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QUANTUM+

Uncovering technology for business

D2.4 Comprehensive HE Curriculum

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1. Introduction

1.1 Introduction of HE Curriculum

Based on extensive professional and industrial feedback project work on curriculum proposal, the project developed a comprehensive Higher Education (HE) Curriculum totaling 30 ECTS, structured into six specialized courses. The program integrates over 100 micro learning pills (approximately one hour each) and 10 practical training labs, combining theoretical foundations with hands-on exercises. The curriculum ensures both technical proficiency in quantum technologies and a market-oriented perspective, equipping learners with the competencies required by research institutions and industry alike. This design directly reflects stakeholder feedback and establishes a strong bridge between academic training and emerging industrial needs.

The curriculum is composed of 6 theoretical courses on quantum technologies and business applications, i.e.

- Foundations Concepts of Quantum Technology
- Quantum Communication: Principles, Protocols and Applications
- Quantum Computing: Principles, Algorithms and Applications
- Quantum Sensing & Metrology: Single Photons, Spins, And Applications
- Quantum Simulations and Applications
- Quantum Business

complemented by 10 hands-on labs -fully aligned with the theoretical courses- with the aim of providing students with practical experience with quantum technologies:

- Introduction to QISKIT
- QISKIT intermediate
- QISKIT quantum algorithms
- QISKIT application for finance and industry
- Quantum measurement
- Quantum Communication: quantum Key Distribution (BB84 protocol)
- Quantum optics simulator
- Quantum game (QTris)

- Quantum communication: quantum Key distribution (BB84 protocol) [in-person lab at iLamp]
- Quantum optics [in-person lab at iLamp]

1.2 Objective of HE Curriculum

The Higher Education Curriculum in Quantum Technologies developed under the Quantum+ project aims to establish a comprehensive and industry-oriented curriculum that bridges the gap between academic theoretical research and implementation. Consisting of six specialist courses, Fundamental Concepts, Quantum Communications, Quantum Computing, Quantum Sensing and Metrology, Quantum Simulations, and Quantum Business and Innovation. The course equips students with essential skills in quantum theory, computing, and business innovation, positioning them for tackling current and future technological challenges. By way of interdisciplinary studies, sustainability, responsiveness, and inclusivity, the curriculum equips graduates to be able to contribute to Europe's digital transformation and leadership in the global world of quantum.

1.3 Target group and beneficial of HE Curriculum

Undergraduate and postgraduate students in physics, engineering, computer science, and business-related disciplines are the main beneficiaries of the HE curriculum. Those stakeholders are interested in gaining specialized knowledge in quantum technologies and understanding their business applications.

Training and education providers have access to a well-structured higher education curriculum addressing both technical and business aspects of quantum technologies. In addition, students receive a comprehensive, interdisciplinary education that prepares them for both academic research and industrial applications, while professional development access to tailored learning modules enhancing career prospects.

2. Propose Six HE Course Curriculum

2.1 Foundations Concepts of Quantum Technology

Course Title: "Foundations Concepts of Quantum Technologies"

Pre-requisite (If any): N/A

Total Credit Value: 3 ECTs

Credit Hours: 75 hours

Total Marks: 100

Rationale of the Course:

This course provides an introductory overview of the fundamental principles of quantum mechanics, whose applications include quantum computing, quantum communication, and quantum sensing. It is structured around micro-learning modules and labs, designed to promote in-depth understanding while ensuring flexible learning. Applications are foreseen in fields such as optimization in finance and logistics, industrial sensing, and communication security, among many others. As companies in communication security, financial services, pharma, automotive, AI, and materials science begin to capitalize on quantum innovation, students and professionals need to be equipped with interdisciplinary knowledge and skills to navigate this quantum revolution.

Learning Outcomes (LOs):

After completing the course, students should be able to:

- **Understand the conceptual foundations** of quantum mechanics, including the differences from classical physics. (LO1)
- **Contextualize the second quantum revolution** and assess the potential of quantum technologies in scientific and industrial sectors. (LO2)
- **Describe and interpret** the concept of wavefunction, quantum state, superposition, and entanglement. (LO3)

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- **Recognize and discuss experimental implementations** of quantum concepts through electronic spin, light polarization, cold atoms and superconducting resonators. (LO4)

Assessment Methods:

Type	% contribution
Evaluation quiz #1	10%
Evaluation quiz #2	10%
Evaluation quiz #3	10%
Evaluation quiz #4	10%
Evaluation quiz #5	10%
Final assessment (MCQ, Short Question, Fill in The Gaps etc.)	50%

Grading Policy:

Final course grade: calculation and grade scale Final grade (100 points).

Total points	Final grade
0-49	0/Fail
50-59	1
60-69	2
70-79	3
80-89	4
90-100	5

Teaching methods and time allocation:

The course is based on online lectures, and a final assessment.

Methods	Learning Hours
Online Module sessions	15 h
Quizzes and final exam	5 h
Independent study	55 h
Total	**75 h**

Topics to be covered in the course	**LOs**	**Estimated effort in hours**
• Historical Overview • 2nd quantum revolution • wavefunctions and Schroedinger equation	LO1, LO2, LO3	3

Topics to be covered in the course	LOs	Estimated effort in hours
Quiz Test 1		.5
• Quantum states and superposition • Entanglement • Density matrix and coherence	LO1, LO3	3
Quiz Test 2		.5
• Implementation with electronic spin • Implementation with light polarization • superconductivity and macroscopic quantum effects	LO3, LO4	3
Quiz Test 3		.5
• superconductivity and applications • Implementation with superconducting resonators (transmons) • From macroscopic phase coherence to states with defined number of quanta	LO3, LO4	3
Quiz Test 4		.5
• Bose-Einstein condensation • cold atoms and applications • Electromagnetic field and single photons	LO 1, LO 4 & LO 5	3
Quiz Test 4		.5
Final Assessment	LO1 to LO4	2.5
Total Hours		**20**

2.2 Quantum Communication: Principles, Protocols and Applications

Course Title: Quantum Communication: Principles, Protocols and Applications

Pre-requisite (If any): Fundamental Concepts of Quantum Technologies

Total Credit Value: 3 ECTS

Credit Hours: 75 hours

Total Marks: 100

Course Rationale

Quantum communication applies the principles of quantum mechanics to achieve secure and efficient information transfer. This course introduces both the theoretical foundations, such as the no-cloning theorem, and practical technologies including quantum key distribution (QKD) and quantum random number generation (QRNG).

Students will learn how quantum communication addresses the limitations of classical cryptography, enhances protocol security, and enables applications across finance, defense, aerospace, and transportation. By combining conceptual understanding with real-world use cases, the course prepares participants to engage with the emerging shift towards quantum-safe communication systems.

Learning Outcomes

After completing the course, students should be able to:

- Understand the theoretical basis of quantum communication, including the no-cloning theorem, quantum cryptography protocols and quantum noise correction. **(LO 1)**
- Understand and evaluate current technologies, such as quantum key distribution (QKD) and quantum random number generation (QRNG). **(LO 2)**
- Analyze the limitations of classical cryptography and describe how quantum approaches address security challenges. **(LO 3)**
- Assess real-world applications of quantum communication in sectors such as secure communications, aerospace, defense, automotive/transport, and banking/finance. **(LO 4)**

Assessment Methods

Type	**% Contribution**
Evaluation quiz #1	10%
Evaluation quiz #2	10%
Evaluation quiz #3	10%
Evaluation quiz #4	10%
Evaluation quiz #5	10%
Evaluation quiz #6	10%
Final assessment (MCQ, Short Question, Fill in The Gaps, etc.)	40%

Grading Policy:

Final course grade: calculation and grade scale Final grade (100 points).

Total points	Final grade
0-49	0/Fail
50-59	1
60-69	2
70-79	3
80-89	4
90-100	5

Teaching methods and time allocation:

The course is based on online lectures, quizzes and a final assessment.

Methods	Learning Hours
Online Module sessions	8 h
Case Studies and applications	7 h
Quiz tests and assessments	6 h
Independent study	54 h
Total	**75 h**

Topics to be Covered in the course	LOs	Est. Effort (hrs)
• Introduction to Quantum Communication • Classical cryptography & RSA protocol.	LO	2
Quiz Test 1		0.5
• No-cloning theorem • Quantum cryptography protocol without Eve • Quantum cryptography protocol with Eve	LO	3
Quiz Test 2		0.5
• Current technology: Quantum Key Distribution (QKD) • Quantum noise correction • Current technology: Quantum Random Number Generation (QRNG)	LO	3
Quiz Test 3		0.5
Case studies and applications		
• Case studies in secure communications 1 • Case studies in secure communications 2	LO	2
Quiz Test 4		0.5
• Aerospace applications	LO	3

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• Defense applications • Automotive & transport applications		
Quiz Test 5		0.5
• Banking and finance applications 1 • Banking and finance applications 2	LO	2
Quiz Test 6		0.5
Final assessment		3
Total Hours		**21**

2.3 Quantum Computing: Principles, Algorithms and Applications

Course Title: Quantum Computing: Principles, Algorithms and Applications

Pre-requisite (If any): Fundamental Concepts of Quantum Technologies

Total Credit Value: 5 ECTS

Credit Hours: 125 hours

Total Marks: 100

Course Rationale

Quantum computing is an emerging field of computation that applies the principles of quantum mechanics to solve problems too complex for classical computers. This course provides a solid introduction to the fundamentals of quantum computing, including qubits, the Bloch sphere, quantum gates, and the structure of quantum algorithms. Students will study both foundational algorithms (Deutsch–Jozsa, Shor, Grover) and more advanced methods such as quantum annealing, adiabatic quantum computing, and the Quantum Approximate Optimization Algorithm (QAOA).

Beyond the theoretical aspects, the course highlights current hardware technologies, such as trapped ions, superconducting qubits, and photonic systems, as well as programming tools like Qiskit.

Practical applications are examined in diverse sectors, including optimization in finance, transport, and energy, as well as data security, cybersecurity, drug discovery, and protein design. Finally, students will explore the interplay between quantum

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computing and artificial intelligence, gaining the knowledge and skills required to address cross-disciplinary challenges and opportunities in the quantum era.

Learning Outcomes

After completing the course, students should be able to:

- Differentiate between classical and quantum computing paradigms: explain the fundamental differences in logic, information processing, and computational power, and assess the potential advantages offered by quantum computing over classical approaches. (LO1)
- Understand the fundamentals of quantum computing: describe the concept of the qubit, its representation on the Bloch sphere, and the use of operators and quantum gates to manipulate quantum states. (LO2)
- Analyze the main quantum algorithms: describe the purposes and applications of key quantum algorithms such as Deutsch–Jozsa, Shor, and Grover, highlighting the types of problems they address and how they differ from classical approaches. (LO3)
- Evaluate enabling technologies: compare physical platforms for quantum computing (trapped ions, superconductors, photonics), highlighting strengths, challenges, and potential applications. (LO4)
- Explain the principles of quantum optimization methods: describe, at a conceptual level, adiabatic computing, quantum annealing, and QAOA, recognizing their potential and limitations. (LO5)
- Explore interdisciplinary perspectives: discuss how quantum computing interacts with emerging fields such as AI, drug discovery, and cybersecurity, analyzing practical and societal implications. (LO6)

Assessment Methods

Type	% Contribution
Quiz Test 1	5%
Quiz Test 2	5%
Quiz Test 3	5%
Quiz Test 4	5%
Quiz Test 5	5%
Quiz Test 6	5%

Quiz Test 7	5%
Quiz Test 8	5%
Final assessment (MCQ, Short Question, Fill in The Gaps, etc.)	60%

Grading Policy:

Final course grade: calculation and grade scale Final grade (100 points).

Total points	Final grade
0-49	0/Fail
50-59	1
60-69	2
70-79	3
80-89	4
90-100	5

Teaching methods and time allocation:

The course is based on online lectures, quizzes and a final assessment.

Methods	Learning Hours
Online Module sessions	18 h
Case Studies and applications	10 h
Quiz Tests and assessments	7 h
Independent study	90 h
Total	**125 h**

Course Outline

Topics to be Covered in the course	LOs	Est. Effort (hrs)
• Introduction to quantum computing • Classical logic operations and transistors	LO1	2
Quiz Test 1		0.5
• Qubit and Bloch sphere • Single qubit gates • multi qubit operators	LO1, LO2	3
Quiz Test 2		0.5
• Decoherence and interactions • Quantum error correction	LO1, LO2	2
• Current technologies: trapped ions • Current technologies: superconductors, • Current technology: light	LO4	3
Quiz Test 3		0.5

• Quantum algorithm structure and languages • QISKIT	LO2, LO3	2
• Deutsch-Josza algorithm • Shor's algorithm and factorization of prime numbers • Grover's algorithm	LO3	3
Quiz Test 4		0.5
• Adiabiatic quantum computing • Quantum annealing • Quantum Approximate Optimization Algorithm	LO5	3
Quiz Test 5		0.5
Case studies and applications		
• Optimization problems in finance: portfolio optimization • Optimization problems in finance: pricing • Optimization problems in finance: risk evaluation	LO6	3
Quiz Test 6		0.5
• Optimization problems: transport and logistics • Optimization problems: energy • Data security risks	LO6	3
Quiz Test 7		0.5
• Protein design • Drug discovery • Cybersecurity • Quantum AI	LO6	4
Quiz Test 8		0.5
Final assessment		3
Total Hours		**35**

2.4 Quantum Sensing & Metrology: Single Photons, Spins, And Applications

Course Title: Quantum Sensing & Metrology: Single Photons, Spins, and Applications

Pre-requisite (If any): Fundamental Concepts of Quantum Technologies

Total Credit Value: 3 ECTS

Credit Hours: 75 hours

Total Marks: 100

Course Rationale

Quantum sensing and metrology exploit the unique properties of quantum systems to achieve levels of precision and sensitivity that surpass classical methods. A central element in this field is the ability to generate, detect, and control single photons, which form the basis for advanced applications in communication, imaging, and measurement.

This course introduces students to the fundamentals of single-photon technologies and solid-state systems such as nitrogen-vacancy in diamonds, which enable innovative approaches in sensing and healthcare. It also explores quantum-enhanced microscopy and spectroscopy, as well as case studies in communications, bio-imaging, magnetic field detection, and bacteria tracking.
By connecting theory with practical examples, the course provides a foundation for understanding the role of quantum technologies in next-generation measurement and diagnostic systems.

Learning Outcomes

After completing the course, students should be able to:

- Understand the principles of quantum sensing and metrology: explain how quantum phenomena can enhance measurement precision beyond classical limits. **(LO1)**
- Describe single-photon technologies and spin-based systems: illustrate the generation, detection, and use of single photons, and analyze the role of spin and nitrogen-vacancy centers in diamonds for sensing applications. **(LO2)**
- Evaluate quantum-enhanced microscopy and spectroscopy: discuss how quantum resources improve imaging and detection techniques, providing examples from current technologies. **(LO3)**
- Assess real-world applications of quantum sensing: identify and analyze case studies in communications, bio-imaging, healthcare, magnetic field detection, and bacteria tracking. **(LO4)**

Assessment Methods

Type	**% Contribution**
Quiz Test 1	10%
Quiz Test 2	10%
Quiz Test 3	10%
Quiz Test 4	10%
Quiz Test 5	10%
Quiz Test 6	10%
Final assessment (MCQ, Short Question, Fill in The Gaps, etc.)	40%

Grading Policy:

Final course grade: calculation and grade scale Final grade (100 points).

Total points	Final grade
0-49	0/Fail
50-59	1
60-69	2
70-79	3
80-89	4
90-100	5

Teaching methods and time allocation:

The course is based on online lectures, in class exercises including case discussions, individual assignments including peer feedback, Lab work and presentations, and a final exam.

Methods	Learning Hours
Online Module sessions	8 h
Case Studies and applications	6 h
Quiz Tests and assessment	6 h
Independent study	55 h
Total	**75 h**

Topics to be Covered in the course	LOs	Est. Effort (hrs)
• Introduction to Quantum Sensing and Metrology	LO1	1
• Single photon generation • Single photon sources • Single photon detection	LO1, LO2	3
Quiz Test 1		0.5
• Spin and nitrogen vacancies in diamonds • Spin and nitrogen vacancies in diamonds: applications	LO1, LO2	2
Quiz Test 2		0.5
• Quantum-Enhanced Microscopy & Spectroscopy • Quantum-Enhanced Microscopy & Spectroscopy: Examples	LO1, LO3	2
Quiz Test 3		0.5
Case studies and applications		
• Communications	LO1, LO4	1
Quiz Test 4		0.5
• Bio-Imaging & Healthcare (1)	LO1, LO4	2

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Topics to be Covered in the course	LOs	Est. Effort (hrs)
• Bio-Imaging & Healthcare (2)		
Quiz Test 5		0.5
• Metrology and Magnetic Field Detection (1) • Metrology and Magnetic Field Detection (2) • Bacteria Tracking	LO1, LO4	3
Quiz Test 6		0.5
Final assessment		3
Total Hours		**20**

2.5 Quantum Simulations and Applications

Course Title: Quantum Simulations and Applications

Pre-requisite (If any): Fundamental Concepts of Quantum Technologies

Total Credit Value: 3 ECTS

Credit Hours: 75 hours

Total Marks: 100

Rationale of the course:

This course introduces students to the theoretical foundations and practical uses of quantum simulators for process optimization, materials science, and chemistry. By studying interacting systems, quantum chemistry, and trapped ion and photonic simulators, students will be able to apply quantum principles to real-world problem-solving in materials design, healthcare, drug discovery, and agriculture.

Learning Outcomes

After completing the course, students should be able to:

- Understand the foundations of quantum simulations: explain the role of the Hamiltonian in interacting systems and how it underpins the simulation of quantum phenomena. **(LO1)**
- Describe the connection between quantum chemistry and quantum simulations: analyze how chemical bonds can be modeled and studied using quantum approaches. **(LO2)**

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- Recognize different quantum simulation platforms: compare the principles of trapped-ion and photonic simulators and their relevance to current research. **(LO3)**
- Evaluate applications of quantum simulations: discuss how simulations support novel materials design and the optimization of chemical processes in healthcare, drug discovery, and agriculture. **(LO4)**

Assessment Methods

Type	**% Contribution**
Quiz Test 1	10%
Quiz Test 2	10%
Quiz Test 3	10%
Quiz Test 4	10%
Final assessment (MCQ, Short Question, Fill in The Gaps, etc.)	60%

Grading Policy:

Final course grade: calculation and grade scale Final grade (100 points).

Total points	**Final grade**
0-49	0/Fail
50-59	1
60-69	2
70-79	3
80-89	4
90-100	5

Teaching methods and time allocation:

The course is based on online lectures, quizzes and a final assessment.

Methods	**Learning Hours**
Online Module sessions	7 h
Case Studies and applications	4 h
Quiz Tests and assessments	5 h
Independent study	59 h
Total	**75 h**

Topics to be Covered in the course	LOs	Est. Effort (hrs)
• Introduction to Quantum Simulations	LO1	1
• The Hamiltonian of Interacting Systems • Hamiltonian of Interacting Systems: Examples	LO1	2
Quiz Test 1		0.5
• Chemical Bonds and Quantum Chemistry • Chemical Bonds and Quantum Chemistry: Examples	LO2	2
Quiz Test 2		0.5
• Trapped ions simulators • Photonic simulators	LO3	2
Quiz Test 3		0.5
Case studies and applications		
• Novel Materials Design • Optimization of Chemical Processes – Healthcare • Optimization of Chemical Processes – Drug Discovery • Optimization of Chemical Processes – Agriculture	LO4	4
Quiz Test 4		0.5
Final assessment		3
Total Hours		**16**

2.6 Quantum Business

Course Title: Quantum business

Pre-requisite (If any): Fundamental Concepts of Quantum Technologies, one among: Quantum Communications, Quantum Computing, Quantum Sensing & Metrology, Quantum Simulations

Total Credit Value: 3 ECTS

Credit Hours: 75 hours

Total Marks: 100

Course Rationale

Quantum technologies are to become a disruptive force in industries, slated as a keystone for the next generation of deep technologies. This course familiarizes students with the business of quantum technologies, including service models, industrial ecosystems, funding mechanisms, and commercialization strategies. The course emphasizes strategies to build quantum-ready teams and breaking the technology roadmap to market adoption success.

Learning Outcomes

After completing the course, students should be able to:

- Explain the role and significance of quantum technologies in the broader deep-tech landscape, including emerging business models and scalability challenges. (LO1)
- Analyze global quantum ecosystems (EU, US, Asia), identifying key players, research hubs, and industrial collaborations. (LO2)
- Evaluate market dynamics and industry trends, including start-ups, funding schemes, and commercialization opportunities. (LO3)
- Develop strategic insights for building and managing quantum ventures, including team structures, required expertise, roadmaps, and sustainable growth strategies. (LO4)

Assessment Methods

Type	**% Contribution**
Quiz Test 1	10%
Quiz Test 1	10%
Quiz Test 1	10%
Case study	20%
Final assessment (MCQ, Short Question, Fill in The Gaps, etc.)	50%

Grading Policy:

Final course grade: calculation and grade scale Final grade (100 points).

Total points	**Final grade**
0-49	0/Fail

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50-59	1
60-69	2
70-79	3
80-89	4
90-100	5

Teaching methods and time allocation:

The course is based on online lectures, quizzes and a final assessment.

Methods	Learning Hours
Online Module sessions	17 h
Case Studies	4 h
Quiz Tests and assignments	5 h
Independent study	49 h
Total	**75 h**

Topics to be Cover in the course	LOs	Est. Effort (hrs)
• Quantum as a Deep Tech • Quantum as a Service	LO1	2
Quiz Test 1		0.5
Quantum Ecosystem 1: EU • Global strategy • Key players and initiatives • Research hubs and industrial collaborations	LO2	3
Quantum Ecosystem 2: US • Global strategy • Key players and initiatives • Research hubs and industrial collaborations	LO2	3
Quantum Ecosystem 3: ASIA • Global strategy • Key players and initiatives • Research hubs and industrial collaborations	LO2	3
Quiz Test 2		0.5
Quantum Industry • Global players and start-ups • Market trends • Quantum Funding Schemes (e.g. QuantoNation)	LO3	3
Quiz Test 3		0.5
• The Importance of Building a Quantum Team • Quantum Technology Roadmap	LO3, LO4	2
• Integration & Future of Quantum Business	LO3	1
Quiz Test 4		0.5
Case studies		4
Final assessment		3

Topics to be Cover in the course	LOs	Est. Effort (hrs)
Total Hours		**26**

3. Quantum+ proposed Labs

3.1 Introduction to QISKIT

Prerequisite courses:

- Fundamental Concepts of Quantum Technologies
- Quantum Computing

Total credit value: 1 ECTS

Credit hours: 25

Methods	Learning Hours
Laboratory	10 h
Independent study, readings, report preparation	15 h
Total	**25 h**

Laboratory mode: online

Laboratory rationale:

This laboratory introduces students to the **IBM Quantum platform** and the Qiskit programming environment, providing the first practical experience in quantum programming.

Students will learn how to access and use IBM's online quantum simulators, explore the basic structure of Qiskit, and understand how quantum circuits are built and executed. The activities will include the implementation of single- and multi-qubit gates, the visualization of states on the Bloch sphere, and the interpretation of measurement outcomes.

Learning Outcomes:

By the end of the lab, students will be able to:

- Access and navigate the IBM Quantum platform.

- Build and execute simple quantum circuits using Qiskit;
- Visualize and analyze quantum states on the Bloch sphere.
- Interpret measurement results and connect them to theoretical quantum principles;
- Develop confidence in using real quantum programming tools.

3.2 QISKIT intermediate

Prerequisite courses:

- Fundamental Concepts of Quantum Technologies
- Quantum Computing
- Lab. Introduction to QISKIT

Total credit value: 1 ECTS

Credit hours: 25

Methods	**Learning Hours**
Laboratory	10 h
Independent study, readings, report preparation	15 h
Total	**25 h**

Laboratory mode: online

Laboratory rationale:

This laboratory deepens the use of the IBM Quantum platform and the Qiskit framework, focusing on the creation and manipulation of entangled qubits.

Students will design and implement simple quantum algorithms that exploit entanglement. Through guided exercises, they will learn how to construct multi-qubit circuits, apply controlled operations, and visualize correlations between qubits.

Assignments will require students to build and test small quantum algorithms and to analyze how entanglement affects computational outcomes. By the end of the lab, students will be able to design, simulate, and interpret intermediate-level quantum circuits using Qiskit.

Learning Outcomes:

By the end of the lab, students will be able to:

- Construct and simulate multi-qubit circuits using Qiskit;
- Implement and analyze algorithms involving entanglement and superposition;
- Visualize correlations and measurement outcomes between qubits;
- Interpret intermediate-level quantum circuits using Qiskit.

3.3 QISKIT quantum algorithms

Prerequisite courses:

- Fundamental Concepts of Quantum Technologies
- Quantum Computing
- Lab. Introduction to QISKIT
- Lab. QISKIT intermediate

Total credit value: 1 ECTS
Credit hours: 25

Methods	**Learning Hours**
Laboratory	10 h
Independent study, readings, report preparation	15 h
Total	**25 h**

Laboratory mode: online

Laboratory rationale:

This advanced laboratory provides a step-by-step guided exploration of two landmark quantum algorithms, **Shor's algorithm** and **Grover's algorithm**, both implemented using Qiskit on the IBM Quantum platform. These algorithms represent two of the most celebrated achievements in quantum computing, demonstrating possible quantum advantages over classical computation.

Students will first gain a conceptual understanding of each algorithm and then progressively implement simplified versions in Qiskit.

By the end of the lab, students will be able to understand the logical structure and purpose of Shor's and Grover's algorithms.

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Learning Outcomes:

By the end of the lab, students will be able to:

- Understand the logical structure and purpose of Shor's and Grover's algorithms;
- Implement small-scale versions of both algorithms using Qiskit;
- Visualize and interpret intermediate quantum states and measurement outcomes;
- Explain how quantum interference and entanglement enable computational advantages;

3.4 QISKIT application for finance and industry

Prerequisite courses:

- Fundamental Concepts of Quantum Technologies
- Quantum Computing
- Lab. Introduction to QISKIT
- Lab. QISKIT intermediate

Total credit value: 1 ECTS
Credit hours: 25

Methods	**Learning Hours**
Laboratory	10 h
Independent study, readings, report preparation	15 h
Total	**25 h**

Laboratory mode: online

Laboratory rationale:

This laboratory explores real-world applications of quantum computing in the fields of finance and industry, through a collaboration project with private companies and non-academic institutions. A possible example is testing and analyzing a quantum portfolio optimization algorithm, implemented with Qiskit.

Students will learn how quantum algorithms can be applied to optimization and decision-making problems, where classical computation faces scalability limits. The activities guide participants through the formulation of the portfolio optimization problem.

Learning Outcomes:

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By the end of the lab, students will be able to:

- Model a financial optimization problem;
- Implement and run a quantum portfolio optimization algorithm;
- Analyze and interpret the obtained results from both business and technical perspectives;
- Understand the challenges and opportunities of integrating quantum computing into industrial and financial workflows.

3.5 Quantum measurement

Prerequisite courses:

- Fundamental Concepts of Quantum Technologies

Total credit value: 1 ECTS
Credit hours: 25

Methods	Learning Hours
Laboratory	10 h
Independent study, readings, report preparation	15 h
Total	**25 h**

Laboratory mode: online

Laboratory rationale:

This laboratory offers an experimental verification and visualization of the fundamental quantum concepts presented in the Fundamental Concepts of Quantum Technologies course. Students will explore the phenomena of superposition, quantum measurement, photon polarization, and electron spin, represented on the Bloch sphere.

Through guided simulations, students will analyze how measurement affects quantum states, how probabilistic outcomes emerge, and how spin and polarization can be used to encode and manipulate quantum information. The visual interface of the simulator allows learners to build strong intuition about the geometry of quantum states and the meaning of measurement in different bases.

By the end of the lab, students will be able to connect abstract quantum principles to measurable phenomena, describe how measurement defines information in quantum systems, and interpret visual representations of qubit states in terms of real physical quantities.

Learning Outcomes:

By the end of the lab, students will be able to:

- Connect abstract quantum principles to measurable physical phenomena;
- Describe how measurement defines and changes information in quantum systems;
- Interpret visual representations of qubit states on the Bloch sphere;
- Explain how polarization and spin illustrate superposition and state collapse;
- Develop conceptual intuition about the probabilistic nature of quantum measurement.

3.6 Quantum Communication: quantum Key Distribution (BB84 protocol)

Prerequisite courses:

- Fundamental Concepts of Quantum Technologies
- Quantum Communication

Total credit value: 1 ECTS

Credit hours: 25

Methods	Learning Hours
Laboratory	10 h
Independent study, readings, report preparation	15 h
Total	**25 h**

Laboratory mode: online

Laboratory rationale:

This laboratory introduces students to the fundamental principles of quantum communication through the BB84 quantum key distribution (QKD) protocol, one of the first and most influential applications of quantum information theory. Using the QuVis online simulator, students will explore how quantum states of photons can be used to securely exchange cryptographic keys between two parties.

The activities guide students through each phase of the BB84 protocol: state preparation, transmission, measurement, basis reconciliation, and error checking. Students will observe how the quantum nature of light — specifically the impossibility of measuring without disturbing the state — guarantees communication security and reveals the presence of potential eavesdroppers.

Hands-on simulations will demonstrate the practical aspects of photon polarization encoding, basis selection, and bit-string generation, as well as the post-processing steps required for key sifting and error correction.

Learning Outcomes:

By the end of the lab, students will be able to:

- Explain the logic and security foundations of the BB84 protocol;
- Perform and analyze QKD experiments using the QuVis simulator;
- Understand the relationship between quantum measurement, disturbance, and information security;
- Discuss the relevance of quantum communication for future cryptographic systems.

3.7 Quantum optics simulator

Prerequisite courses:

- Fundamental Concepts of Quantum Technologies

Total credit value: 1 ECTS

Credit hours: 25

Methods	**Learning Hours**
Laboratory	10 h
Independent study, readings, report preparation	15 h
Total	**25 h**

Laboratory mode: online

Laboratory rationale:

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This laboratory introduces students to the foundations of quantum optics through interactive virtual experiments conducted on online simulators (e.g. Quantum Flytrap and Virtual Quantum Optics Lab). The activities focus on the generation of single photons, the creation and manipulation of entangled states, and the design of basic experimental setups used in modern quantum optics.

Students will explore how photons can be produced, guided, and measured within optical circuits, and how quantum correlations arise from entanglement and interference. The simulators allow the visualization of real laboratory components — such as beam splitters, mirrors, polarizers, and detectors — and demonstrate how these elements combine to reproduce fundamental experiments in quantum physics.

Learning Outcomes:

By the end of the lab, students will be able to:

- Understand the operational principles of single-photon and entangled-photon experiments;
- Design and analyze simple quantum optical setups using online simulators;
- Interpret interference and coincidence data in terms of quantum superposition and entanglement;
- Appreciate the role of optical platforms in the implementation of quantum communication and computation protocols.

3.8 Quantum game (QTris)

Prerequisite courses:

- Fundamental Concepts of Quantum Technologies

Total credit value: 1 ECTS

Credit hours: 25

Methods	Learning Hours
Laboratory	10 h
Independent study, readings, report preparation	15 h
Total	**25 h**

Laboratory mode: online

Laboratory rationale:

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This laboratory introduces students to quantum concepts through interactive gaming, using QTris, an educational quantum game developed to visualize and experience the principles of quantum mechanics and quantum computing in a playful environment.
QTris combines the logic of the classic Tris game with quantum rules such as superposition, measurement, and state collapse, allowing students to understand how quantum behavior differs from classical intuition. Through gameplay, students experience how quantum states evolve, how measurements affect the system, and how quantum uncertainty introduces probabilistic outcomes.
The laboratory aims to strengthen conceptual understanding by translating abstract quantum ideas into tangible, game-based interactions. Students will analyze the mechanics behind the game, link them to formal quantum postulates, and reflect on how gamification can support learning and outreach in quantum education.

Learning Outcomes:

By the end of the lab, students will be able to:

- Explain the quantum principles implemented in QTris;
- Connect game dynamics to superposition, measurement, and decoherence;
- Discuss the pedagogical role of serious games in quantum education;
- Reflect on the potential of interactive tools for communicating complex quantum phenomena.

3.9 Quantum communication: quantum Key distribution (BB84 protocol) [in-person lab at iLamp]

Prerequisite courses:

- Fundamental Concepts of Quantum Technologies
- Quantum communication

Total credit value: 1 ECTS

Credit hours: 25

Methods	Learning Hours
Laboratory	10 h
Independent study, readings, report	15 h

Co-funded by the European Union

preparation	
Total	**25 h**

Laboratory mode: in-person session held at the i-LAMP Laboratory, Università Cattolica del Sacro Cuore, Brescia, Italy.

Laboratory rationale:

This hands-on laboratory, conducted at the iLamp Laboratory (Università Cattolica del Sacro Cuore, Brescia, Italy), provides students with practical experience in quantum communication through the implementation and testing of a simulator of the BB84 quantum key distribution (QKD) protocol. Building on the theoretical foundations introduced in Quantum Communication course, this lab enables participants to simulate the process of quantum encryption using real optical components.

Students will work directly with sources, polarizers, beam splitters, and detectors to reproduce the essential steps of the BB84 protocol: quantum state preparation, transmission, basis selection, measurement, and key reconciliation. The experimental setup allows learners to visualize how the laws of quantum mechanics guarantee secure key exchange.

Learning Outcomes:

By the end of the laboratory, students will be able to:

- Understand the operational principles of the BB84 key distribution protocol.
- Perform basic optical alignment and measurement tasks using quantum communication hardware.
- Analyze experimental data and evaluate key generation rates and error probabilities.
- Discuss the role of quantum communication in modern information security infrastructures.

3.10 Quantum optics [in-person lab at iLamp]

Prerequisite courses:

- Fundamental Concepts of Quantum Technologies

Total credit value: 1 ECTS

Co-funded by the European Union

Credit hours: 25

Methods	Learning Hours
Laboratory	10 h
Independent study, readings, report preparation	15 h
Total	**25 h**

Laboratory mode: in-person session held at the i-LAMP Laboratory, Università Cattolica del Sacro Cuore, Brescia, Italy.

Laboratory rationale:

This in-person laboratory, held at the i-LAMP laboratories of Università Cattolica del Sacro Cuore (Brescia, Italy), introduces students to the experimental foundations of quantum optics through direct manipulation of optical components and measurement devices. The activities focus on the generation, control, and detection of single photons, the creation of entangled photon pairs, and the realization of fundamental interferometric setups used in modern quantum optics research.

Students will perform real experiments involving beam splitters, polarizers, lenses, mirrors, and single-photon detectors, learning how to align optical elements, collect coincidence data, and analyze interference and polarization effects. These experiments provide a tangible understanding of key quantum phenomena such as superposition, interference, and entanglement, and illustrate how they underpin technologies like quantum communication and quantum computing.

Learning Outcomes:

By the end of the laboratory, students will be able to:

- Operate basic optical instrumentation for quantum optics experiments;
- Generate, manipulate, and detect single photons and entangled states;
- Analyze interference and coincidence data to interpret quantum behavior;
- Relate laboratory observations to the principles of quantum communication and information processing.

4. Conclusion

The creation of the Higher Education Curriculum in Quantum Technologies within the Quantum+ initiative is a significant step towards fulfilling the current and future skills gap within the quantum sector. By means of systematic, flexible, and multidisciplinary design, the curriculum bridges the divide between academic theoretical training at university and industrial experience, so that students acquire both scientific knowledge and hands-on competence. By including six specialization courses ranging from quantum fundamentals and computing to sensing, simulation, communications, and business innovation, the programme provides an integrated path of study that meets evolving needs of research centers, businesses, and society. The modular structure of the curriculum, based on micro-learning "pills" and learning-by-doing laboratory experiments, enhances the capacity for adaptation and lifelong learning. Moreover, its emphasis on inclusion, sustainability, and digitalization demonstrates the project's alignment with the spirit of the European Education Area and the European Green Deal. The consortium partners' collaborative work has produced a curriculum that is cognitively challenging, market-oriented, and future-proof.

Overall, the Quantum+ Higher Education Curriculum offers a solid foundation for developing the future generation of quantum technology professionals. It makes it possible for students to contribute positively towards European leadership in science, technological innovation, and sustainable digital future, as well as collaboration between academia, industry, and society in the rapidly changing quantum world.

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