Quantum Computing and the Future of ICT : I SEE teaching-learning module

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Quantum Computing and the Future of ICT

Teaching-learning module; 20 August 2019

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I SEE

It's your time to imagine the futures

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Overview of the Module

This module aims to develop upper secondary school students' future-thinking skills, imagination and agency with regard to societal issues in the context of quantum computing and the future of ICT. The duration of the full module is ca. 20 teaching hours, but it consists of distinct activities, which can also be applied individually to teach separately about computers, quantum mechanics, systems thinking, and scenario building.

Students learn about the historical development of computing, its connection to societal development, and the complexity of predicting the technological future. By studying different numeral systems, logical operations, algorithms and hardware components, students prepare themselves to make the fundamental shift in computing paradigm and to replace bits with qubits. Learning quantum properties using the "spin first" approach paves the way for understanding quantum algorithms and thereby the superior computing power and future opportunities offered by quantum computers.

Throughout the module, students work on their "future projects" on a complex topic of their choice. To facilitate students' problem-solving, they carry out activities in creative thinking, defining and mapping the problem, systems thinking, and scenario building. They employ three different ways of futures thinking to develop a variety of scenarios. At the end of the module, students present their projects – i.e. their ICT-based solution to a societal issue – using the empowering "backcasting" method.

Summary

The Timetable of the First Finnish Module Implementation

Day 1
Lecture: The history, present and future of ICT
Getting to know each other
Starting the course projects
Creative thinking
Electronic computer
Information as bits

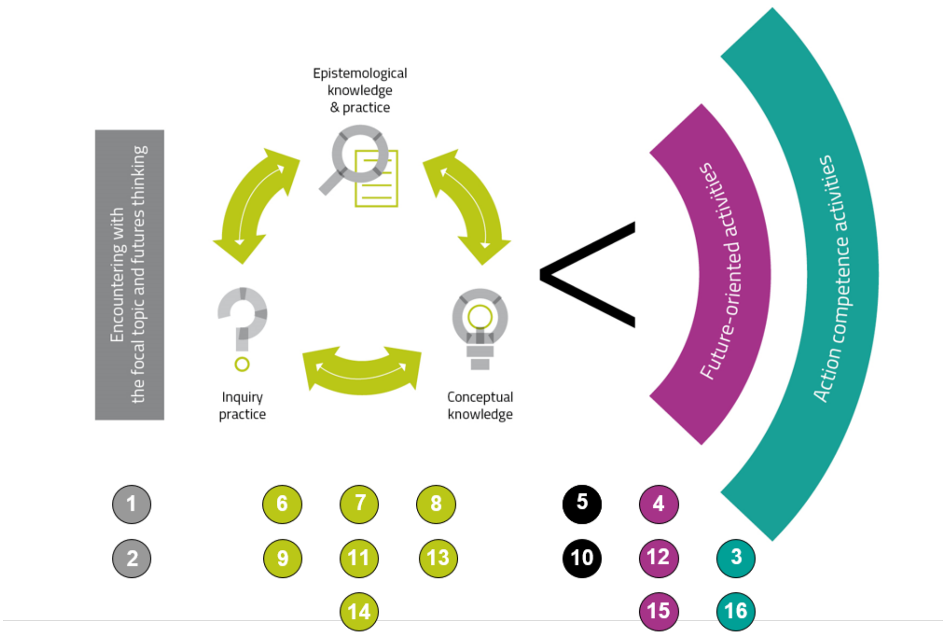
Day 2
Components of a computer
Operations of a computer
Algorithms
Algorithms: live demo
Back to the future

Day 3
Introduction to quantum mechanics
Quantum exercises
Defining a problem & systems thinking

Day 4
Quantum computing
Deutsch's algorithm
Scenarios
Backcasting

Last meeting
Welcoming words
Presentations of the final projects

Activities in the Overall Module Structure



Most of the activities in this module are in more than one activity category. Only the primary categories are presented in this picture.

It's your time to imagine the futures

Pre-Essay Before the Implementation

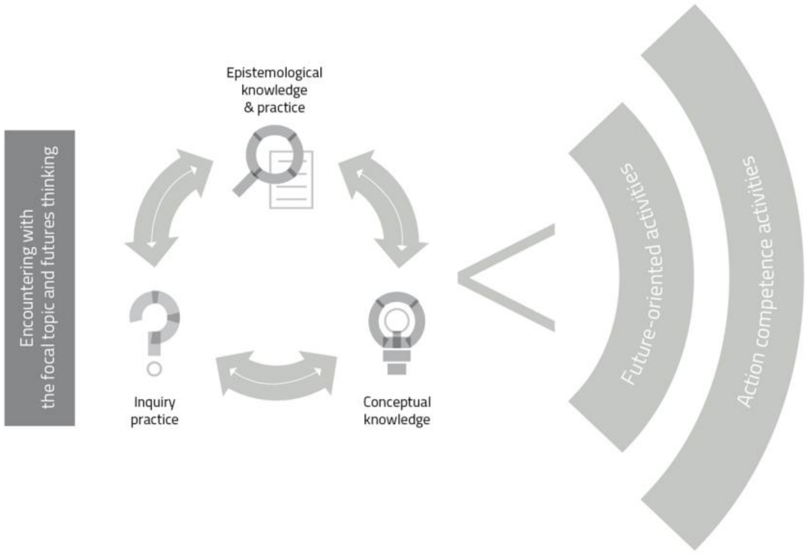
If the teacher wishes, they may give students a pre-assignment, in which students are asked to write an essay about a summer day in 2035 (or another year about 20-25 years from now). The aim of the assignment is to make students' assumptions, hopes and fears about the future explicit.

In the *Back to the Future* and/or *Backcasting* activities, students are guided to revise their previously written future visions in light of the new knowledge and perspectives acquired during the module, and see how their ideas have changed.

The assignment can be found here (word & pdf).

ACTIVITY 1: Overview Lecture
The History, Present and Future of ICT

<table>
<tr><td>Position in the module

Encountering with the focal issue</td><td>

This activity consists of an overview lecture on the topics of ICT and quantum computing. The lecture aims to introduce the conceptual and epistemological knowledge that will be developed and deepened in the module.
The lecture introduces the evolution of ICT and computing power throughout history and speculates on their possible future development. It guides students to contemplate their own attitude towards technology and shows alternative ways of seeing it. The activity provides a good opportunity to discuss the role of technology in changing our society and working life. Quantum computing is introduced as a possible future step in the progression of ICT and computing power. </td></tr>
<tr><td>Goals</td><td>conceptual/epistemological

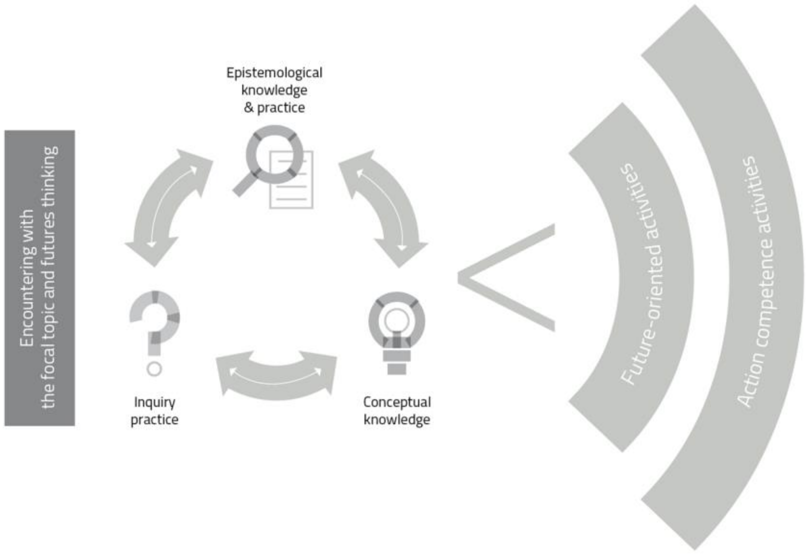
to begin to understand the role of ICT in society
to get an overview of technological development in history
to begin to get an idea of what quantum mechanics and quantum computing mean
to learn to identify prevalent assumptions and paradigms about working life in our society
to move from the idea of a single future to the idea of a plurality of futures

social/emotional

to learn to face the future more open-mindedly
to broaden one's imagination about the future of the job market and working life
</td></tr>
</table>

	• to begin to broaden one's imagination about possible future STEM careers
Time required	About 45 min for the lecture + 15 min for discussion
Materials	We encourage the teacher to create their own slides and build the lecture from scratch. This way the end result will be more authentic. The activity is a good opportunity to ask an expert (e.g. a researcher) to give the lecture. They can be asked to organise the lecture as they wish, keeping in mind, however, the importance of engaging the students during the presentation. A good overview lecture introduces, for example, the following topics: ➢ What does "computing" mean? ➢ How has computing power evolved over time? ➢ Pros and cons of technological development ➢ Is Technology good or bad per se? ➢ How has technological development affected the job market? What possible changes will there be in the future? ➢ Is the change in the job market good or bad per se? ➢ What is quantum mechanics? ➢ What is quantum computing? ➢ What could be the implications (for the job market, society, etc.) of developing quantum computing technology in the future?
Teaching methods	***Interactive lecture*** Small group discussions can also be used to make the lesson more engaging.
Other notes	In the first Finnish I SEE module implementations, the overview lecture was arranged as an expert lecture. The experts were researchers in computer science.

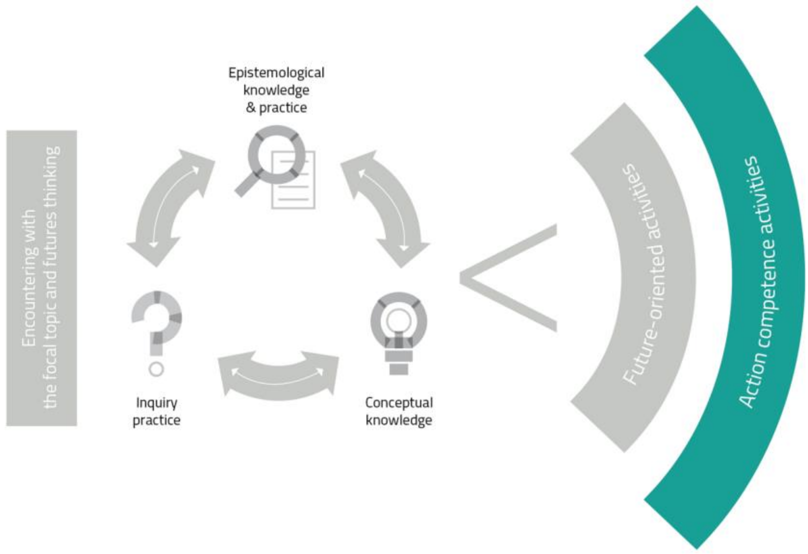
ACTIVITY 2: Introduction to Futures Thinking

Position in the module ***Encountering with the focal issue***	 The activity serves as a light introduction to the field of Futures Studies and the thinking used in that field. In the activity, students respond to a test about their assumptions about the future. Students’ responses are discussed together to understand how the future can be thought of in multiple different ways, and why some assumptions may be more effective than others in understanding, anticipating and influencing the future.
Goals	***conceptual*** • to identify the key ideas and approaches in Futures Studies • to identify the assumptions commonly employed in Futures Studies to anticipate futures • to understand the plurality and complexity of futures • to understand the difference between prediction and anticipation ***epistemological*** • to understand the fundamental role of assumptions in forecasting • to identify and question one’s assumptions about the future ***social/emotional*** • to evoke interest in Futures Studies and futures thinking • to motivate students to develop their futures thinking and to conceive alternative plausible futures with their peers • to motivate students to prepare themselves for the future by developing alternative scenarios

	• to empower students with the idea that the multiplicity and indeterminacy of the future gives us room to influence it
Time required	30-40 minutes
Materials	The activity uses an adapted version of "The Futurist Quiz" developed by Prof. Peter Bishop and available at teachthefuture.org. The adapted version of the Quiz contains the following questions and their multiple-choice options: 1. Can we know the future? (yes/no) 2. Are there one or many futures? (one/many) 3. What is the longest period that we can usefully forecast? (1-2 years/3-5 years/5-10 years/10-25 years/more than 25 years) 4. Is the future already determined? (yes/no) 5. Which influences the long-term future the most? (Trends/Events/Choice/All influence the future equally) 6. Which influences the long-term future the most? (Demographics/Environment/Technology/ Economy/Governance/Culture/All influence the future equally) 7. Which is the most serious cause of forecasting errors? (Lack of information/The forecaster's assumptions/External events) 8. Telling stories about possible but unlikely futures is useful. (Agree/Don't know/Disagree)
Teaching methods	***The Futurist Quiz*** Students are first asked to respond to all of the multiple-choice questions (see Materials) using an online voting system such as Mentimeter, Socrative or Presemo. They can discuss among themselves while responding, but all students should send their individual responses. ***Discussing results*** After all students have finished responding, the teacher goes through all of the questions revealing students' responses one question at a time. Students' responses are anonymous, but the teacher can ask volunteers to explain and rationalise their response. The teacher should stress that the quiz is about assumptions and there are no wrong answers, but still the field of Futures Studies considers some assumptions more effective than others in understanding, anticipating and influencing the future. The teacher gives examples and encourages the students to come up with their own arguments.

Tips for teachers from previous classroom experiences	This activity has worked well. The teacher has to be sensitive and careful not to judge students' views. The students may not be ready to engage in deep discussion this early in the module, particularly as they don't necessarily know the other students yet.
Other notes	The activity uses an adapted version of "The Futurist Quiz" developed by Prof. Peter Bishop and available at teachthefuture.org.

ACTIVITY 3: Future Projects

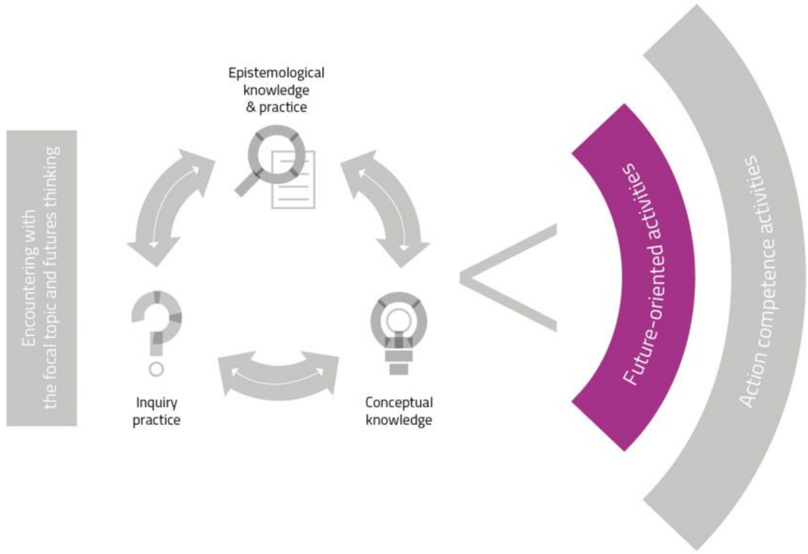
Position in the module ***Action competence activities*** ***Future-oriented activities*** ***Encountering with the focal issue***	 The future projects activity is planned to run through the whole module. These instructions are meant to be given to students at the beginning of the module so they can start to think of interesting topics and applications right away. During the module, the teacher supports the students in doing the projects that are presented and commented on at the end of the module. In this activity, students are given the overview of the phases of "future projects". These will form a common thread for the whole module. Next, they are asked to choose a topic they are interested in. After the activity, the teacher will put the students into groups of about four according to their interests.
Goals	***conceptual*** • to recognise the steps of defining a problem • to become acquainted with the basics of scenario building ***epistemological*** • to get an overview of the epistemic process of approaching a problem within a complex system ***social/emotional*** • to focus on a topic which is personally relevant • to start thinking about personal and professional visions of the future and their relatedness • to start realising one's own potential in taking action to change the future

	• to start developing ownership of one's own future
Time required	20-30 minutes
Materials	***Slides* (ppt & pdf)** The lesson and slides consist of two parts: Phases of Future Projects; and Topics. The part Topics contains instructions for students' individual work. ***Topics printout* (word & pdf)** Students are asked to write down topics they are interested in. The teacher may use the printout to collect the topics for grouping the students.

Teaching methods	***Lecture***
	
	The teacher should introduce the phases of the "future project" and students should be given a chance to ask questions.
	
	Phases of Future Projects
	
	1. Topics and forming groups
	2. Defining the problem
	3. Mapping the system
	4. Developing scenarios
	5. Backcasting
	6. Preparing presentations and videos
	7. Presenting the projects
	
	Individual work
	
	Students are asked to choose topics that interest them. Ideally, students do this alone and not together with their friends. In the optimal case, student groups are as inhomogeneous as possible, and based only on the students' genuine interests.
	
	Instructions to students:
	
	• Choose a topic
	    ○ ... which involves general challenges, problems, big questions
	    ○ ... which interests you.
	• Write it down on a piece of paper.
	• We will form groups according to your interests.
	    ○ Groups of four.
	
	After collecting the completed topic papers, the teacher groups the students based on their interests. If there are some students who do not have anything in common with others, then the teacher must speak with those students and let them choose a group to join based on the topics of the groups.

Tips for teachers from previous classroom experiences	It might be difficult for students to connect quantum computing to their projects. The teacher should encourage them to choose topics related to quantum computing – or at least ICT.
Other notes	This activity forms a common thread for the whole module, and because of this, the activity should take place at the very beginning of the implementation. The rationale behind this solution is that all future-scaffolding and action competence skills are most effectively studied in the context of students' own interests and projects.

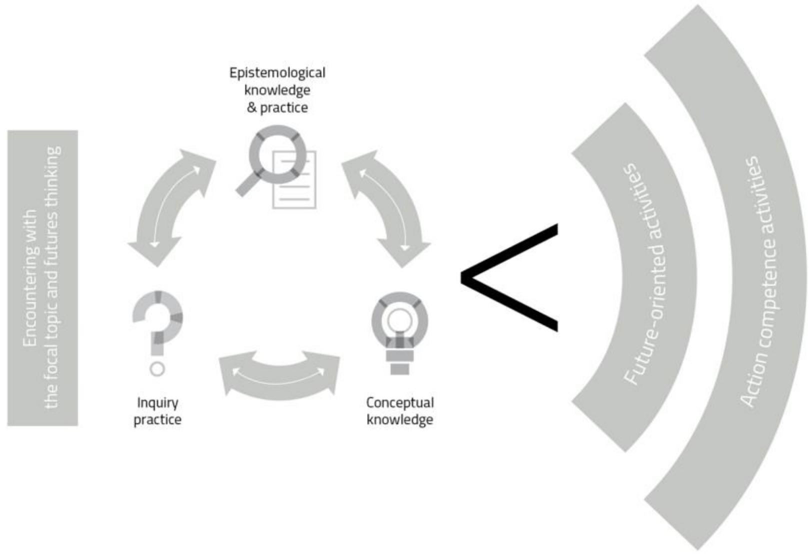
ACTIVITY 4: Basics of Creative Thinking

Position in the module ***Future-oriented activities***	 This activity highlights the importance of creativity in futures thinking and action competence. It shows how even experts struggle in predicting the future and why rigid and formal ways of thinking often lead to bad predictions. The aim is to encourage students to use their imagination and to hold on to their dreams and creativity. At the beginning of the activity, three components of creativity are introduced: expertise, motivation, and creative thinking skills. The paradoxes of creative work are discussed and old, incorrect predictions contemplated. The predictions are chosen from the field of technology and they also connect the activity to technological development. Finally, students are introduced to some blocks and blockbusters to creativity and asked to rethink their own future scenarios. Taking this new, more open-minded perspective to their "future projects", they may see new possibilities in their own scenarios.
Goals	***conceptual*** • to identify the key concepts and components of creative thinking • to identify the blocks and blockbusters to creativity (also in their own thinking) • to recognise the role of assumptions and values behind predictions • to understand that making predictions is difficult even for experts • to move from the idea of a single future to the idea of a plurality of futures ***epistemological*** • to learn to point out how all thinking (incl. scientific) and predictions are based on assumptions, values and cultural factors • to identify assumptions

	• to practise creative thinking methods in making predictions within their own topic ***social/emotional*** • to practise groupwork in creative thinking • to broaden their imagination about the chosen topic of interest
Time required	30-45 minutes
Materials	***Slides* (ppt & pdf)** The lesson and slides consist of four parts: Creative Thinking; Paradoxes of Creative Work; Making Predictions; and Blocks and Blockbusters to Creativity. The part Blocks and Blockbusters to Creativity also contains the instructions for the groupwork.
Teaching methods	***Interactive lecture*** The discussion on the contents of the lesson is fostered by the teacher. In the parts Paradoxes of Creative Work and Blocks and Blockbusters to Creativity, the teacher should introduce different sides of the phenomena to facilitate a comparison of the different points of view, and let students contemplate the information freely. ***Groupwork*** At the end of the lesson, students are asked to consider their own "future projects" in the light of what they have learnt. Students can follow the whole lesson in the project groups. If the groups have not been formed yet, students need to be grouped into project teams at this point at the latest. *Instructions to students:* Think about your own topic and problem in it: • What assumptions do you find? Question them! • Are there any rules? Can you break them? • What kind of relationship is there between logic and intuition? • Is there a fear of failure in your solutions? Could you take more risks?
Tips for teachers from previous classroom experiences	As the teacher is aware of the topics students have chosen for their projects, they can help students in the groupwork discussion by asking questions to help students to develop their ideas.
Other notes	• If the module needs to be shortened, this activity can be omitted. The purpose of the activity is to support students' imagination and creativity when developing their "future projects", but it may be enough to do it implicitly by inspirational supervision when students work on their projects.

	• The ideas presented in this activity deal with basic and common techniques of creative thinking that some teachers and students may already have studied elsewhere.

ACTIVITY 5: Electronic Computing

Position in the module ***Bridge between science ideas and future***	 In this activity, students familiarise themselves with the historical development of computing. The aim is to show how rapid the development has been and help them to reflect this knowledge in their scenarios of the technological future. It is also highlighted how the development of computing has been connected with the development of society. The main part of the activity is the video of *Crash Course Computer Science* about electronic computing. It tells the history of computing technology from electro-mechanical relays to vacuum tubes and transistors. Because of the then-current technology, classical computers used two states to express information.
Goals	***conceptual*** • to become familiar with the history of computing and computing technologies • to understand the connection of computing technology and the use of the binary system in computing • to learn to recognise computers and computer-based devices in everyday life • to get to know some of the applications of modern computing and to understand their enormous implications for our lives ***epistemological*** • to realise the power computing gives to science and businesses • to get to know computers' usage in simulating and modelling

	social/emotional • to broaden one's imagination about the possibilities for the future development of ICT • to broaden one's imagination about possible future STEM careers in physics and electronics
Time required	• Altogether 30-45 min • The video's length is 10 min 43 s
Materials	***Slides* (ppt & pdf)** The slides consist of four parts: Modern Computer; History of Electronic Computing; Electronic Computer; and Digital Computer. ***Video*** In the part History of Electronic Computing of the slides, there is a link to the video: *Electronic Computing: Crash Course Computer Science #2:* https://youtu.be/LN0ucKNX0hc
Teaching methods	***Small group discussions*** The part Modern Computer can be used for small group discussions (takes about 10 minutes). Students are asked to think about what a computer is in their opinion: • What is a computer? • What counts as a computer (i.e. what can be called a computer)? • Where are computers used in our society? After small group discussions, the ideas of the groups are collected and discussed together. ***Interactive lecture*** In the part History of Electronic Computing, watch the video *Electronic Computing: Crash Course Computer Science #2* together. Students are asked to pay attention to computers' • size; • speed; • users; • applications. Their observations should be discussed after watching the video. In the part Electronic Computer, the teacher goes through some applications of electronic computers. On the slides, there are some examples (molecular simulations,

	genetics, medicine, mobile phones) of the fields and devices that make use of computers. The teacher may also choose their own topics and applications here.
Tips for teachers from previous classroom experiences	• This activity bridges the past and present, and leads towards future-oriented activities. • Before teaching, remember to check the availability of the links and videos you are going to use. • To make the lesson more engaging, the teacher may split the time into 5-10 min periods with student discussions.
Additional resources	***videos:*** • Computers in society: https://youtu.be/O5nskjZ_GoI • Applications of computers: https://youtu.be/ac7T3ocg9gk • High-performance computing in science: https://youtu.be/VqqN94Bdvak • High performance computing in business: https://youtu.be/A_i5kOlj_UU ***other resources:*** • History of computer science: https://en.wikipedia.org/wiki/History_of_computer_science • History of computing: https://en.wikipedia.org/wiki/History_of_computing • History of computing hardware: https://en.wikipedia.org/wiki/History_of_computing_hardware
Other notes	• Electronics is not a central topic of the module. If the teacher wants to shorten the module, the electronics part can be dropped. However, learning the basic idea of bits and the binary system is essential for the rest of the module. • In this activity, it would be beneficial to highlight the significance of computers in our society and the role they have had in history. This point can also be connected to the future development of society.

ACTIVITY 6: Information as Bits

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Position in the module

Conceptual knowledge

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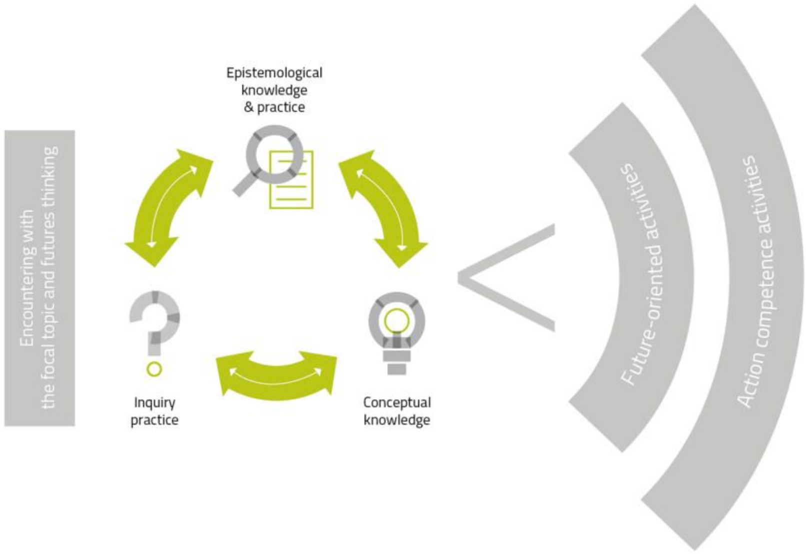

This activity introduces the idea of different numeral systems. Earlier, students learnt that computers use binary numbers in presenting information. Now they are asked to make the leap from the customary decimal numeral system to the binary numeral system. This shift gives them the ability to "think like a computer" and prepares them to understand the logic of qubits later on.

At the beginning of the activity, the basic idea of numeral systems is introduced. Students are used to the decimal numeral system that is taken as an example system. After this, the binary numeral system is introduced, and conversions from decimal to binary (and vice versa) and basic algebraic operations on binary numbers are taught. After the lesson, students get to practise the conversions and calculations by themselves.

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Goals

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<td>

conceptual

- to understand the concept of a numeral system
- to learn to convert numbers from the decimal system to the binary system, and vice versa
- to learn to make the basic algebraic operations with binary numbers
- to understand the amount of information presented by bits

epistemological

- to shift one's thinking from the customary decimal numeral system to the binary system, and to understand that they are just ways of representing numbers

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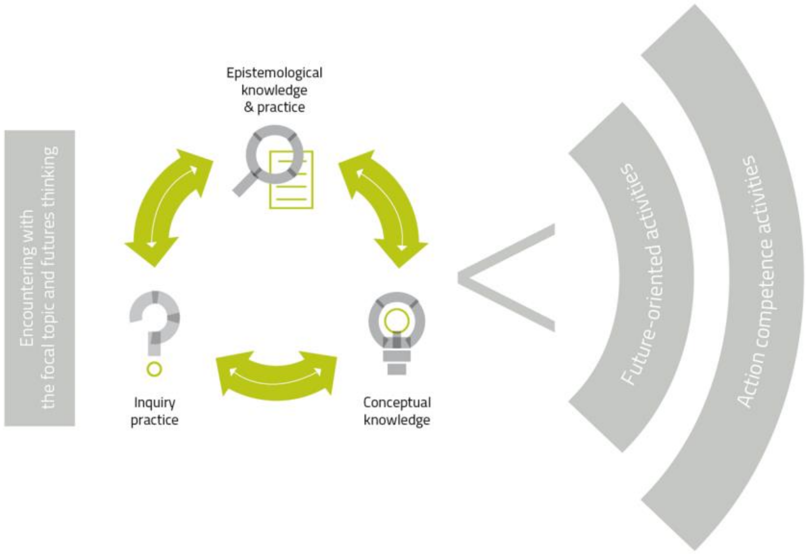
</table>

Time required	• Going through the material (and possible additional examples of algebraic operations) takes 45-60 min • Doing binary exercises takes another 45-60 min
Materials	***Slides* (ppt & pdf)** The lesson consists of four parts: Decimal Numeral System; Binary Numeral System; Arithmetic Operations in Binary; and Amount of Information in Bits. ***Exercises*** Printout: Binary Exercises (word & pdf) The exercises cover the following topics: • *Binary numeral system:* conversions from binary to decimal and from decimal to binary • *Addition and subtraction* • *Multiplication and division*
Teaching methods	***Interactive lecture*** The discussion on the contents of the lesson is facilitated by the teacher. Optimally, the teacher could show more examples of operations than is provided in the slides. ***Exercises*** Students may do exercises either individually or in groups. The exercises also contain instructions for doing the required calculations. The correct answers can be found at the end of the printout.
Tips for teachers from previous classroom experiences	The time the exercises take can vary considerably. The teacher should be prepared to give some additional exercises for the students who progress fast. It is also good if the teacher has some additional help (an assistant) to support the more slowly progressing students.
Additional resources	***videos:*** • Boolean logic: https://youtu.be/gI-qXk7XojA • Binary system & algebraic operations: https://youtu.be/1GSjbWt0c9M ***other resources:*** • Binary numbers: https://en.wikipedia.org/wiki/Binary_number

Other notes	The module can be shortened by cutting out some of the electronics activities. If this activity is omitted, the binary numeral system and the conversions between the binary and decimal systems have to be discussed elsewhere, as they are important later on in the module.

ACTIVITY 7: Components of a Computer

Position in the module ***Conceptual knowledge*** ***Inquiry practice***	 As students may be more familiar with mobile phones, tablets, and laptops, they might see a computer as a black box; both the inner logic and the components can be unfamiliar to them. The goal of this activity is to show students what is inside a computer; a computer has macroscopic parts that can be handled. Ideally, students get to open up desktop computers by themselves, and at the same time the teacher talks about the purpose of the main components. The activity can also be implemented so that only the teacher opens up a computer and students follow, or by watching a video.
Goals	***conceptual*** • to get to know what kind of components there are inside a computer • to understand that a computer is not a black box • to become familiar with the basic functions of a motherboard, a CPU, RAM, expansion cards, a power supply unit, an optical disc drive, and a hard disk drive ***social/emotional*** • to raise interest in electronics • to make computers as devices more accessible

Time required	The time required depends on how the activity is implemented. • If students get to open up computers by themselves or in small groups, plenty of time should be reserved for the activity, say **1-1.5 hours**. • If the teacher opens up a computer and introduces the components to students, the time requirement is **30-60 min** (depending on how detailed an introduction the teacher wants to give for each component). • If only a video clip of opening up a computer is watched together in the class, the time needed is only **the length of the video + 20 min** for discussion.
Materials	***Slides* (ppt & pdf)** The slides begin by focusing on the Modern (Desktop) Computer and an overview of its Hardware Components. The rest of the slides introduce the • Motherboard • Processor • Random-Access Memory (RAM) • Expansion Cards • Power Supply • Optical Disc Drive • Hard Drive ***Computers*** In the optimal situation, students get to open up old desktop computers. For this there should be one old computer that is no longer used for each student/group. ***Video*** *Components of a computer:* https://youtu.be/4eNTlwnnhss There are plenty of alternative videos about the components available on YouTube. The teacher may choose the one they like best.
Teaching methods	***Option 1: Groupwork*** Students get to open up computers by themselves or in small groups. The teacher asks them to find and detach certain components and explains their function. ***Option 2: Demonstration*** The teacher opens up a computer and introduces the components to students. ***Option 3: Video & discussion*** A video clip of opening up a computer is watched together. The content should be discussed afterwards and perhaps summarised by going through the slides.

Tips for teachers from previous classroom experiences	• Some students may be familiar with the components of a computer, and some students may have opened up computers before. On the other hand, for some students everything in the lesson can be new. This imbalance should be somehow addressed. • The teacher needs to tell students to stop working with the computers while the components are introduced. Otherwise, it can be difficult for them to focus on the teaching.
Additional resources	***videos:*** • CPU: https://youtu.be/FZGugFqdr60 • RAM: https://youtu.be/fpnE6UAfbtU ***other resources:*** • Computer hardware: https://en.wikipedia.org/wiki/Computer_hardware
Other notes	This activity is not essential for the rest of the module. The idea is only to demonstrate the electronic side of computers and make them more approachable to students.

ACTIVITY 8: Operations of a Computer

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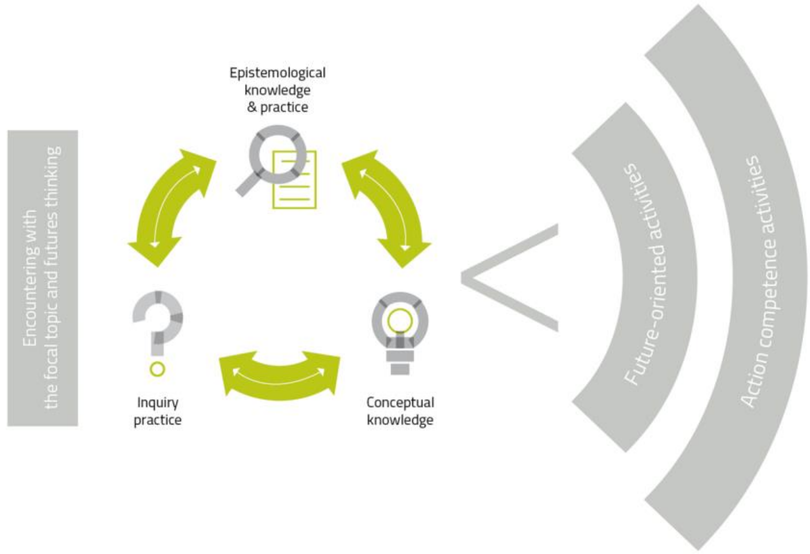
Conceptual knowledge</td><td>

Earlier students have learnt about basic computing technology: that computers' functioning relies on transistors and because of that they use binary numbers to present information. This activity shows how we get from individual transistors to logic gates, and can build up circuits that perform more complicated operations.
The activity starts by introducing the basic idea of transistors as electronic switches. It is then shown how logic gates can be built by combining transistors. The logical operations TRUE, AND, OR, NOT, and XOR are introduced. As examples of logic circuits the half and full adders are introduced. To make a connection to the higher functionality of a computer, a CPU's and computers' most basic logic is recapped. </td></tr>
<tr><td>Goals</td><td>conceptual

to become familiar with the basics of the functioning of transistors
to become familiar with Boolean logic and learn to use truth tables
to learn to make truth tables for logic gates
to understand the function of the logic gates AND, OR, NOT, and XOR
to understand the idea of how the basic logic operations build up the complicated functioning of a computer

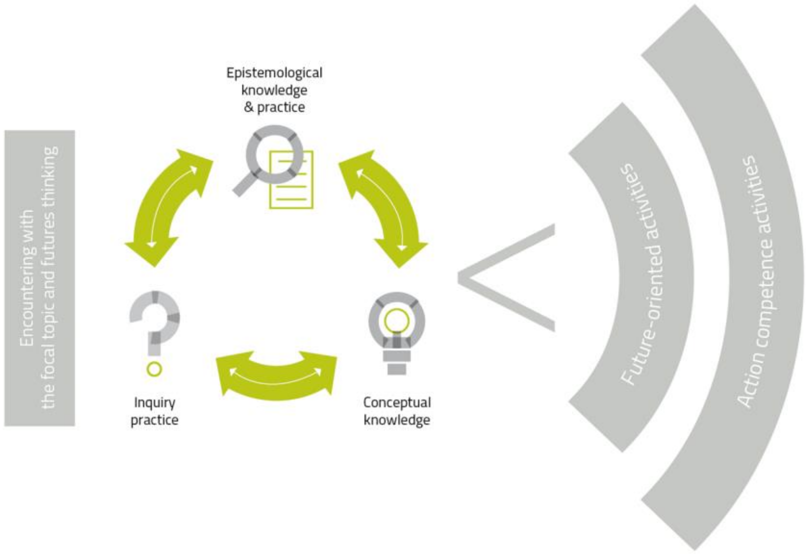
epistemological

to practise logical reasoning and argumentation
</td></tr>
</table>

Time required	45-60 min
Materials	***Slides*** **(ppt & pdf)** The slides consist of four parts: Transistors; Logic Gates; Logic Circuits; and Central Processing Unit. ***Optional demonstration equipment*** If possible, the teacher could introduce some real electronic components (especially transistors) to students.
Teaching methods	***Interactive lecture*** Discussion on the contents of the lesson is facilitated by the teacher. Some video clips and demonstrations may be used to make the lesson more versatile. Optimally, the teacher could show more examples of operations than is provided in the slides.
Tips for teachers from previous classroom experiences	It is important to check that students remember how binary sums are calculated.
Additional resources	***videos:*** • Transistors: https://youtu.be/7ukDKVHnac4 • Water analogy for a transistor: https://www.youtube.com/watch?v=8f3l8KaVcBg • Boolean logic and logic gates: https://youtu.be/gI-qXk7XojA • How computers calculate: https://youtu.be/1I5ZMmrOfnA ***other resources:*** • Boolean algebra: https://en.wikipedia.org/wiki/Boolean_algebra • Logic gates: https://en.wikipedia.org/wiki/Logic_gate • Processor 1: http://www.righto.com/2017/03/inside-vintage-74181-alu-chip-how-it.html • Processor 2: http://www.righto.com/2017/01/die-photos-and-reverse-engineering.html

Other notes	The aim of introducing logic gates and circuits is to prepare students for algorithmic thinking. In Finland, some students may have encountered Boolean algebra on mathematics courses but it is not likely that they would know more than the very basics. A more thorough understanding of logic gates will be essential in the quantum computing part of the module.

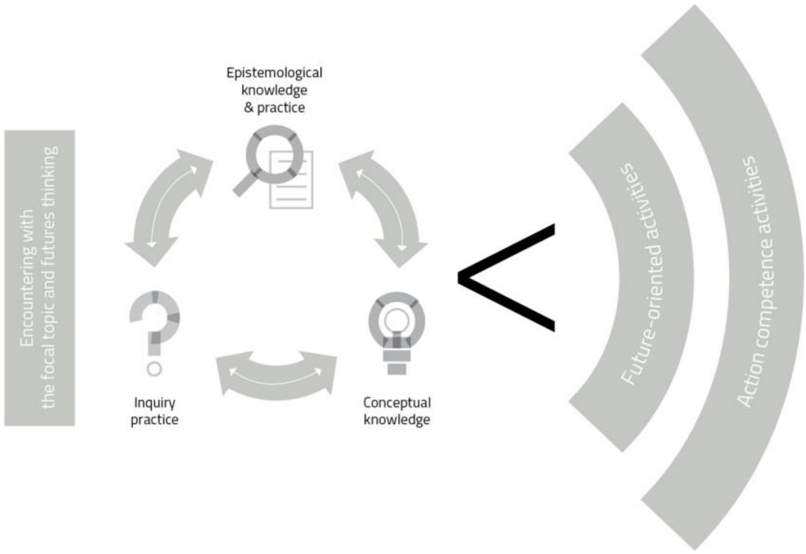
ACTIVITY 9: Algorithms

Position in the module ***Conceptual knowledge***	 This activity introduces the basic idea of algorithms through a couple of exercises. It illustrates the simple logic that computers use in solving problems. The connection between the most basic logic of logic gates and the higher level functionality of a computer is made clear by examining some basic examples of algorithms. At the beginning of the activity, algorithms are introduced as recipes given to a computer. After the short introduction, students get to play two games that illustrate the idea of algorithms. The tic-tac-toe exercise shows how a computer plays the game. The battleships exercise demonstrates three different search methods that computers often use.
Goals	***conceptual*** • to understand the concept of an algorithm • to understand the idea of a computer's logic in executing an algorithm • to become familiar with some simple search algorithms ***social/emotional*** • to raise interest in electronics and related careers
Time required	45-60 min

Materials	***Slides* (ppt & pdf)** The slides consist of three parts: Algorithms; Tic-tac-toe; and Battleships. ***Printouts*** • Intelligent-Paper (tic-tac-toe; word & pdf) • Battleships-Searching-Algorithms (pdf) ○ parts *A Linear Searching Game, A Binary Searching Game*, and *A Search Game using Hashing* The printouts contain the instructions to students for playing the games.
Teaching methods	***Interactive lecture*** At the beginning of the lecture, the teacher introduces the basic idea of algorithms. Demonstrations or videos may also be used in doing this. ***Games*** Students are organised into pairs for playing the games. **Tic-tac-toe** *Instructions to students:* Let's play tic-tac-toe in pairs. • One of you play normally. • The other plays according to the instructions on the paper. Can you play not thinking about your moves? Can you play not knowing the rules? **Battleships** *The instructions for playing the game are in the printouts.*
Tips for teachers from previous classroom experiences	• The time playing the games (especially Battleships) can vary considerably. The teacher should be prepared to give some additional exercises for the students who finish the games quickly. • Some of the students may have a lot of programming experience and for them the activity can even be frustrating. There are numerous good games and activities about algorithms available on the internet. If the teacher knows beforehand that there are students who are advanced in programming and algorithmic thinking, they are encouraged to collect some additional materials for those students.

Additional resources	***videos:*** • simple algorithms 1: https://youtu.be/l26oaHV7D40 • simple algorithms 2: https://youtu.be/rL8X2mlNHPM ***other resources:*** • Algorithms: https://en.wikipedia.org/wiki/Algorithm
Other notes	• In this activity, making connections to linear thinking is possible. Computers' way of solving problems can be regarded as schematic and formal – which is the opposite of what thinking about futures requires from students. • ***Source of the games:*** Computer Science Unplugged (www.unplugged.canterbury.ac.nz)

ACTIVITY 10: Back to the Future

Position in the module ***Bridge between science ideas and future*** ***Future-oriented activities***	 This activity builds a bridge from history to the future in the field of ICT. The aim is to show how rapid the technological development of the last few decades has been and that the changes have had wide effects on the whole of society. Furthermore, the activity illustrates the difficulty of making predictions and shows how initial assumptions may lead to erroneous forecasts. Students are encouraged to consider the limitations of their own thinking and broaden their imagination about the future. The activity begins with analysing old documentaries about ICT from the 1980s and 1990s, and exploring fictional predictions of the world in 2015 from the 1980s. The differences and similarities to the present are discussed and their reasons contemplated. At the end of the activity, students are asked to think again about their own future scenarios and consider their previously made predictions in the light of the newly acquired knowledge.
Goals	***conceptual/epistemological*** • to become familiar with the historical development of ICT; especially its status in the 1980s and 1990s and the rapid development since then • to recognise the multidimensional impacts of technological development on society – and societal development's impact on technology • to learn to apply the ideas of creative scenario thinking in the field of ICT • to understand the challenges of predicting/ forecasting in the field of ICT • to understand the role of assumptions in making predictions • to move from the idea of a single future to the idea of a plurality of futures

	social/emotional • to learn to share different points of view about technological development • to raise interest in futures thinking through a concrete and relevant context • to broaden one's imagination about the futures of ICT • to grasp the feeling of agency regarding the development of ICT and the student's own future • to facilitate creative thinking and the collective process of scenario building and envisioning the future of ICT
Time required	1.5 hours in total.
Materials	***Slides* (ppt & pdf)** The lesson and slides consist of four parts: History of ICT; "Back to the Future Part II", 1989; Scenarios; and A Summer Day in 2035. The slides include the instructions for the student work and the links to the video clips (also listed below). ***Video clips*** History of ICT • Computers and internet in the 80s & 90s (in Finnish): https://youtu.be/Z3LomahS6nk • Internet magazines in the 80s (in English): https://youtu.be/X84muuaySVQ • Computer Chronicles: Home PCs (1990) (in English): https://youtu.be/m-DHVClSvTo • The 90s Kids Guide to the Internet (in English): https://youtu.be/mfMrVKnGzwg "Back to the Future Part II", 1989 • Downtown: https://youtu.be/d68yRIE9OvQ • Café 80s: https://youtu.be/2zYu_TxIFDM • Chase: https://youtu.be/TkyLnWm1iCs • At home: https://youtu.be/5ztwns5PkJY ***Online whiteboard (Flinga):*** https://edu.flinga.fi/s/EJJE2JJ
Teaching methods	***Interactive lecture & groupwork*** At the beginning of the activity, students are put into small groups where the topics are examined. The teacher facilitates the discussions throughout the lesson. History of ICT Watch together an old video clip/clips about ICT from the 80s or 90s.

	The students are asked to
	• take notes while watching the video
	• discuss in the group the following points:
	  ○ What has changed after filming the video?
	  ○ How well did the interviewees predict the future?
	
	"Back to the Future Part II", 1989
	
	Watch together a video clip/video clips from the movie "Back to the Future Part II" made in 1989.
	
	The students are asked to
	• make notes while watching the video about…
	  ○ What similarities to the present do you notice?
	  ○ What differences to the present do you notice?
	• discuss their observations in groups:
	Place your observations on the online whiteboard (Flinga).
	• discuss further:
	  ○ What was missing in the prediction?
	  ○ What predictions hit the mark?
	  ○ What predictions missed the mark?
	  ○ Can you think of any reason for this?
	
	Scenarios
	
	Students are asked to consider their written future scenarios in the light of the new ideas they got from the discussions.
	• Students have to think again about their own scenarios.
	• They are asked to consider:
	  ○ How much have things changed from the present?
	  ○ What is different from the present?
	  ○ What is similar to the present?
	
	A Summer Day in 2035
	
	This part can be left as homework for students. Students are asked to reread their future scenario essays and modify/comment on them.

Tips for teachers from previous classroom experiences	• Especially societal dimensions in the video clips should be emphasised by the teacher to make sure they are noticed: for example, the gender polarisation ("only boys need computers"). • This activity can create good discussions and it seems to be fun for the students.

Other notes	• This activity offers a good opportunity to link the conceptual and future dimensions of the module. The teacher should keep this connection in mind when planning their implementation of the activity. • This activity was inspired by the activity "View from the Past" obtained from teachthefuture.org.

ACTIVITY 11: Introduction to Quantum Mechanics

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Position in the module

Epistemological knowledge and practice

Conceptual knowledge

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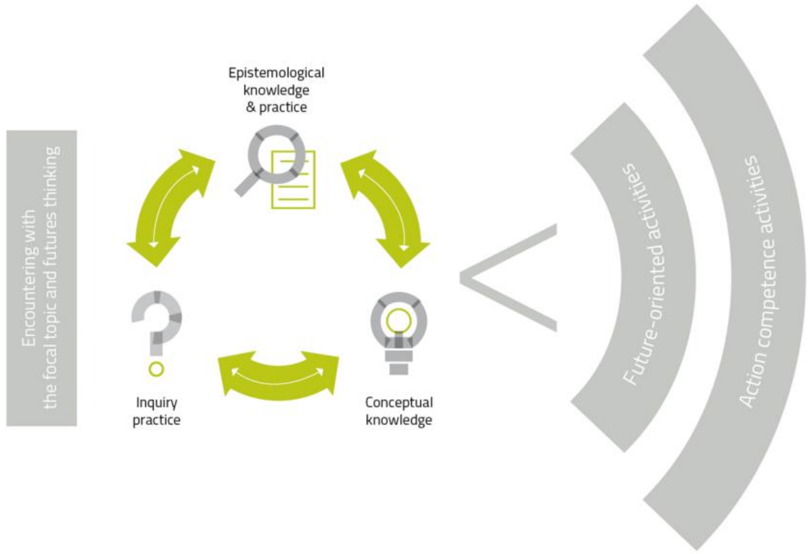

This activity introduces the core concepts of quantum mechanics and quantum computing. The introduction is done using a simplistic description of synthetic experiments (the Stern-Gerlach experiment), and the aim is to make quantum mechanics as approachable as possible without losing scientific accuracy. Students are encouraged to abandon the classical way of thinking and step from causal logic to making probabilistic predictions.

The introduction to quantum mechanics begins by noting that an electron has certain binary properties (spin). Using the Stern-Gerlach experiment, it is shown how these binary properties manifest themselves in measurements, and the concept of superposition and quantum mechanical probability interpretation are introduced. Students also learn to express simple quantum mechanical systems mathematically using the so-called Dirac notation.

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Goals

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conceptual

- to understand the concepts of a vector and superposition of vectors
- to become familiar with the concept of a state vector
- to become familiar with the ideas of the probability interpretation and normalisation of a state vector

epistemological

- to discuss and cross the epistemological barriers between classical and quantum realms
- to realise that physics problems do not always have a definite solution

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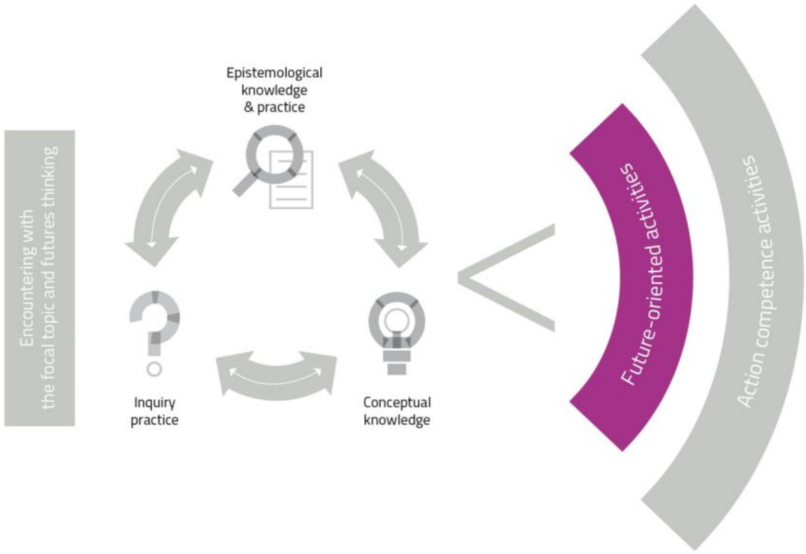
	social/emotional • to learn to tolerate uncertainty in solving quantum physics problems • to arouse students' curiosity and interest in quantum phenomena • to get involved personally in group and collective discussions about quantum physics • to adopt quantum physics concepts in students' own vocabulary and discuss different points of view • to enlarge one's imagination about possible future STEM careers related to quantum physics
Time required	*The teacher can choose if they want to teach using only the slides or also make use of the video lessons.* • If the teacher wants to lecture using only the slides, about **an hour** should be reserved for the lesson. • The length of the videos is altogether about **27 minutes** (7:18 min; 11:2 min; 8:23 min). The teacher should be prepared to stop the video every now and then, and engage students in discussion. Altogether, the discussions are expected to take **at least 15 minutes**. If the discussions are arranged in small groups, **a longer discussion time** should be reserved. • Doing quantum exercises takes about **an hour**. They can also be left as homework or be done in a separate exercise session.
Materials	***Slides* (ppt & pdf)** The lesson and slides consist of four parts: General Introduction; Introduction to Electron's Binary Properties; Stern-Gerlach Experiment; and Summary. • The purpose of General Introduction is to give students an idea of quantum mechanics' strange and often counterintuitive nature, and to encourage them to approach the topic open-mindedly. • In General Introduction, the teacher can also include some historical background of the development of quantum physics. • In the part Stern-Gerlach Experiment, various questions are posed and those should be discussed in the classroom. ***Video lessons*** ***Chapter 1 part 1*** This video concentrates on the binary properties of an electron. It essentially covers the contents of the part Introduction to Electron's Binary Properties in the slides. ***Chapter 1 part 2*** This video covers the contents of the part Stern-Gerlach Experiment in the slides. It goes a little bit further and connects the synthetic experiment presented to the famous double-slit experiment.

	Chapter 2 part 1 This video goes even further and provides some mathematical notations and theoretical background for the previous videos. This is not essential information for the module but may give useful background knowledge for the teacher. *The video lessons have been created by university lecturer Kimmo Tuominen and postdoctoral researcher Venus Keus.* ***Exercises*** Printout: Quantum exercises (pdf) & solutions (pdf) The exercises cover the following topics: • state vectors • normalisation • the probability interpretation ***Homework video*** *https://youtu.be/VsBuuwGj3zs*
Teaching methods	***Interactive lecture*** Whether the lesson is arranged using the videos or not, students should be engaged in discussions throughout the lesson. • If the video lessons are used, the videos should be paused every now and then and students asked to contemplate the questions posed on the videos. • If the teacher wants to teach not using the videos, the lesson should be similarly paused at suitable moments and possible questions asked and answered. ***Optional: Small group discussions*** The students can also be divided into groups of four or five students. The groups are asked to discuss the questions posed during the lecture and to present their reasoning to the class. ***Exercises*** Students may do exercises either individually or in groups. The solutions are provided as another printout. ***Homework*** *Instructions to students:* Watch the video and think of the topic your group has chosen to work on. Take notes on the applications and problems connected to your topic. Did you get other thoughts or ideas for the groupwork watching the video? Bring your notes to the next lesson.

Tips for teachers from previous classroom experiences	• We recommend the teacher to consult the video lessons before teaching – even if the videos are not used in the lesson. • The topics learnt in the lesson should be practised as soon as possible by doing the related exercises as homework or in a guided exercise session. • Teachers can encourage students by explaining that it is okay if they do not understand everything in this activity.
Additional resources	***simulation the of Stern-Gerlach experiment:*** • https://phet.colorado.edu/en/simulation/legacy/stern-gerlach • https://phet.colorado.edu/en/contributions/view/2988 ***other resources:*** • Stern-Gerlach experiment: https://en.wikipedia.org/wiki/Stern-Gerlach_experiment • Quantum state: https://en.wikipedia.org/wiki/Quantum_state • Dirac notation: https://en.wikipedia.org/wiki/Bra-ket_notation • Quantum superposition: https://en.wikipedia.org/wiki/Quantum_superposition
Other notes	• It would be very good if the teacher made the shift in thinking (from classical to quantum) explicit. This shift can be connected to the other shift made in thinking about futures in other parts of this module. • Also highlighting the uncertainty of quantum mechanics in connection to predicting the future would be ideal.

ACTIVITY 12: Mapping the Problem and Systems Thinking

Position in the module ***Future-oriented activities*** ***Action competence activities***	 This activity introduces practical tools for mapping problems and systems thinking. The content is connected to students' "future projects" and contemplating their own future scenarios. The broader aim of the activity is to offer students new means to think about the futures in a changing and complex world, and to support their feeling of agency in their lives. The activity defines a process of building up students' "future projects". First, students are guided to choose a problem within the topic their group has chosen. Next, groups define the chosen problem more precisely and place it as a part of a wider, complex system. The components and parameters of the system are defined and estimated, and at the end, students choose one aspect (a leverage point) of the system they want to change.
Goals	***conceptual*** • to understand the concept of a stakeholder and recognise the multidimensionality of every system • to understand the concepts of a system, emergence, feedback, complexity, and a complex system • to learn to recognise feedback loops and causal relations in systems • to learn to apply problem defining methods such as "5 WHYs" • to learn to identify leverage points in a system ***epistemological*** • to learn the basic principles of modelling a system • to recognise the power of simulations as a scientific tool

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to learn to identify and form feedback loops and other connections between the parts of a system, and to estimate their nature
to learn to use epistemic practices (borrowed from science), such as arguing, explaining, posing questions, and formulating hypotheses to specify an unclear problem, and to find the fundamental problem under the surface
to recognise arguing, explaining, posing questions, formulating hypotheses as important epistemic practices that can be used to analyse any complex context
to recognise the concept of a "dimension" (political, social, economic, scientific, ethical, environmental, professional …) as important for unpacking the relationships among the different components of a complex context and among stakeholders

social/emotional

to learn to negotiate and justify one's choices in a group
to develop a feeling of one's own agency in solving problems

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<tr><td>Time required</td><td>1-1.5 hours</td></tr>
<tr><td>Materials</td><td>
Slides (ppt & pdf)
The lesson and slides consist of seven parts: Choosing Topics; Defining the Problem; Attacker/Defender Game; What is a System?; Systems Thinking; Defining the System; and Identifying Leverage Points. The slides contain all the instructions for the groupwork.
Other
Defining the Problem printout

"5 WHYs" printout (word & pdf)

"5 WHYs" is a method used to explore the cause-and-effect relationships underlying a particular problem. It aims to determine the root causes of a problem by repeating the question "Why?". Each answer forms the basis of the next question. With five iterations a root cause can usually be found. Yet, not all problems have a single root cause. The 5 WHYs method can be applied several times to reveal all the root causes.
Attacker/Defender Game

The rules of the game can be found in the slides.
A video recorded as an example of the game: https://youtu.be/vPVbdV3FqoI

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<tr><td>Teaching methods</td><td>
Teacher facilitated discussions and work in the project groups
At the beginning of the activity, students gather in their project groups. The topics are discussed in the groups and together in the class. The groups are supposed to document their ideas and findings during the discussions as they will need documentation in doing the project work.
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Choosing Topics

Instructions to students:

1. In your group, take turns speaking briefly about your topic of interest and thoughts about it.
    - Did you get new ideas from the homework video?

Referring to this video: https://youtu.be/VsBuuwGj3zs

2. Find one topic which you all are interested in
    - The topic may concern society, technology, the environment, culture, the economy, politics...
    - Find a connection to ICT/the development of quantum computers

Defining the Problem

Every group is given their own "5 WHYs" printout.

Instructions to students:

Write down the definition of the problem

- Specify, clarify, negotiate an agreement!
- Why is it a problem?
- "5 WHYs" method
- Take different points of view
  (different stakeholders, environment...)

Defining the System

Instructions to students:

3. Make a mind map of the problem and the factors and parameters affecting it.
    - The factors and parameters of the system may concern e.g. technology, the economy (investments, etc.), infrastructure, laws and regulations, attitudes, values...
    - Also note down all the stakeholders you recognise (different groups, industry, businesses, environmental organisations...) – What kinds of effects do they have?
4. Think also about possible feedback loops – note those down on the map.

Identifying Leverage Points

Instructions to students:

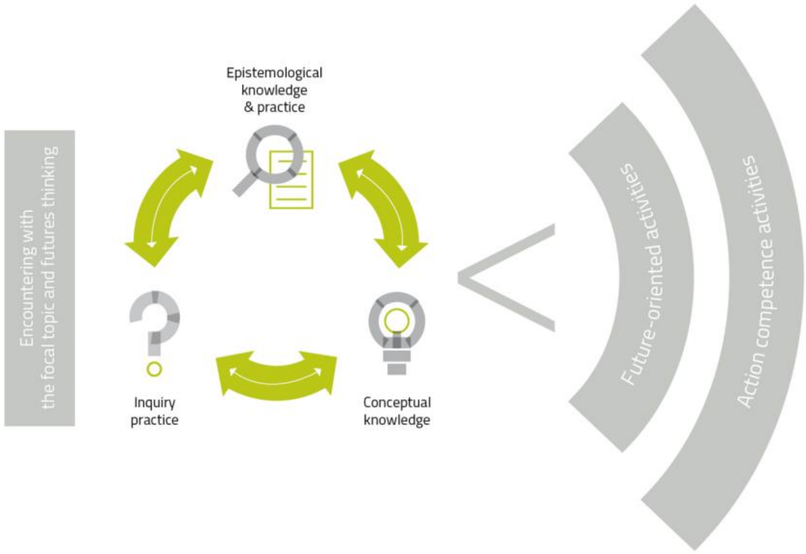
5. Estimate how easy/hard it is to affect different factors of the system
    - green: factors that can be changed easily or with the help of something that is easily acquired (these are the "leverage points" in the system)
    - yellow: factors that would require something in order to change them
    - red: factors that are very difficult to change

	6. Choose one leverage point!
	• The chosen leverage point should somehow concern ICT/quantum computing (e.g. computing power, modelling, collecting data, machine learning...)
	
	Complex system game
	
	Attacker/Defender Game
	
	The game requires a larger space. You may need to move to a corridor or hall to play it.
	
	Instructions to students:
	
	Randomly select two individuals (A and B).
	
	1. A attacks you, and B defends you against A.
	  • Move so that you keep B in between yourself and A!
	  • Think first: What will happen?
	2. Next, you are the defender! Move so that you stand between A and B!

Tips for teachers from previous classroom experiences	• The attacker/defender game is a nice and fun way to teach how a small change in a system can have a significant impact on the end result. • 5 WHYs, mind map: The teacher should follow the discussions in every group and steer the discussions with support questions if students have difficulty figuring out the key points. If a group slips to discussions irrelevant to the task or they do not use QC (or another given topic/tool) in their idea, the teacher should bring the discussion back to the given problem and tools. • In learning about complex systems, students can be reminded about the simulating power of (quantum) computers. They can be encouraged to utilise that point in planning their future project.
Other notes	• In this activity, students develop their own "future projects" while studying the skills of problem mapping and systems thinking. The purpose of this integrated solution is to make learning more motivating by making the students immediately apply the newly acquired skills and techniques to the problem of their choice. • The attacker/defender game was adapted from teachthefuture.org.

It's your time to imagine the futures

ACTIVITY 13: Quantum Computing

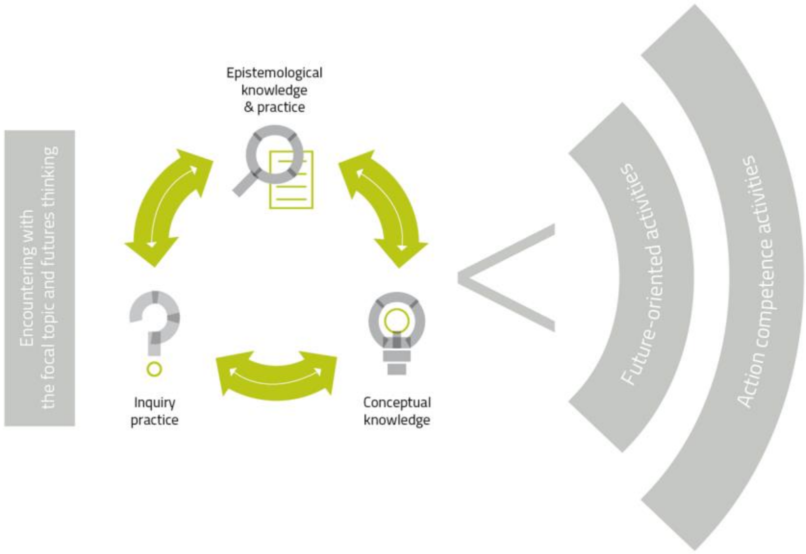
Position in the module ***Epistemological knowledge and practice*** ***Conceptual knowledge*** ***Inquiry practice*** ***Bridge between science ideas and future***	 This activity demonstrates the limits of classical computers in simulating complex systems and introduces the possibilities offered by quantum computers for simulations. The explanation for their superior computing power and ability to run complex simulations is found in their quantum properties introduced in the previous activity. Students are pushed to make a shift in computing paradigms and replace bits with qubits (i.e. quantum bits). The activity starts by contemplating the simulating power of quantum computing. The activity makes use of IBM Q's resources in teaching the logic of qubits and different quantum gates (measurement, X, H, and CNOT). A video of IBM's quantum computer is shown to students and they get to run programs on a real quantum processor.
Goals	***conceptual*** • to understand the concept of a qubit • to become familiar with different quantum logic gates • to learn to apply quantum mechanical properties in the context of computing ***epistemological*** • to form a more concrete idea of a measurement in quantum physics • to understand the opportunities of making complex simulations using quantum computers • to learn new ways of thinking about computing and adapt to a new kind of logic

	social/emotional • to arouse students' curiosity and interest in quantum phenomena • to get involved personally in working on quantum algorithms using the IBM Q Quantum Composer • to enlarge one's imagination about possible future STEM careers related to quantum physics and quantum computing
Time required	The required time depends on how much time the teacher wants to give students for trying out the IBM Q Composer. Going through just the materials takes approximately **45-60 minutes**.
Materials	***Slides* (ppt & pdf)** The lesson consists of four parts: Complexity; Quantum Computer; From Bits to Qubits; and Quantum Computing in Practice. ***Video clip*** In the part Quantum Computer of the slides, there is a link to the following video: *The Sounds of IBM, IBM Q:* https://youtu.be/o-FyH2A7Ed0 ***Other equipment*** If possible, students should be given an opportunity to try the quantum composer by themselves. They should be provided with computers (preferably not tablets or smart phones) or they should be asked to bring their own devices. If this is not possible, at least the teacher should be able to show students how the composer is used on a computer.
Teaching methods	***Interactive lecture*** The first three parts of the lesson, Complexity; Quantum Computer; and From Bits to Qubits, can be taught as an interactive lecture. The teacher should facilitate the discussion about the topics of the lesson and answer possible questions. • In the part Complexity, students can also be asked to think about different complex systems and the limitations of studying them. • In the slides, there are some example pictures of complex systems (climate, cities/transportation, the human body) and fields that work on complex systems (medicine, chemistry). The teacher can add and replace examples if they wish. • In the part Quantum Computer of the slides, there is a video of IBM's quantum computer. There is no need to watch the whole video (4 min 45 s). The purpose of the video is to show students what a quantum computer looks like and make it a bit more concrete.

	Option 1: Demonstration If there is no possibility to get computers for the students, the teacher can go through the last part of the lesson, Quantum Computing in Practice, by showing them how different quantum logic gates operate. Every gate's operation should be demonstrated with the IBM Q Quantum Composer. ***Option 2: Individual/groupwork*** If the students can have computers, they can familiarise themselves with the IBM Q Quantum Composer by themselves or in small groups. They can be asked to run the introduced algorithms at the same time, and the results can be compared. This demonstrates nicely the probabilistic nature of quantum mechanics (results/probabilities for results should vary a little).
Tips for teachers from previous classroom experiences	• The teacher can emphasise that IBM Q is a real quantum computer, not just a simulation, which makes this activity more exciting for the students. • However, running programs on the quantum processor takes time and the results are sent to the programmer by email, which is not very handy for a lesson. It might be good to demonstrate the usage of the quantum processor only once and otherwise use the simulations on the Composer. • It would be good to go through the materials of IBM Q carefully before teaching. They provide many good resources that can be integrated into the lesson. There might also be an opportunity to contact the personnel working at IBM and ask them to give a Skype lesson on the course or otherwise help with the quantum computing part.
Additional resources	***IBM Q resources:*** • https://www.research.ibm.com/ibm-q/learn/what-is-quantum-computing/ • https://quantumexperience.ng.bluemix.net/qx/tutorial?sectionId=beginners-guide&page=introduction • https://quantumexperience.ng.bluemix.net/qx/tutorial?sectionId=full-user-guide&page=introduction • https://quantumexperience.ng.bluemix.net/qx/editor ***videos:*** • The future of supercomputers? https://youtu.be/VsBuuwGj3zs • Why do we need Quantum Computers in the Cloud? https://youtu.be/wfsUxdYSOFs • Quantum and chemistry: https://youtu.be/qarc7AA4-wM • How quantum computing works: https://youtu.be/WVv5OAR4Nik • Qubits: https://youtu.be/RApkNeVYmeM • Quantum logic: https://youtu.be/YTNug9tQOzU

	other resources: • Quantum computing: https://en.wikipedia.org/wiki/Quantum_computing • Qubit: https://en.wikipedia.org/wiki/Qubit • Quantum logic gate: https://en.wikipedia.org/wiki/Quantum_logic_gate
Other notes	***Instructions for registering a user with IBM Q computing resources*** Register here: https://quantumexperience.ng.bluemix.net/qx/signup ➢ In the field "Enter your institution", write the name of your school. ➢ In the field "What would you like to use the IBM Q Experience for?" you may answer, for example: We use IBM Q Experience on a quantum computing course at [your school]. ➢ You will get a confirmation email. You have to click on the link in the email before you can sign up on the webpage. After signing up, you can use IBM Q's real quantum processor. Note that every user has a limited amount of runs per day.

ACTIVITY 14: Deutsch's Algorithm

Position in the module ***Epistemological knowledge and practice*** ***Conceptual knowledge***	 After getting to know the basic logic of qubits and quantum gates in the previous activity, the simplest real quantum algorithm, Deutsch's algorithm, is introduced in this activity. The power of quantum computing is illustrated by solving Deutsch's problem first classically and then quantum mechanically. We see that the classical solution takes two trials while the quantum mechanical solution takes only one trial. First, Deutsch's problem is explained and solved classically. After that, the quantum mechanical algorithm for solving the problem is uncovered step by step together with the students. Finally, a couple of other quantum algorithms are also briefly discussed and the lesson summarised.
Goals	***conceptual*** • to understand the idea of what kind of algorithms are run on quantum computers • to learn to build more complicated operations using quantum logic gates • to become familiar with some example algorithms • to get an idea of what kind of problems can be solved by quantum computers ***epistemological*** • to practise the logic of quantum computers and to understand the shift in thinking from classical to quantum computing • to realise the potential of quantum computing in practice

	social/emotional • to learn to tolerate uncertainty in solving quantum physics problems • to arouse students' curiosity and interest in quantum computers • to broaden their imagination about possible future STEM careers related to quantum computing
Time required	1-1.5 hours
Materials	***Slides* (ppt & pdf)** The slides consist of four parts: Quantum Algorithms; Deutsch's Problem; Deutsch's Algorithm; and Summary. ***Other*** Deutsch's Algorithm • Mathematical steps of the algorithm (pdf)
Teaching methods	***Interactive lecture & groupwork*** • The teacher facilitates a discussion of the parts Quantum Algorithms and Summary. • In the part Deutsch's Problem, the problem has to be explained thoroughly to students and their questions answered. • In the part Deutsch's Algorithm, students are asked to make step-by-step calculations at the same time with the teacher. They can make calculations in small groups and discuss their reasoning. Every step should be well explained by the teacher.
Tips for teachers from previous classroom experiences	• Even though students should be familiar with the notation from the previous lessons, they will probably find the algorithm and calculations difficult. The teacher should still encourage them to accept the challenge. • Deutsch's algorithm should be introduced to students at a slow enough pace. Students need time to think about every step and the teacher needs to make sure nobody loses their track of thought.
Additional resources	***videos:*** • Quantum algorithms: https://youtu.be/-ysVGWtAjio • Deutsch's algorithm: https://youtu.be/5xsyx-aNClM ***other resources:*** • Quantum algorithm: https://en.wikipedia.org/wiki/Quantum_algorithm • Deutsch's algorithm: https://en.wikipedia.org/wiki/Deutsch-Jozsa_algorithm

	• Deutsch's algorithm in IBM Q's User Guide: https://quantumexperience.ng.bluemix.net/proxy/tutorial/full-user-guide/004-Quantum_Algorithms/080-Deutsch-Jozsa_Algorithm.html • Shor's algorithm: https://en.wikipedia.org/wiki/Shors_algorithm • Grover's algorithm: https://en.wikipedia.org/wiki/Grovers_algorithm
Other notes	Studying Deutsch's algorithm has to be justified to students. After all, this algorithm has no practical application but is merely an illustration of the power of quantum computing.

It's your time to imagine the futures

ACTIVITY 15: Scenarios

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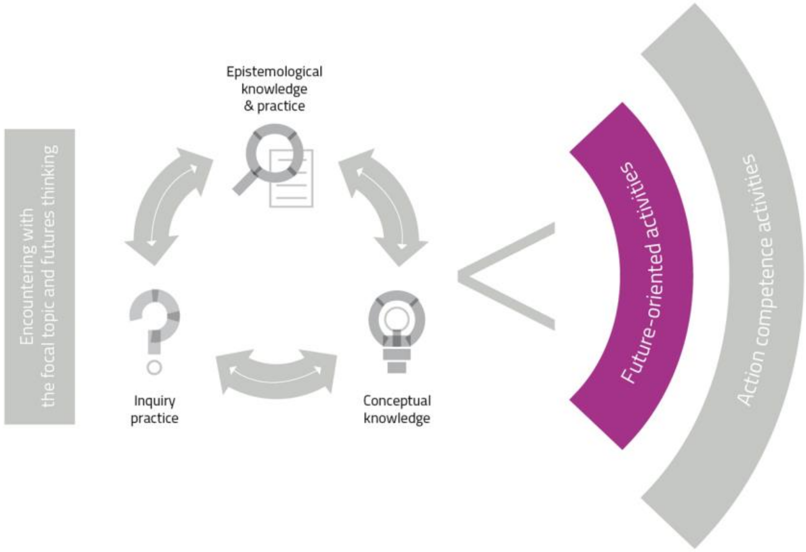
<tr><td>Position in the module

Future-oriented activities

Action competence activities</td><td>

In this activity, scenario development techniques and storytelling are used to broaden students' views of futures. The activity highlights the multitude of possibilities, and students learn to see the plurality of futures. They also learn to consider the complexity of reaching a single future. The plurality of futures is seen as offering plenty of opportunities, and students are led to think about how to reach the most desirable scenario.
The activity introduces to students the concept of a scenario as a story about the future. They learn the idea of the Futures Cone that illustrates the plurality of futures. At the end of the activity, students get to work on their "future projects" and to develop scenarios using three fundamentally different ways of futures thinking. </td></tr>
<tr><td>Goals</td><td>conceptual

to understand the concepts of a scenario and the futures cone
to identify three fundamentally different ways to think about the future (expected, plausible and preferable)
to use these three ways of thinking to develop a variety of scenarios
to move from the idea of a single future to the idea of a plurality of futures

epistemological

to employ the epistemic practices of arguing, explaining, questioning assumptions, and formulating hypotheses to create scenarios
</td></tr>
</table>

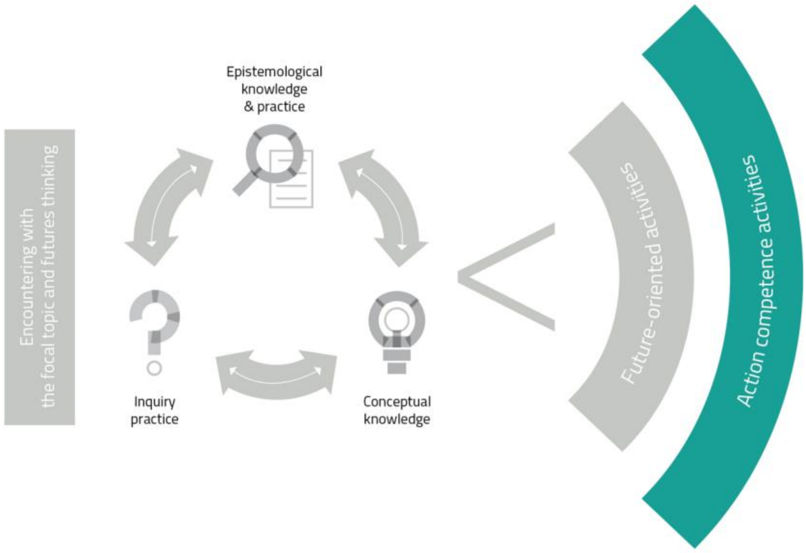
	social/emotional • to broaden one's imagination about the future within the chosen topic • to employ an emotional, value-driven element in futures thinking (creation of preferable scenarios) • to share and discuss hopes and values with peers
Time required	45 minutes or preferably more to support students' groupwork. The groupwork part can be extended and students given more time to work on their "future projects". The "theory" part of this activity is relatively short and takes only approximately 10-20 minutes.
Materials	***Slides* (ppt & pdf)** The lesson and slides consist of four parts: Stories; Futures Cone; Three Ways to Think about Future; and Thinking of Different Scenarios. The part Thinking of Different Scenarios contains instructions for the groupwork. ***Other*** Thinking of Different Scenarios • Scenarios printout (word & pdf) • The printouts can be used in doing the exercise. Alternatively, students can use computers in writing down their scenarios.
Teaching methods	***Interactive lecture*** The discussion on the contents of the lesson is facilitated by the teacher. Students may also discuss the topics in small groups (especially the idea of the Futures Cone) if the groups are formed at the beginning of the lesson. ***Groupwork*** At the end of the lesson, students are asked to consider their own "future projects" in the light of the information given in the lesson. Students may also follow the whole lesson in the project teams. Thinking of Different Scenarios Students are guided to develop scenarios of their chosen problem using three fundamentally different approaches, focusing in turn on 1. trends and extrapolation, 2. discontinuities and alternative assumptions, and 3. their own preferences and choices. *Instructions to students:* How could your chosen problem develop by 2035? Describe the scenarios with a few sentences/bullet points. Think about the whole system.

	1. **Expected scenario** • Where do current trends lead? 2. **Plausible scenario** • What could happen, if we question assumptions and rules, take risks, face surprises? Exaggerate the effect of some leverage points! 3. **Preferable scenario** • Envision a desirable scenario: It is 2035. What is the status of the problem? And the whole system? • Make up a couple of news headlines (3 May 2035)! For the last step (preferable scenario), a helpful thought experiment has been the following: You swallow a magic pill, wake up in 2035 and your problem has been solved! Look around: what else has changed in the system?
Tips for teachers from previous classroom experiences	• The teacher should walk around, talk to groups and help students develop their scenarios with steering questions. • The teacher should support students especially in identifying and questioning their assumptions when developing alternative scenarios ("What is your assumption there? What would happen if it wasn't so?"), and in sustaining systemic thinking ("What leverage points are you using now? How does that affect the other parts of the system? How do other stakeholders react to that?") • This activity calls for creativity and collaboration, and is sensitive to group dynamics. Teachers' role may be important in encouraging students to use their imagination, think freely and overcome mental blocks. Thereby, it is advisable not to leave the scenario development completely to self-directed homework but to devote teaching time to this.
Other notes	The set of scenario development methods used in this activity is a combination of well-known ideas in Futures Studies. The notion of "3 Ways to think about future" is inspired by teachthefuture.org, especially the material "System thinking, complexity, forecasts, & the future".

ACTIVITY 16: Backcasting

<table>
<tr><td>Position in the module

Action competence activities

Future-oriented activities</td><td>

The aim of this activity is to give students tools to take an active role in impacting their future and to imagine possible actions in practice. To do this, the backcasting method is introduced. Backcasting is an empowering way of connecting emotionally to a preferable future and planning actions. Students are encouraged to imagine a preferable future and find the steps toward it.

In the activity, students are walked through the backcasting exercise. The method involves thinking of the future in the past tense to find a path from the present to the desirable future. The results of this exercise are turned into presentations. The goal is to make a synthesis of the whole module in the presentations of the projects started at the beginning of the module. The instructions for the presentations are given in the lesson materials. At the end of the lesson or after the lesson, students are asked to revise their personal, written future visions in light of their newly acquired knowledge and perspectives.</td></tr>
<tr><td>Goals</td><td>conceptual
to learn to use the backcasting method
to learn to revise one's own future visions in light of new knowledge and perspectives
to learn to articulate a strategy to achieve a desirable solution to the problem
to learn to relate one's personal and professional visions of the future and one's own role and identity to the knowledge and perspectives learnt during the module
to employ creative thinking techniques</td></tr>
</table>

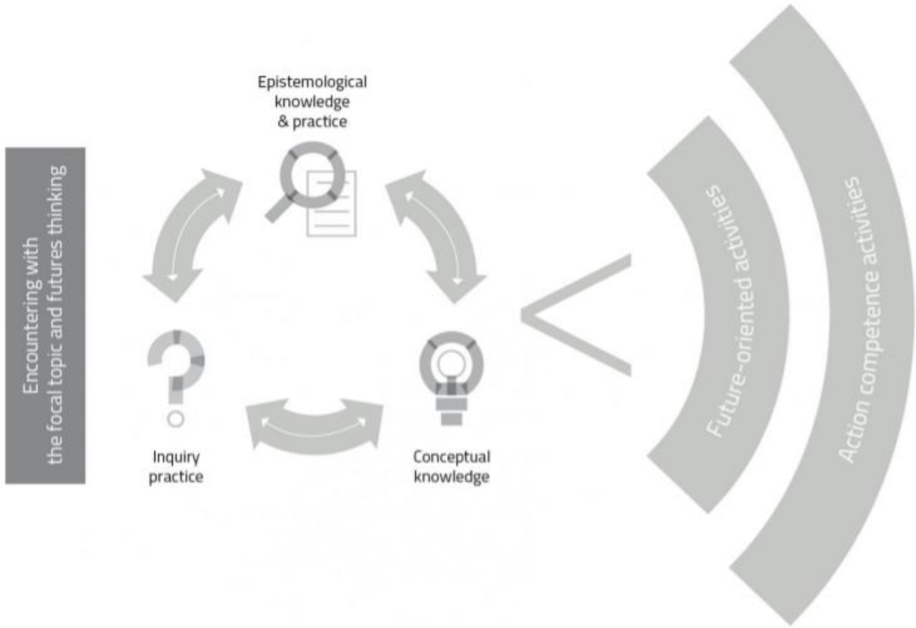
	social/emotional • to realise one's own potential in taking action to change the future within the chosen topic • to learn to project oneself to one's desirable future • to learn to cooperate and work in a small group
Time required	• one hour + time for preparing the presentations • homework
Materials	***Slides*** **(ppt & pdf)** The lesson and slides contain three parts: Backcasting; Presentations; and Homework. • The first part, Backcasting, contains the step-by-step instructions to students for the backcasting exercise. • The second part, Presentations, contains the instructions to students for preparing the presentations of their work. • The final part, Homework, contains the instructions to students for revising their written future scenarios. This can be left as homework or carried out in the lesson. ***Facilities for preparing and giving the presentations*** For the backcasting exercise and preparing the presentations, students should be provided with some paper or electronic devices for note-taking and making a timeline. The teacher should check if students have the means of making video clips before making the task mandatory. Students should be given appropriate devices and facilities to create their presentations.

Teaching methods	***Groupwork***
	
	The whole lesson consists of groupwork. Students are placed in their project work groups and they do the exercises in those groups.
	
	Instructions to students:
	Backcasting
	
	• Take your desirable scenario
	• Go back, step by step, from 2035
	    o What caused the system to change?
	    o What did you do to impact the system? Did you need help? Who helped you?
	    o What obstacles did you encounter? How did you overcome them?
	    o What were your roles in this process?

	• Make a timeline 2019-2035
	    ○ Mark down all the significant steps and events that led to the solution.
	    ○ What was your first action (summer of 2019)?
	
	Presentations
	
	• Introduce your chosen problem and the leverage point you applied.
	• Present your scenario for the year 2035: What is the status of the problem? Who are you then?
	• Tell your success story: What happened between 2019 and 2035?
	    ○ What did you accomplish and how? What obstacles did you overcome? Who helped you and how?
	• The length of the presentation is about 10 minutes.
	• As part of your presentation, prepare a short (about 3 min) video clip
	    ○ In the video, you can describe your experience of the project, introduce the problem/its solution/the 2035 scenario...
	• All the other aspects of your presentation you can do in any way you like!
	
	Individual work
	
	The last exercise can be left as homework or some time needs to be reserved for individual work at the end of the lesson. Ideally, students should be given space and time to concentrate on the exercise.
	
	Instructions to students:
	Homework
	
	• Reread your future scenario essay. Have you got new ideas for it?
	• Modify/comment on the original version
	    • Highlight the modifications
	    • You may add comments in places where your thinking has changed

Tips for teachers from previous classroom experiences	• It may be difficult for students to backcast as they easily slip into forecasting. Because of this it is essential that the teacher holds students to the task and reminds them to use the past tense in their discourse. • The previously mentioned reminding and encouragement are also needed during the final presentations, and the teacher should ask complementary questions after the presentations. The teacher may also ask an outsider (a colleague, a researcher, etc.) to host the event in order to have new perspectives.
Other notes	• The backcasting method is a much-discussed technique in Futures Studies, and it aligns well with the action competence approach. • In the interviews after the first Finnish I SEE module implementations the students have frequently mentioned the backcasting activity as an empowering method and something they intend to use in other contexts too.

ALTERNATIVE ACTIVITY 1:
A Brief History of Classical Computers

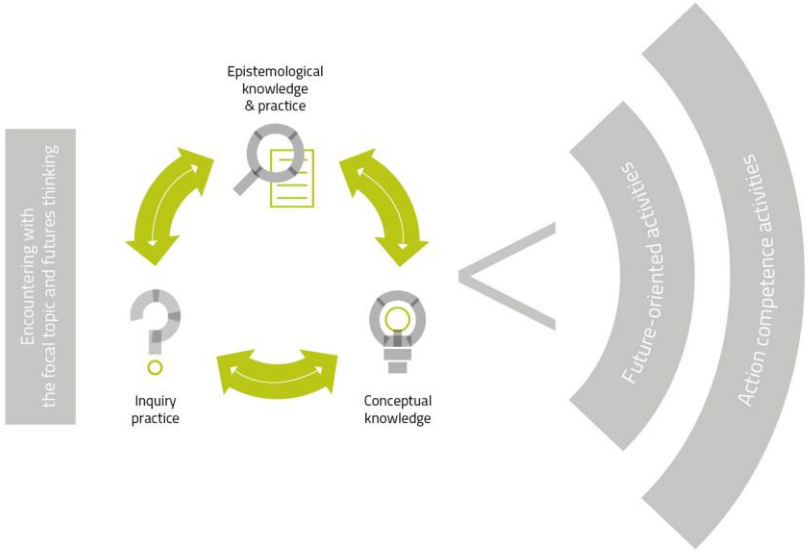
Position in the module ***Encountering with the focal issue***	 This activity consists of a lecture on the brief history of classical computers. In this introductory lecture, the evolution of computers and the logic on which they are based are presented. The lecture has been specifically designed to pave the way for contrasting classical logic with quantum logic in the following activities. The focus of the activity is on the following questions: • What do encoding and processing of information mean for a classical computer? • How have encoding and processing of information changed with technological progress?
Goals	***conceptual*** ● to understand what it means that a classical computer follows classical logic in encoding and processing information ● to understand the meaning of logical operators, truth tables, logic gates: OR, AND, and NOT ● to understand the changes that made it possible to move from one generation of computers to the next ***epistemological*** ● to recognise three different levels of analysis in encoding and processing information: o the mathematical level linked to Boolean algebra

	○ the level of logic gates ○ the implementation level linked to the technologies used ***social/emotional*** ● to reflect on the speed with which technology has developed and how the performance of computers has changed in the last few decades
Time required	1 hour + 15-20 minutes for discussion
Materials	***Slides*** **(ppt & pdf)** The focus of the lecture is on: ● reflections on the fact that classical computers follow classical logic: ✓ the information is processed using algorithms with a succession of operations performed sequentially ✓ the elaboration process is deterministic: an algorithm gives a certain result ✓ the basic information is presented by two possible states that are mutually exclusive: 0 or 1/true or false ● the meaning of logical operators, truth tables, and logic gates: OR, AND, NOT ✓ How the sum of two binary numbers is calculated using logic gates ● reflections on the fact that the logic of a classical computer remains the same even though the hardware and software change very rapidly over time ● reflections on the fact that logic gates (OR, AND, NOT) can also be made mechanically with ropes and pulleys (see Dewdney, 1988) ● explication of the fact that encoding and processing information can be analysed on three different levels: ✓ the mathematical level linked to Boolean algebra ✓ the level of logic gates ✓ the implementation level linked to the technologies used ● a brief history of the evolution of computers: significant changes in devices until the discovery of the internet ● reflections on the fact that technological progress has allowed the development of software that is increasingly far from classical sequential logic ● reflection on the fact that software develops according to the types of problems to be solved
Teaching methods	***During the lecture:*** Students are invited to comment or request clarification. ***At the end of the lecture:*** Students are invited to participate in the debate.

Tips for teachers from previous classroom experiences	Although students regularly use computers to process data, many of them do not know the logic behind the coding and processing of information by a computer.
Additional resources	A. K. Dewdney. (1988). An ancient rope-and-pulley computer is unearthed in the jungle of Apraphul. *Scientific American*. Vol. 258, No. 4, pp. 118-121.

It's your time to imagine the futures

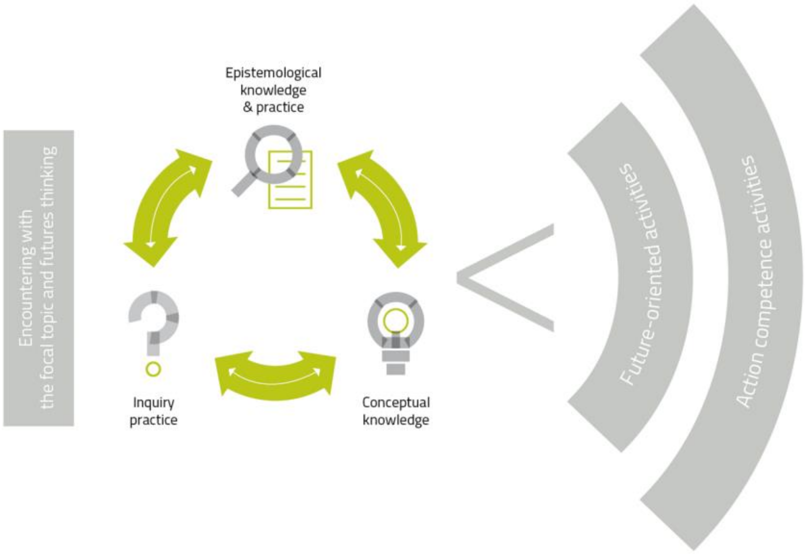
ALTERNATIVE ACTIVITIES 3 & 4:
Two-Qubit System and Cryptography

Position in the module ***Conceptual knowledge*** ***Epistemological knowledge & practice***	 This activity aims to apply the superposition principle in describing a two-qubit system and to introduce entanglement as a genuine quantum property of a system. The conceptual meaning and potential of entanglement is emphasised by the introduction of cryptography that is presented as an example of a quantum protocol. The focus of the activity is on: • the encoding and processing of information in a quantum computer; • logic gates as manipulators of signals and information; • the concept of entangled states.
Goals	***conceptual*** • to understand that the state of a two-qubit system can be described by the superposition of states ($\|\psi\rangle = a\|00\rangle + b\|01\rangle + c\|10\rangle + d\|11\rangle$) that represents information • to become familiar with the concept of entanglement • to get to know an example of a two-qubit logic gate CNOT • to become familiar with the concept of a measurement in quantum physics and its circuit symbol • to gain more confidence in the formalism introduced in the previous activities • to start to gain confidence in circuit representation • to gain confidence in the new type of logic gates: CNOT, Hadamard gate, X, Z • to understand that the new quantum mechanical logic is needed to solve the problems that are unsolvable using classical systems

	• to understand what cryptography is and what the main differences between classical and quantum cryptographies are • to understand the effect of an observer on a system when two people are exchanging information • to understand that cryptography opens up new opportunities whose impacts span different dimensions (political, social, economic, ethical, environmental, professional…) • to start to grasp the essence of entanglement as a real resource for many applications ***epistemological*** • to recognise the effects of a measurement on quantum systems • to recognise that some problems can be solved with quantum physics and the new quantum logic • to begin to recognise the importance and efficiency of some quantum protocols (e.g. the cryptography protocol) • to begin to recognise the impact and scope of applications based on quantum mechanics ***social/emotional*** • to begin to reflect on the potential and risks of quantum cryptography according to one's own worldview and values • to broaden one's imagination about possible future STEM careers • to get personally involved in class discussion and sharing one's views
Time required	1.5 hours
Materials	***Slides for the dialogic lesson*** • ***Two-qubit systems* (ppt & pdf)** • ***Cryptography* (ppt & pdf)** • an introduction to the concept of measurement as another difference between classical and quantum computers • an introduction to quantum measurement as probabilistic and destructive • an introduction to the probabilistic meaning of the coefficients *a* and *b* of the overall state $\|Q\rangle = a\|0\rangle + b\|1\rangle$ of a system: $p_0 = \|a\|^2$ is the probability of measuring value 0, $p_1 = \|b\|^2$ is the probability of measuring value 1 • an introduction to multi-qubit systems, in particular two-qubit systems • an introduction to the two-qubit logic gate CNOT, its operation, circuit representation, and truth table • an introduction to the concept of correlation between the outcomes of a measurement • an introduction to the concept of entanglement as a particular correlation between the states of two quantum objects

	• an introduction to the Bell states describing maximally entangled states • a presentation of the circuit that realises maximally entangled states • an introduction to cryptography: *A technique of representation of a message in such a way that the information can be received and read only by the receiver* • public key cryptography • a brief history of cryptography • RSA protocol and the decryption limits of a private key • the potential of quantum computers to overcome the limits of classical computers • an introduction to the BB84 protocol through a simulation: How is it possible to exchange a key without the two users having secret information in common? • a presentation of the results that Alice and Bob obtain if they carry out the measurements on the same axes or on different axes • an introduction to the effect of the quantum measurement if a third observer tries to intercept the message
Teaching methods	***A dialogic lesson*** The teacher helps each student to take an active part in the dialogic lesson and to get involved especially when the effect of the measurement on a two-qubit system is introduced.
Tips for teachers from previous classroom experiences	• Students seemed very interested in the subject. • Students seemed very engaged especially during the introduction of a measurement as something that disturbs the system. They got really involved with the quantum logic part (the introduction of a CNOT gate, the circuits that realise maximally entangled states). • Students were also very engaged during the last part of the dialogic lesson, in which cryptography was introduced. Students seemed to have begun to understand the potential of these new technologies, starting to reflect on their positive and negative aspects.
Additional resources	***BB84 protocol:*** https://www.standrews.ac.uk/physics/quvis/simulations_html5/sims/BB84_photons/BB84_photons.html

ALTERNATIVE ACTIVITY 5:
Teleportation as a Comparison Between Experiment and Circuit

Position in the module ***Conceptual knowledge*** ***Epistemological knowledge & practice***	 The activity aims to grasp the idea of how an experiment can be reread in terms of the circuit by using a comparison between the experiment and the standard teleportation protocol. It reinforces the concept of entanglement, and stresses the presence of a new logic and the notion of information encoded in the qubit. The focus is particularly on: • experimental tools as manipulators of information • a simulation of an experiment • logic gates as manipulators of signals and information • the potential of teleportation
Goals	***conceptual*** • to understand that a state is described by a superposition of states ($\|H\rangle$ and $\|V\rangle$; $\|\uparrow\rangle$ and $\|\downarrow\rangle$; $\|0\rangle$ and $\|1\rangle$) • to reinforce the concept of entanglement and “the spooky action at distance” (the EPR paradox) • to understand the logic of the experiment ○ creation of two pairs of entangled photons (c and d; a and b) ○ projection of photons b and c in a Bell state ○ measurement and communication of the outcomes via a classical channel ○ operation to recover the initial state • to understand that experimental tools manipulate the overall state of the system so that teleportation occurs

	• to gain confidence in circuit representation • to understand that nowadays the new quantum mechanical logic is needed to solve many kinds of problems • to gain confidence in the new logic and formalism • to gain confidence in new types of logic gates CNOT, Hadamard gate, X, Z • to understand the effect of a measurement in quantum mechanics • to start to understand how an experiment can be interpreted and reread with logic gates • to start to understand the importance of simulations by looking at a concrete example • to understand that manipulating a state corresponds to manipulating information • to understand that teleportation opens up new opportunities whose impact span different dimensions (political, social, economic, ethical, environmental, professional…) • to understand that entanglement and its "spooky action at distance" represent a real resource for many applications • to understand how entanglement can turn out to be a turning point for the development of a quantum internet ***epistemological*** • to recognise that there are problems that could be solved only with quantum physics • to begin to recognise how it is possible to reinterpret an experiment in terms of logic gates • to recognise that the experiment and the circuit are two ways to solve the same task • to understand the role of simulations • to begin to recognise the impact and scope of the applications based on quantum mechanics ***social/emotional*** • to begin to reflect on the potential and risks of quantum computers and a quantum internet according to one's own worldview and values • to broaden one's imagination about possible future STEM careers • to get personally involved in class discussion and sharing one's views
Time required	1 h 15 min

Materials	***Slides for the dialogic lesson* (ppt & pdf)**
	
	• A reminder of the levels of analysis used in the first lesson:
	  ○ narrative
	  ○ logic
	  ○ mechanism
	• The story of Alice and Bob to contextualise the task
	• Emphasising the fact that the task is resolvable only with quantum teleportation
	• A presentation of the physical setup stressing the logic of the experiment:
	  ○ creation of two pairs of entangled photons
	  ○ projection of two photons, initially non-entangled, in a Bell state
	  ○ the measurement made by Alice, and communication through the classical channel
	  ○ Bob's operation to recover Alice's initial state, after knowing Alice's results
	• A presentation of the teleportation protocol
	
	• The calculations following what happens to the state passing through the logic gates, and a step-by-step comparison between the experiment and the circuit
	  ○ consecution of CNOT and Hadamard gates in order to project two non-entangled states in a Bell state
	  ○ the measure operator in the circuit and Alice's corresponding action
	  ○ communication of the measure in the circuit (00, 01, 10, 11) and in the experiment
	  ○ application of X and Z gates and corresponding application of a tension to EOM in order to recover the initial teleportation state
	
	• A presentation of quantum networks as the bases of
	  ○ cloud computing
	  ○ the quantum internet
	• A presentation of the main ingredients for the quantum internet:
	  ○ presentation of entanglement as a fragile link depending on different environmental conditions (as thermal noise)
	  ○ the concept of a maximally entangled state
	  ○ the use of a quantum repeater in order to extend the range of quantum communication between a sender and a receiver

Teaching methods	***Dialogic lesson*** The teacher helps each student to take an active part in the dialogic lesson and to get involved especially when the mathematical passages are presented, and takes care that the whole class is engaged in the collective activity.

Tips for teachers from previous classroom experiences	• Students seemed very interested in the subject. • The experiment part, both the logical level and the mechanism level, was not immediately easy to follow, but at the end of the discussion students seemed to be convinced. During the second part, that of the circuit, students seemed very engaged and they got involved especially with the logic part. • The final part helped students to understand and realise the potential of teleportation in terms of the quantum internet.

ALTERNATIVE ACTIVITY 6:
Applications and Implications of Quantum Computers in Society

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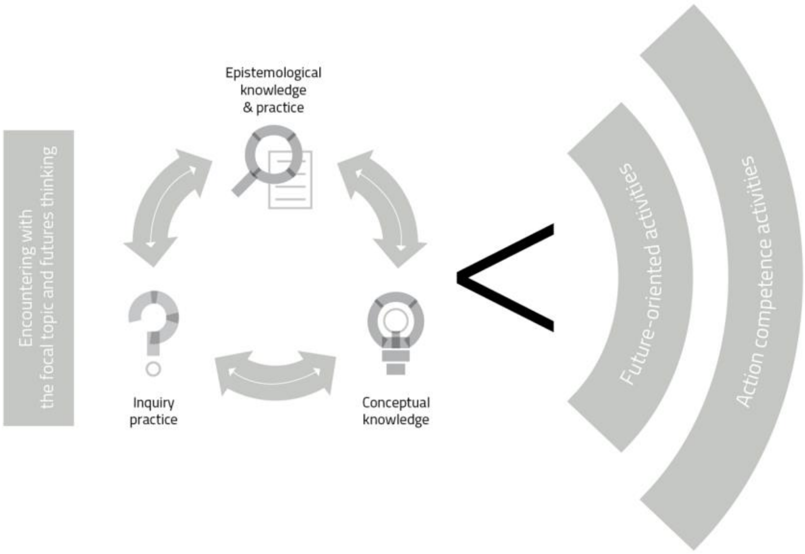
<tr>
<td>Position in the module

Bridge between science ideas and future</td>
<td>

The main aim of this activity is to contextualise quantum technologies within the present and future world in order to make students think about the possible implications and applications of quantum technologies. The implications and applications stressed in the activity cover not only scientific and technological research but also fields that can initially appear less related to the issue, such as politics and society. The common thread of the whole activity is the Quantum Manifesto, a 2016 document edited by a group of European researchers calling on the European Union to launch initiatives in support of research into quantum technologies.</td>
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<td>Goals</td>
<td>conceptual

to understand the concepts of “Second Quantum Revolution” and “Quantum Computational Supremacy”
to understand the relevance of the Quantum Manifesto, its objectives and its hopes, within the European and global context
to understand the implications of quantum technologies in four areas: communication, politics, scientific and technological research, and society
to grasp the future and present relevance of quantum technologies
to identify the current stakeholders within the Second Quantum Revolution
to be introduced to the concepts of quantum optimisation, quantum simulators, quantum sensors, quantum internet, and quantum programming
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	epistemological • to understand the complexity of the close relationship between science, technology and society • to recognise the different dimensions involved when contextualising science and technology in society • to recognise the importance of the concept of "dimension" (political, social, economic, scientific, ethical, environmental, professional...) for unpacking the relationships among the different components of a complex context and among the stakeholders • to get acquainted with the future-oriented nature of scientific practices • to be able to creatively grasp new connections between quantum technologies and various aspects of life ***social/emotional*** • to become aware of one's own ethical values implied in the emergence of new technologies • to comprehend the relevance of one's own role within society and to aspire to actively take part in it (citizenship competences) • to get involved personally in group or collective discussions (teamwork skills) • to be able to explain one's own point of view to others (public speaking skills) • to learn to share different points of view and to cope rationally, emotionally, creatively and responsively with their future (future-scaffolding transversal skills) • to broaden one's imagination about possible future STEM careers
Time required	**2.5 h**: 30 minutes for explaining the activity, one hour for working in teams on a chosen topic, one hour for having each team present its results.
Materials	***Slides* (ppt & pdf)** • The Quantum Manifesto: A presentation of the document and its objectives • Explanation of the activity and formation of working teams on the basis of personal interest in a topic from among the four on the worksheets. ***Four worksheets for each student*** The worksheets present the topic both with some definitions and examples, and by posing some captivating questions about the topic in order to engage students in creative thinking about the present and the future. They also contain a list of hyperlinks to websites that students should use as a resource for their reflection. The topics are the following: • Quantum Computing & Communication (word & pdf); • Quantum Computing & Politics (word & pdf); • Quantum Computing & Scientific and Technological Research (word & pdf); • Quantum Computing & Society (word & pdf).

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Map: "Quantum Computing &…" (one for each team) (<u>word</u> & <u>pdf</u>)

The map contains several aspects on which quantum technologies can/could impact and some blank spaces for finding new aspects. The team should read it carefully and discuss it together, in order to find some links between the team topic and these aspects. This map belongs only to the team and they must explain to the other teams the work that has been done.

Instructions for the teams: A New Era of Technology —Which possible applications and implications? (one for each team; <u>word</u> & <u>pdf</u>)

The instructions for completing the activity are fully explained here. The activity is divided into two parts:

Activity 6a: Reading the map and exploring the four worksheets, looking for possible applications and implications in the use of quantum computers, drawing arrows and potentially adding new aspects in the blank spaces;
Activity 6b: Discussing together the connections and the map, by paying close attention to the different dimensions of impact on the applications/implications of quantum computers; highlighting the connections that the team finds most meaningful. Later, speaking about the results of analyses in front of the whole class.

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<tr><td>Teaching methods</td><td>

The teacher presents the content and the objectives of the Quantum Manifesto and contextualises it within the European Union and scientific and technological research by introducing the Second Quantum Revolution and by highlighting the stakeholders involved in it.

Then the teacher explains the activity and forms the teams, grouping students together on the basis of their interests with regard to the four topics on the worksheets.

After writing the chosen topic on the map, each team has to explore and analyse the corresponding worksheet with different aims:

to recognise and highlight on the map the aspects "touched or involved" by their topic
to find valuable connections between the topic and the various aspects selected on the map, by drawing arrows between their topic and the ovals
to reason about the connections.

Throughout the activity, the students are asked to reflect on the distinction between applications and implications of the technologies and, if their discussion leads them to recognise an aspect that does not appear on the map, they are asked to add it in the blank spaces.

The arrows have to be clarified and discussed by paying close attention to the different dimensions of impact on the applications of quantum computers (scientific, environmental, social, ethical, economic, political, etc.). The team should also be able to say which connections are the most meaningful and why. Writing some keywords or

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	sentences for the arrows could be useful for describing why the team considers something more important than something else. At the end of the teamwork session, each team has to present its findings and analyses to the others, by means of slides, a short video, a poster, or simply a short speech.
Tips for teachers from previous classroom experiences	• When explaining the Quantum Manifesto, it is important to highlight the connection between it and the activity. In particular, it is important to stress that the activity has been designed as a guide to navigate and analyse scientific and institutional texts and resources. In particular, it is important to foster an *analytic attitude* toward the activity where "judgement in terms of good or bad" is suspended and postponed after an engagement with scientific texts and a process of analysis. • The teacher should emphasise the fact that quantum technologies are still on their way to be implemented, but also that this fact did not stop institutions, scientists and stakeholders from thinking about the implications and applications. • Finally, it is very important to highlight the importance of creativity in the team activity, so as to create in students the right mindset for thinking creatively about the future of their topic.
Additional resources	Quantum Flagship website: https://qt.eu/ de Wolf, R. (2017). *The Potential Impact of Quantum Computers on Society*. https://arxiv.org/abs/1712.05380v1 Harrow, A.W. & Montanaro, A. (2018). *Quantum Computational Supremacy*. https://arxiv.org/abs/1809.07442

ANNEX: Notes on the Implementation in Italy and the Italian Path
Module Implementation in Italy, 5.2.-12.3.2019

Overview	The Quantum Computing module was implemented within PLS laboratory, at the University of Bologna in winter 2019. The module was implemented as an extra-curricular course outside school hours. The implementation lasted about 20 hours and involved 25 secondary-school students (16-17 years old) from different schools. The 20 hours (6 days) of the module were part of the program '*Alternanza Scuola Lavoro*'. The module was designed and implemented by the research group in STEM Education of the University of Bologna in collaboration with Elisa Ercolessi, a theoretical physics professor from the Department of Physics and Astronomy.
Activities	The main activities implemented on the course in timely order were: ACTIVITY 1: *A brief history of classical computers* ACTIVITY 2: *Introduction to QM* ACTIVITY 3: *Two-qubit systems* ACTIVITY 4: *Cryptography* ACTIVITY 5: *Quantum Teleportation* ACTIVITY 6: *Quantum Computing & …* ACTIVITY 7: *Mapping the problem and system thinking* ACTIVITY 8: *Back to the Future* ACTIVITY 9: *Basic Creative Thinking* ACTIVITY 10: *Scenarios & Backcasting* *Presentations of the final projects*: the student groups presented their final projects to the class. Activities 1, 3, 4, 5, 6 are new activities that were integrated in the Finnish module. In Activity 2 we used, as the Finnish partner, a simplification of the *spin first* approach to introduce quantum concepts, and we developed it until introducing two-qubit systems and the concept of entanglement that was, in our path, crucial. This concept was indeed introduced in order to address cryptography and teleportation as concrete examples of the potentialities of quantum technologies. In particular, teleportation protocol was chosen instead of Deutsch's algorithm. While the Finnish module envisaged that each day was dedicated in part to the content lessons (encountering with the focal issue) and partly to the future-future oriented activities, the Italian module saw the first 3 lessons mainly dedicated to quantum physics (activity 2, 3), to the introduction of quantum technologies and their implications (activity 4, 5, 6)

	Future-oriented activities (10, 11, 12 and 13) have been completely taken from the Finnish module.
Comments	• We had to schedule the course differently than the Finnish partner: the PLS laboratory included 6 meetings (1 per week) of 3 hours each. The differences in the temporal structure of the module and the difficulties highlighted by the Finnish partner (the connection between quantum computers and future; quantum algorithm) led us to make some different choices, based on the work shared within our research meetings. o In order to strengthen the connection between quantum computing and the future we developed some specific activities that explore the impact of quantum computers in the society, through the introduction of the Quantum Manifesto and a synthetic presentation of some developing applications of quantum computing (see activity 5). o In the light of problems that the Finnish partner found with the students' understanding of Deutsch's algorithm, we chose to propose the teleportation protocol and to compare one of its experimental implementations with its algorithmic representation (see activity 6). • The problem with Deutsch's algorithm led us to search for a global approach that then formed the basis for the design of the internal module: re-reading an experiment in terms of circuit and logic gates. • Only a part was dedicated to classical computers and their logic (activity 1). We did not spend much time on computer components and on its structure. Most of the module concerned the introduction of the key concepts of quantum physics, quantum technologies and their implications. As regards the difference between classical and quantum computers, we have particularly leveraged on the new logic that characterize these technologies. • The presentations of the final projects showed some difficulties of the students with the concept of scenario. The future-oriented activities appeared to be effective to foster students to think out of the boxes and to create a deep engagement. However, for "imagining a future scenario" they limited themselves to think about a job that appealed to them and to identify a problem that will be solved in the future.

Italian Path