubits (how to use it to
understand the effect of EM pulses on qubits)
→ I think this is a very useful picture for any
engineering background persons.

2

Atoms, photons, semiconductors

underlying physics (optics, semiconductor physics, superconducting devices)
→ producing working devices

2.1

atomic physics

energy levels, quantization

hyperfine and other transitions

2.2

photons

Atom-photon interactions

Quantum description of light and atoms
→ Understanding the properties of light-matter interaction on a single photon/atom level

knowledge of how interaction with external fields can be used to control qubits, and how it also affects their coherence properties
→ design and control of quantum devices

Technological basis of implementation and manipulation with quantum states (Adequate knowledge needed for designer work on experimental setups and instruments, laser control, timing, coherence, etc.)
→ Designing and operating setups for single atom spectroscopy setups

generation and detection of single photon

practical experience in the generation of photons and their quantum states
→ building real devices for real life applications in the fields of telecom, sensing, possibly quantum computing, etc.

generation of entangled photon states

Polarization degrees of freedom

bunching, antibunching, squeezed states

2.3

semiconductor physics

Quantum dots

understanding of superconductivity
→ design of devices

Superconductivity

Superconductivity
→ comprehension of the basic hardware

Josephson effect

Mesoscopic phenomena

Knowledge of mesoscopic quantum phenomena (D: advanced knowledge of quantum field theory in condensed matter)
→ Design and implement large scale quantum computational systems

Topological effects

3

Enabling technologies

enabling technology like semiconductor technology, vacuum technology, quantum optics, CMOS integration, photonic integration etc.
→ the overall picture is necessary to join work force from different areas

good knowledge about the realization/implementations of optical schemes, detectors, lasers, microwave sources, current circuits
→ Building a device

3.1

Optical Technologies

Classical optics

Lasers

Photonics, fibres

3.2

Semiconductor Technologies

understanding underlying QT concepts for existing devices like FET's and LEDs (reasonable understanding of challenges of miniaturization and integration by semiconductor technology)

3.3

Material Science

Micro- and nanostructuring

micro and nanostructuring
→ build quantum devices in the size range where coherence and quantum effects are relevant

3.4

Mathematical and theoretical methods

signal processing

understanding of signal processing (theory in the context of QT (knowledge of signals and systems, Hilbert/2D Laplace transforms)
→ readout of SC qubits, generation of laser pulses, optical processing in frequency and time domain

3.5

Laboratory techniques

vacuum technology

Electronics

cleanroom technology

Microwave, RF technology

low temperatures

digital/analog electronics, understanding the architecture of classical computers

4

Applications of Quantum Technology

4.1

Quantum Sensors

Knowing quantum advantage and on which quantum phenomena it relies. Users need superficial knowledge about the quantum phenomenology but a clear knowledge what advantage is brought by it.

Quantum imaging

Magnetic field sensors

Quantum logic sensors

NV center sensors

4.2

Quantum Simulation

quantum chemistry

pharmaceutical & medical simulations

4.3

Quantum Communication

Quantum communication hardware

Quantum communication protocols

Repeaters, quantum internet

Quantum cryptography

Understanding of quantum information generation, transmission, and processing. Deeper basic knowledge, especially on the optical transmission characteristics and limitations caused by losses at the single-photon level.
→ Developing free-space-relevant quantum information exchanges and detection

Understanding of quantum communication protocols. Users need deeper basic knowledge of quantum communication protocols and routing algorithms. Good overall understanding of network architecture. No specific knowledge of physical implementation of hybrid classical/quantum internet. Developers need deeper understanding of physical hardware needed to implement hybrid classical quantum internet.
→ determining optimum networking configurations for quantum internet

Understanding of quantum repeaters. Users need deeper basic knowledge of how quantum repeaters work. No specific knowledge of physical implementation of the specific hardware for quantum repeaters. Developers need deeper understanding of specific hardware and implementation for quantum repeaters.
→ determining quantum communication in fibre/free space

understanding quantum hacking. Users need deeper basic knowledge of quantum hacking. No knowledge of physical mechanisms to prevent hacking and security attacks. Developers need deeper understanding of mechanisms to prevent quantum hacking.
→ preventing attacks on security of quantum internet

Cryptography, IT security. Developers need intermediate understanding of real-world requirements on security and cryptographic solutions in quantum communication.
→ Development of quantum communication applications

5

Quantum computer hardware

understanding of quantum hardware operating parameters (gate operations, connectivity, fidelity, gate-speed, ...) for multiple types of qubit architectures (superconducting, trapped ions, photonic, ...) → understanding and developing novel quantum algorithms

knowledge of existing hardware implementations of quantum computing
→ knowing the limitations: which problems can already be solved on an existing quantum computer, which will have to wait until better hardware is available

5.1

Ion trap physics

ion trap internal and external degrees of freedom

cooling

cooled atoms and optical trapping

control with lasers and microwaves

understanding of optoelectronics (knowledge of energetic model of atom, interactions of matter with light)
→ controlling / manipulating quantum states of ions/atoms

integration

decoherence mechanisms

qubit handling
→ optimize performance given the current lack of middleware stacks

for quantum computers based on gates, an understanding of how the characteristics of a given physical realization (i.e. architecture, Qubit connectivity, decoherence times, noise etc.) impacts the performance of the specific circuits chosen to implement a given quantum algorithm
→ suggesting new architectures/connectivity and/or new circuits that optimize performance of the quantum algorithms (or sub-algorithms) on a given physical platform.

5.2

Superconducting qubits

integration, packaging

decoherence mechanisms

5.3

Other architectures (Neutral atoms, NV centers)

5.4

Quantum control

Control of quantum systems. Developers need understanding of quantum control theory, including ab-initio and feedback controls for actual hardware, in a formal way
→ design, control and stabilization of hardware

understanding of, in particular, the causes of decoherence/noise/errors in quantum systems and the implications for performance in a given application.
→ suggesting modifications to physical platforms and/or mitigation strategies

5.5

Quantum error correction (fighting decoherence)

quantum process tomography and benchmarking. Users need rudimentary understanding of calibration toolboxes and approaches for monitoring the quality of quantum hardware
→ monitoring and calibration of hardware

5.6

Benchmarking

Systems with Classical IT & Quantum computing (Designing, integrating and validating IT systems merging Classical and Quantum capabilities)
→ Integrating an efficient system combining the best of both worlds

Architectural Principles for High-End Computing (parallel, simultaneous (Quantum), neuromorphic, ...)
→ Selection of use-cases and solution design

5.7

Integration with classical hardware

6

Quantum algorithms and software

6.1

Quantum gates

Understanding of qubit operations & quantum gates
 → Composing quantum algebras and applying them to specific tasks

gate types (Hadamard, CNOT, Pauli)

understanding of design flow (simulation, compilation, verification)
 (good understanding about the use of corresponding tools; deeper understanding would help to get the most out of it)
 → testing and checking the developed application

6.2

Quantum programming languages, tools and platforms

Basic programming of a quantum computer.
 Users (should be able to) run simple exercises on a platform like QISKit. Developers (should be able to) be able to modify known algorithmic primitives

6.3

Quantum algorithms

understanding of quantum programming languages (deep knowledge how to use languages to realize applications)

Understanding how to create basic algorithms
 → developing a certain understanding of quantum programming and getting familiar with the different way of programming

knowledge of existing quantum-algorithm concepts both for NISQ and FTQC. Quantum-developers need to be fluent in all existing quantum-algorithm concepts so that they can build on those to develop novel algorithms or so that they can apply them to implement quantum solutions

Shor-type / Quantum Fourier Transform

Grover-type / Amplitude amplification

Complexity theory

Understand the limitation of Quantum computing
 → realistic approaches and expectations in applying algorithms to real world problems

Complexity Theory
 → Understanding the limits of classical parallel computing

6.4

Quantum error correction codes

quantum error propagation (Propagation of Pauli errors through Clifford circuits, stabilizer errors do not harm, probability theory with a finite event space)
 → optimization of quantum circuits to avoid errors

Quantum circuit design (gates, measurements, unitary matrix corresponding to the circuit)
 → mitigation of errors, implementation of QEC-cycles

6.5

Quantum annealers

use cases

6.6

Quantum machine learning

Understanding of information science and artificial intelligence
 → Exploit quantum computational power for artificial intelligence

7

Practical and soft skills

7.1

Practical/experimental skills

knowing how to build things that work outside of the lab (passion for engineering and having a functional device at the end of the day)
→ generating products in incremental steps

Understanding experimental techniques in quantum optics (practical experience with laser-based experiments and understanding of theoretical concepts behind entanglement, q. cryptography etc.)
→ efficient designing of new toolbox based on quantum light

Atomic precise manufacturing
→ Miniaturization of quantum computers

7.2

Classical Programming

software development in general (e.g., Python, Assembly) (some experience required but not on a very high level (for quantum application developers))
→ understanding what a computer program is at all and how it is written; writing the control programs which drive the actual quantum computation

programming skills; Developer's good programming skills will help to create an interface between the sensor and the PC to see the measurement result

performing numerical simulations
→ understanding the physical processes and phenomena

7.3

Management/Leadership

Algorithms and data structures

understanding the differences and similarities of QT 1st and 2nd generation
→ having the overall picture, being able to critically evaluate the potential and challenges

understanding the performance trade-offs and limitations associated with the current physical platforms used to realize the quantum systems of QT 2.0.
→ suggesting new physical platforms and/or (engineering) improvements to existing physical platforms.

Knowledge of the panorama of the most appropriate materials and systems with properties exploitable in quantum technologies
→ Conception of new devices which exploit realistically available materials and technologies.

Overview, Potential and Limitations

understanding the limitations of quantum computers (deeper knowledge of quantum and classical algorithms, and complexity theory)
→ identifying hype, and false claims about what a quantum computer could do

Economic impact of QT

Entrepreneurship
→ Create markets for quantum technologies; Innovation
→ find solutions for the future

technological basis for quantum technology Users (should know) examples of quantum solutions, explanations of technology used, development and production process
→ use cases, appreciate resources invested in the development of QT

Entrepreneurship

7.4

Knowledge of industrial processes

Understanding the potential of today's semiconductor technology (silicon, Gallium Nitride...)
→ developing new strategies for integration, miniaturization and scaling of QT systems

understanding scaling, integration and mass production in semiconductor technology
→ bridge the gap from single devices in research to useful device technology for society

7.5

Knowledge in domains of QT applications

Understanding of Applications and Business needs
→ Redefining the problems in Quantum Terms

application domain expertise (e.g. chemistry, finance, ...) Quantum-developers need deep expertise in currently used (conventional) computational workflows including their limitations (which could potentially be developed on the job but ideally pre-existing knowledge)
→ understanding and developing novel quantum algorithms

7.6

Educational Skills

Competencies in the design and management of higher education programs and European collaboration in the field of hard sciences; (knowledge of the European higher education offers and educational structure, of masters and PhD programs on quantum technologies and of the aspect of quantum technologies which are relevant with respect to the need of the society)
→ Preparing professional in the field of higher education, capable of developing in the EU partners countries, and at EU and international level, of European masters and doctorates exploiting the opportunities offered by the EU Educational programs (Erasmus Mundus, Capacity-building projects in the field of higher education)

7.7

Networking Skills

know the programs and projects underway and the main actors of the quantum ecosystem
→ establish project consortia and make the best teams for each case, know who to ask.

Capability of explaining to policy makers and business community representatives the relevance of quantum technologies to boost economic and social growth. (Knowledge of the international panorama on research and development in quantum technologies and of the international policies in the field (at European Commission, USA Department of Energy etc.))
→ Shaping political and business decisions towards the strengthening public and private funding in quantum technologies.

7.8

Intellectual Property Knowledge