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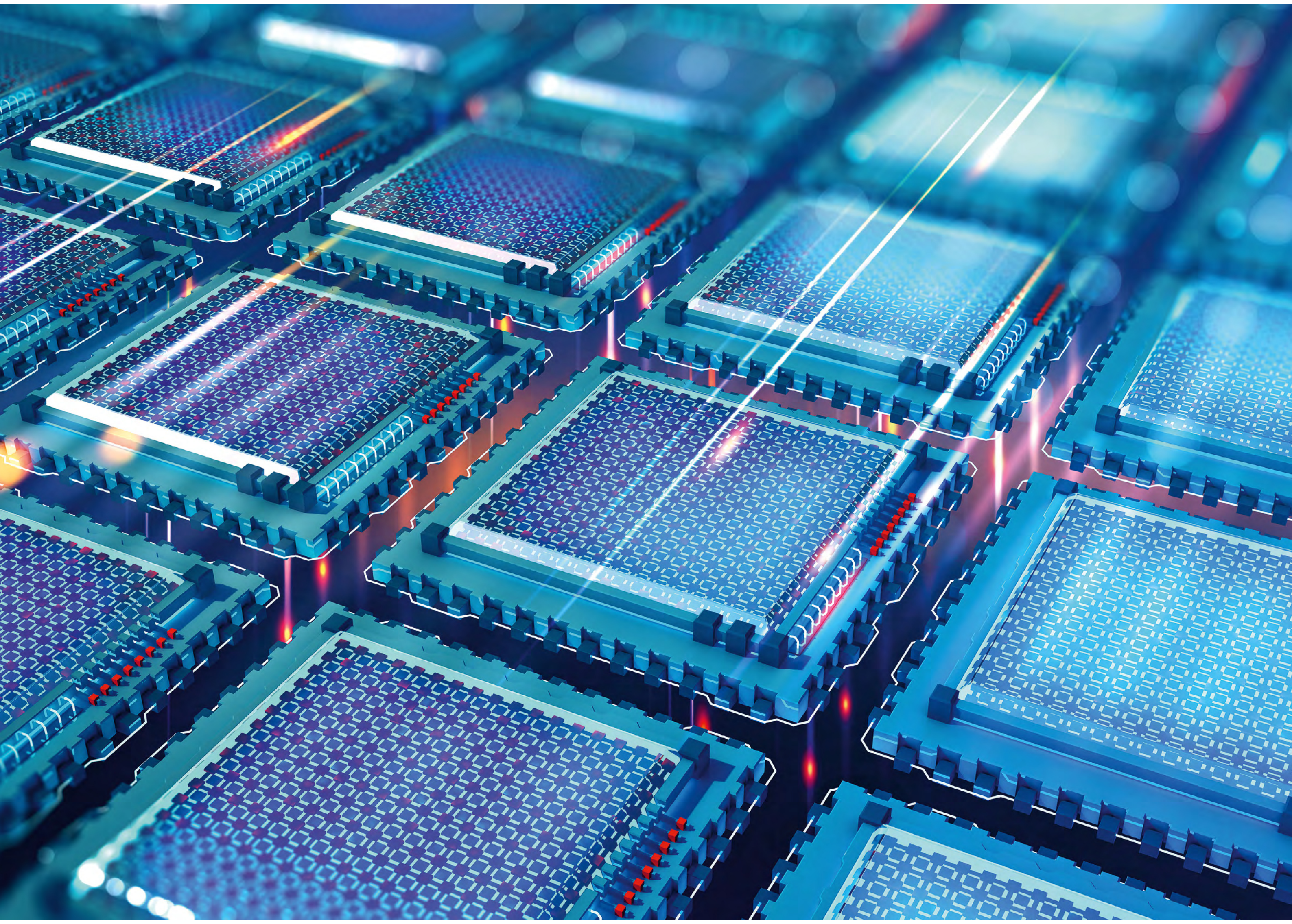
QUANTUM FLAGSHIP



Competence Framework
for Quantum Technologies

compiled by Franziska Greinert and Rainer Müller

Version 1.0 (May 2021)

Overview and General Structure

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1 CONCEPTS OF QUANTUM PHYSICS
- 1.1 Basic concepts
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- 1.3 Qubit dynamics

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- 2.3 Solid-state physics as a basis for quantum technologies

Quantum Technologies

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8 PRACTICAL AND SOFT SKILLS
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- 8.2 Classical programming
- 8.3 Management and leadership skills
- 8.4 Knowledge of industrial processes
- 8.5 Connecting QT with applications and use cases
- 8.6 Teaching and outreach skills
- 8.7 Networking and communication skills
- 8.8 Research ethics, responsible research and innovation
- 8.9 Intellectual property knowledge, standardization, certification

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QTEdu: Coordination and support action for Quantum Technology Education of the European Quantum Technology Flagship
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How to use the competence framework

The European Competence Framework for Quantum Technologies aims to map the **landscape of possible competences and skills in Quantum Technologies**. It has been compiled by the QTEdu CSA in order to facilitate the planning and design of education and training projects in Quantum Technologies.

The Competence Framework consists of seven main fields. They outline the broad structure of Quantum Technologies:

1 CONCEPTS OF QUANTUM PHYSICS

Each of these main fields has several subfields, e.g.

1.1 BASIC CONCEPTS

1.2 MATHEMATICAL FORMALISM

1.3 QUBIT DYNAMICS

On the first page of this document, the main fields and subfields are shown in a graphical scheme. For each subfield there is an extra page with more details:

1.1 BASIC CONCEPTS

- Superposition, interference
- Unitary time evolution
  - Schrödinger equation
  - Energy quantization, bound states
  - Tunneling

Depending on the target audience, each educational offer will address different level of depth and difficulty. To reflect this, there is an additional dimension to the Competence Framework that is not shown in the graphics. For each entry, a **proficiency level** can be specified: from A1 (Awareness) to C2 (Innovation). This scheme was developed for the European Language Reference Framework; it is also used, for example, in the European DigCompEdu framework for digital skills. The use of proficiency levels makes it easier to tailor education and training offers to the needs of the target groups.

A1	Awareness	**A2**	Exploration
B1	Integration	**B2**	Expertise
C1	Leadership	**C2**	Innovation

The Competence Framework has been compiled by the QTEdu team in a bottom-up approach. Between summer 2020 and spring 2021 we conducted a three-round Delphi study with many participants from the QT community. The results were refined by conducting expert interviews for each subfield.

Quantum Technologies are rapidly evolving. New technologies will be developed, others will become less important. The Competence Framework will have to be adapted accordingly. Thus, the Competence Framework is a living document which will be updated in regular intervals. Suggestions for additions and corrections are welcome at any time.

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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.

1 CONCEPTS OF QUANTUM PHYSICS

1.1 BASIC CONCEPTS

- Superposition, interference
- Unitary time evolution
  - Schrödinger equation
  - Energy quantization, bound states
  - Tunneling
- Quantum measurement
  - Statistical nature of quantum physics
  - Measurement dynamics (state reduction)
  - No-cloning theorem, incomplete state information from measurement
- Heisenberg principle, complementarity
- Decoherence
  - Simple examples for decoherence (relaxation, dephasing, photon loss)
  - Decoherence and coupling to the environment
- Entanglement/non-locality
  - Bell inequalities
  - Bell states
  - Quantum teleportation, superdense coding

1.2 MATHEMATICAL FORMALISM

- Mathematical foundations
  - Linear algebra
  - (Linear) differential equations
  - Statistics
  - Topology
  - Combinatorics
- State space, braket notation
- Operators, eigenvectors, eigenvalues
  - Commutation, anticommutation
- Pure and mixed quantum states
  - Wave function
  - Density operator
- Pertubation theory
- Photon states/QED
  - Coherent states
  - Single photon states
- Quantum many-body systems
  - Pauli principle, fermions, bosons
  - Field quantization
  - Composite systems
- Open quantum systems
  - Lindblad master equation

1.3 QUBIT DYNAMICS

- Dynamics of two-level systems
  - Bloch equation
  - Larmor precession
  - Rabi oscillations
  - Dephasing, relaxation
  - Higher-level systems (qudits)
- Qubit manipulation
  - Bloch sphere
  - Manipulating qubits with pulses
  - Mathematical description of qubit rotations

2 PHYSICAL FOUNDATIONS OF QUANTUM TECHNOLOGIES

2.1 ATOMIC PHYSICS AS A BASIS FOR QUANTUM TECHNOLOGIES

- Hyperfine and other transitions
- Electronic levels and forbidden transitions
- Zeeman, Stark effect
- Rydberg states
- Vibrational or rotational levels in molecules
- Quantum degenerate gases and quantum statistics

2.2 QUANTUM OPTICS AS A BASIS FOR QUANTUM TECHNOLOGIES

- Photon interactions with atoms and matter
- Polarization degrees of freedom
    - Poincaré sphere
- Bunching, antibunching, squeezed states
- Quantum machine learning

2.3 SOLID-STATE PHYSICS AS A BASIS FOR QUANTUM TECHNOLOGIES

- Solid state properties
    - Band structure
    - Electrical transport
    - Optical properties
    - Semiconductors
- Superconductivity
    - Josephson effect
    - SQUID devices
- Nanostructures
    - 2D electron gas
    - Quantum dots
    - Nanowires
- Materials science
    - Surface science
- Mesoscopic phenomena
- Topological effects

3 ENABLING TECHNOLOGIES

3.1 OPTICAL TECHNOLOGIES

- Classical optics
- Lasers
- Single photon sources
- Entangled photon sources
- Opto-electronical and opto-mechanical systems
- Single photon detectors
- Photonics, fibres

3.2 SOLID STATE TECHNOLOGIES

- Micro- and nanoelectronics
- SQUIDs

3.3 LABORATORY TECHNOLOGIES

- Vacuum technology
- Cryogenics
- Electronics
- Microwave, RF technology
- Laser cooling
- Laser stabilization
- Noise analysis
- Shielding techniques
- Cleanroom technology
- Micro- and nanostructuring

3.4 OPTICAL TECHNOLOGIES

- Software
- Hardware
- Quantum control algorithms

4 HARDWARE FOR QUANTUM COMPUTERS AND SENSORS

4.1 SUPERCONDUCTING DEVICES

- Superconducting qubit types: charge, flux, transmon, fluxonium
- Josephson junctions for metrology

4.2 SPIN-BASED DEVICES

- NV centers
- Semiconductor quantum dots

4.3 NEUTRAL ATOMS AND IONS

- Ion traps
- Rydberg atoms
- Cold quantum gases
- Optical lattices

4.4 EMERGING QUBIT CONCEPTS

- Topological qubits
- Molecular-spin qubits

4.5 PHOTONIC SYSTEMS

- Linear optical networks
- Photonic integrated circuits
- Boson sampling techniques

4.6 HARDWARE FOR INITIALIZATION, MANIPULATION AND READOUT OF QUBITS

- Microwaves
- Lasers
- Resonators (e.g. readout and gates of superconducting qubits)
- Switches, phase shifters, delays

4.7 UTILIZING HARDWARE PLATFORMS FOR QUANTUM COMPUTING

- DiVincenzo criteria
- NISQ limitations
- Platform-specific limitations
- Integration, packaging, scaling
- Benchmarking
- Middleware
- Integration with classical hardware

5 QUANTUM COMPUTING AND SIMULATION

5.1 QUANTUM GATES

- Single qubit gates
- Two and more qubit gates

5.2 QUANTUM PROGRAMMING LANGUAGES, TOOLS AND PLATFORMS

- Graphical platforms
- Software development kits
- Programming languages

5.3 QUANTUM ALGORITHMS AND COMPUTING TECHNIQUES

- Shor algorithm, hidden subgroup finding
- Grover algorithm, amplitude amplification
- Quantum optimization algorithms
- Quantum machine learning
- Tools
  - Quantum Fourier Transform
  - Quantum phase estimation
  - Quantum linear algebra algorithms
  - Quantum walks
  - E-commerce
- Other algorithms: Overview of the Quantum Algorithm Zoo

5.4 QUANTUM ERROR CORRECTION

- Physical decoherence mechanisms (dynamical decoupling)
- Error mitigation
- Quantum error correction code

5.5 QUANTUM SIMULATION

- Digital quantum simulators
- Analog quantum simulators and quantum annealers

6 QUANTUM SENSORS AND METROLOGY

6.1 ELECTROMAGNETIC FIELD SENSORS

- NV center sensors
- Rydberg atom sensors
- Atomic magnetometers, OPMs
- Superconducting sensors (nanowires, superconducting tunneling junctions, kinetic inductance detectors)

6.2 TEMPERATURE, PARTICLE AND PRESSURE SENSORS

- Spin-qubit based sensors
- Precision spectroscopy gas sensors
- Optomechanical sensors

6.3 INERTIAL AND GRAVITY SENSING

- Micro-electromechanical sensors (MEMS)
- Atom interferometers
- Rotating nanoparticle sensors

6.4 QUANTUM IMAGING

- Ghost imaging, tomography
- Single photon cameras, sub-shot-noise cameras
- Quantum radar, quantum lidar

6.5 ATOMIC CLOCKS

- Microwave clocks
  - Atomic fountain clocks
  - CPT clocks
- Optical clocks
  - Trapped ion clocks
  - Neutral atoms in optical lattices
  - Quantum logic clocks
- Nuclear clocks
- Transportable atomic clocks

6.6 APPLICATION FIELDS FOR QUANTUM SENSORS

- Metrology on single quantum level
  - Definition of SI units
- Medicine and molecular biology
  - Magnetic detection of neuronal and cardiac signals
  - Imaging (eg. living cells)
  - Microwave diagnostics
- Natural resources, civil engineering and earth monitoring
  - Civil engineering
    - Underground surveys
    - Infrastructure monitoring
  - Natural resource exploration
  - Natural hazard prevention
  - Earth monitoring
- Transport and navigation
  - Precise timing and position detection
- Control in industrial processes
  - Inspection in microelectronics
  - Ultraprecise timing and synchronization

6.7 SENSOR INTEGRATION AND HYBRID SENSING

7 QUANTUM COMMUNICATION

7.1 QUANTUM CRYPTOGRAPHY

- Quantum key distribution
- Secure authentication, digital signatures, secure storage
- Application to use cases
  - Financial transactions
  - Health records
  - Protection of critical infrastructure
  - E-government
  - E-commerce

7.2 QUANTUM NETWORKS

- Quantum internet
- Sensor and clock networks

7.3 INFRASTRUCTURE FOR QUANTUM COMMUNICATION

- Fibre-based systems
- Free space communication
- Satellite-based systems

7.4 HARDWARE FOR QUANTUM COMMUNICATION

- Quantum random number generators
- Quantum memory, interfaces, switches
- Repeaters
- End-nodes

8 PRACTICAL AND SOFT SKILLS

8.1 PRACTICAL/ EXPERIMENTAL SKILLS

8.2 CLASSICAL PROGRAMMING

- Programming languages
- Classical algorithms
- Complexity classes
- Classical cryptography
- Post-quantum cryptography

8.3 MANAGEMENT AND LEADERSHIP SKILLS

- Overview, potential and limitations
- Economic impact of QT
- Enterpreneurship
- Project design and implementation

8.4 KNOWLEDGE OF INDUSTRIAL PROCESSES

8.5 CONNECTING QT WITH APPLICATIONS AND USE CASES

- Knowledge within the fields of use cases
- Mapping use cases to quantum algorithms
- Recognizing quantum advantage
- Applying complexity theory

8.6 TEACHING AND OUTREACH SKILLS

8.7 NETWORKING AND COMMUNICATION SKILLS

- Communication with experts in the application fields
- Communication with customers

8.8 RESEARCH ETHICS, RESPONSIBLE RESEARCH AND INNOVATION

8.9 INTELLECTUAL PROPERTY KNOWLEDGE, STANDARDIZATION, CERTIFICATION