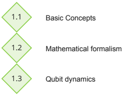
How to read the competence framework

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.

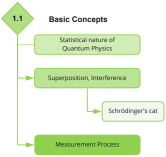
The framework has been created in a combined deductive and inductive approach. A key ingredient was the input from the QT community experts who participated in our Delphi study. There will be a final round of the study to evaluate the framework.

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.

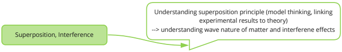


The overview diagram shows the main areas and the sub-areas. In addition, there is an extra page for each area with more details, e. g.



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' opinon 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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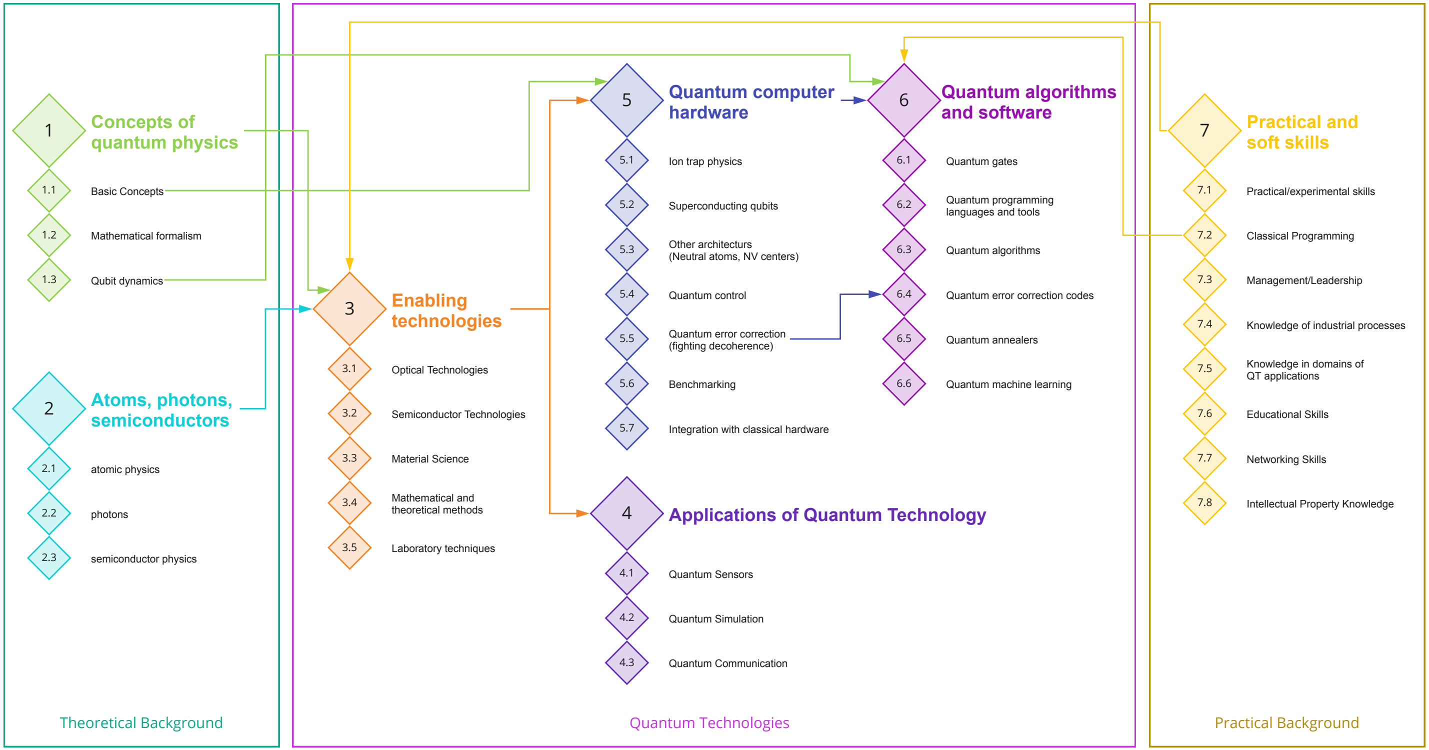
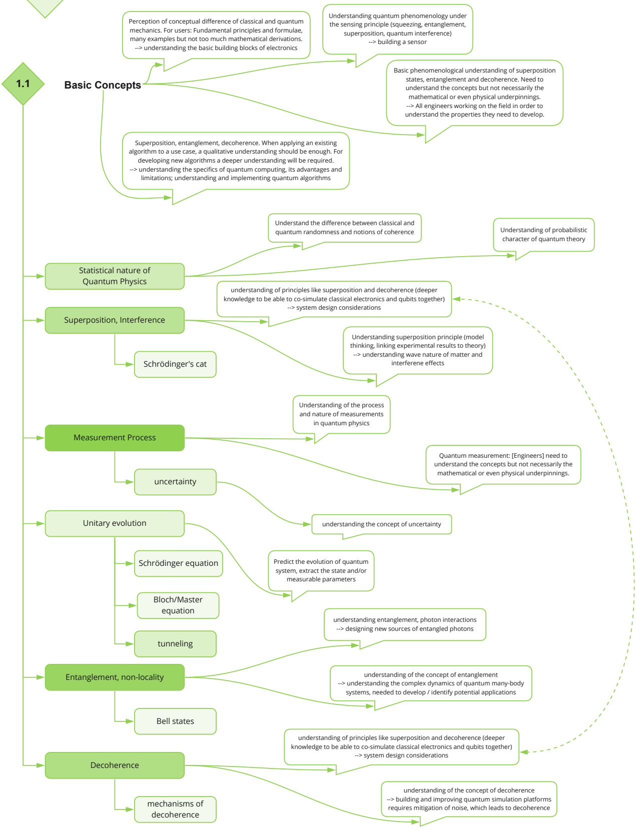
This framework is part of a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 951787.

Quantum Flagship
Competence Framework for Quantum Technologies
Beta version



1 Concepts of quantum physics



1 Concepts of quantum physics II

1.2 Mathematical formalism

- State space, wave function
  - 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
- Bra-ket notation
- operators, eigenvectors, eigenvalues
  - 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
- energy quantization, bound states
- Photon states / QED / Fock space
- Quantum many-body systems
  - 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
- Mathematical foundations (linear algebra, statistics, topology, combinatorics)
  - 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, euler characteristic, topological defects) --> topological codes
  - Combinatorics (binomial theorem, proofs by induction, awareness about oeis.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

1.3 Qubit dynamics

- understanding of physical phenomens 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

- Bloch sphere
  - 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.
- dynamics of qubits
- pulses

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
- Superconductivity
  - understanding of superconductivity
    --> design of devices
  - 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, microware 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 FETs 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/Z/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
  - 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
- Quantum communication protocols
  - 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
- Repeaters, 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
- Quantum cryptography
  - 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

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.

5.1 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 / manipulation of quantum states of ions/atoms
- integration
- decoherence mechanisms

5.2 Superconducting qubits

- integration, packaging
- decoherence mechanisms

5.3 Other architecturs (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

5.5 Quantum error correction (fighting decoherence)

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

5.6 Benchmarking

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

5.7 Integration with classical hardware

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

6 Quantum algorithms and software

6.1 Quantum gates

Understanding of qubit operations & quantum gates
--> Composing quantum algos and applying them to specific tasks

- gate types (Hadamard, CNOT, Pauli)

6.2 Quantum programming languages, tools and platforms

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

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

6.3 Quantum algorithms

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

Unterstanding 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)

Understand the limitation of Quantum computing
--> realistical approaches and expectations in applying algorithms to real world problems

- Shor-type / Quantum Fourier Transform
- Grover-type / Amplitude amplification
- Complexity theory

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