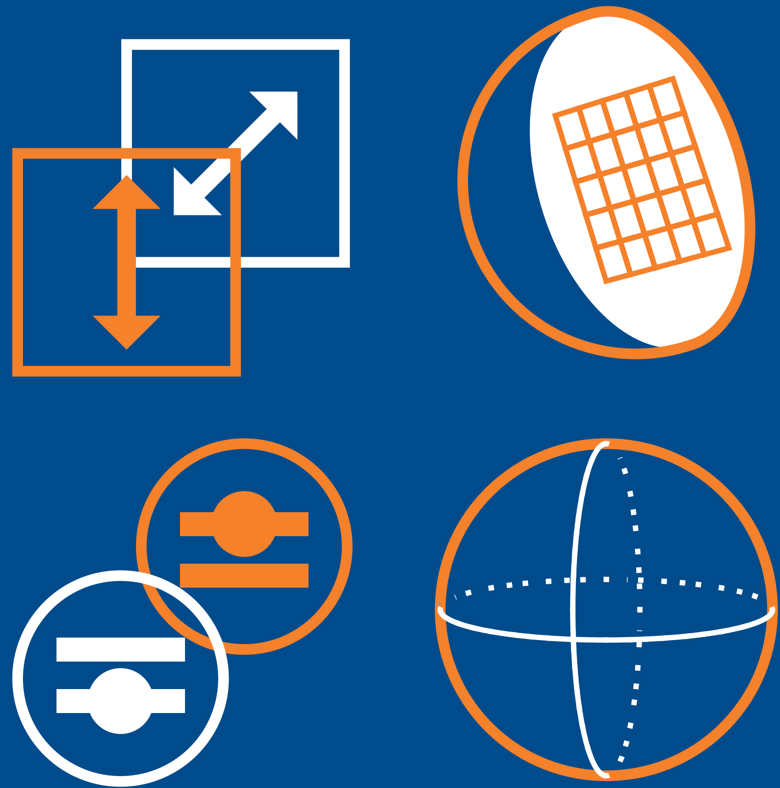
Quantum Technology Student Resources



UK NATIONAL
QUANTUM
TECHNOLOGIES
PROGRAMME

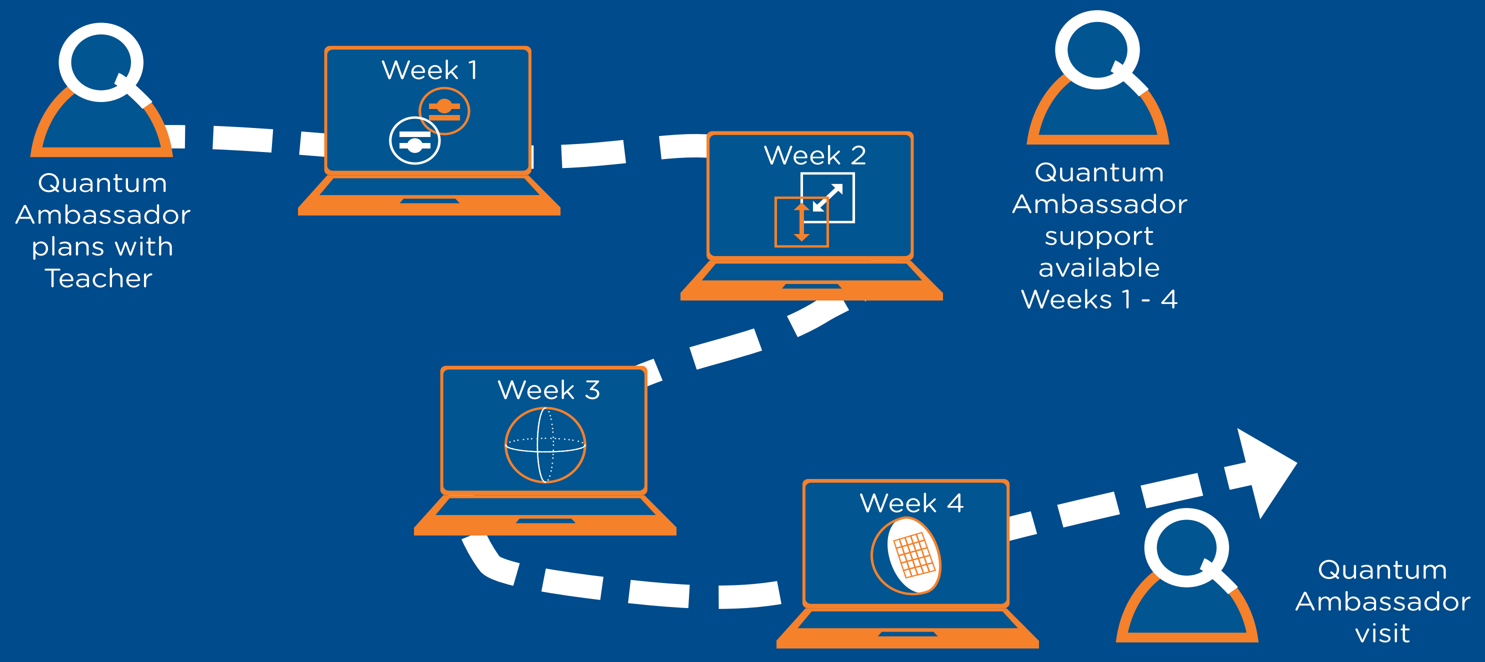
Quantum *noun* :
a discrete quantity of energy proportional in magnitude to the frequency of the radiation it represents[1] (plural **quanta**).

Quantum mechanics *noun* :
the branch of mechanics that deals with the mathematical description of the motion and interaction of subatomic particles, incorporating the concepts of quantisation of energy, wave–particle duality, the uncertainty principle, and the correspondence principle[1].

National Quantum Technologies Programme :
a ten-year £1 billion public and private investment underpinned by the UK government, aiming to accelerate the translation of quantum technologies into the marketplace, boost British business and make a real difference to our everyday lives.

[1] Oxford Online Dictionary. Retrieved via Google Dictionary, April 2021.

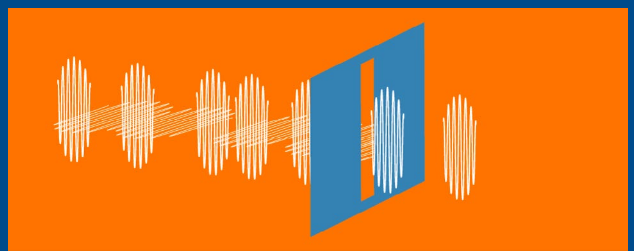
Student Resources Overview

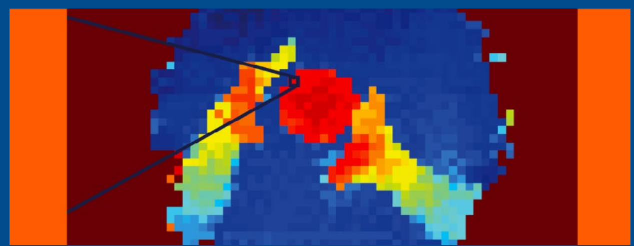


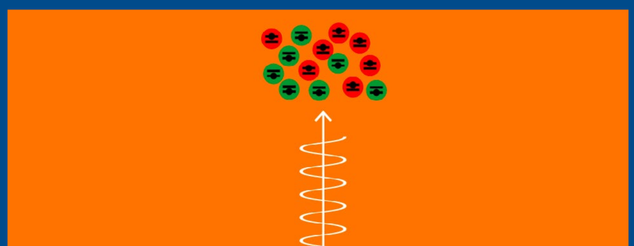
This document accompanies a series of four online lessons in quantum technologies; they have been developed for 16–18-year-old students of physics, maths, and computer science. Each lesson lasts around 40-50 minutes and introduces an aspect of the work going on within one of the four hubs that make up the National Quantum Technologies Programme.

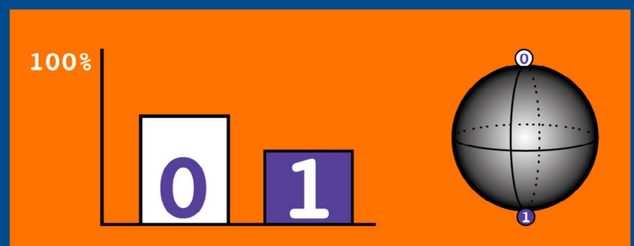
It is expected that these lessons will be studied by students on their own at home over a series of a few weeks; lessons include videos, diagrams, step-by-step guides, questions and more. They are available to students across the UK, and the students' independent study will be supplemented by one or more visits in person or online by a Quantum Ambassador.

Quantum Ambassador: someone working in industry or academia using quantum technologies, working to provide outreach for students.


Quantum Communication


Quantum Imaging


Quantum Sensors and Timing



Quantum Computing and Simulation

Sadly, many students in their school studies may reach the conclusion that quantum mechanics is an interesting but esoteric tool that only has academic applications, for example when trying to catalogue the subatomic particles in CERN or to explain astronomical phenomena. Without programmes like this, students are unlikely to realise the wide-range of industries and universities that are currently developing real-world applicatoins of quantum technologies. The areas in development as part of the National Quantum Technologies Programme are expected to have applications across multi-billion-pound industries in a large number of markets, with profound changes coming as these technologies mature.

It is hoped that as well as increasing knowledge and understanding, some students may be interested in the variety of potential careers that are available to them in related fields.

This guide is written for teachers and the Quantum Ambassadors, to provide an overview of the programme and the resources.

The need for quantum science in the UK

This new era of quantum technologies will transform economies in our maturing digital age and help to address society's challenges; advancing health care and environmental protection, achieving net zero targets and better land use, supporting financial services and communications, providing defence and security capabilities and computing power. These technologies will create new global market opportunities and competitive advantage for those able to develop and exploit them, unlocking innovation by integrating them into complex systems. For this reason, significant efforts are being put into developing quantum technologies globally. The UK is poised to be part of the creation, as well as the application, of quantum technologies.

The National Quantum Technologies Programme (NQTP) was established in 2014 by a range of partners to make the UK a global leader in the development and commercialisation of these technologies. World class research and dynamic innovation, as the Government's R&D Roadmap stresses, are part of an interconnected system. The NQTP's achievements to-date have been enabled by the coherent approach which brings this interconnected system together. This focus sets the UK apart from the international competition.

More information can be found in the Strategic Intent document, which sets out objectives to develop a quantum-enabled economy.

https://uknqt.ukri.org/files/strategicintent2020/

QUANTUM COMMUNICATIONS HUB

Quantum Computing & Simulation Hub

UK Quantum Technology Hub Sensors and Timing

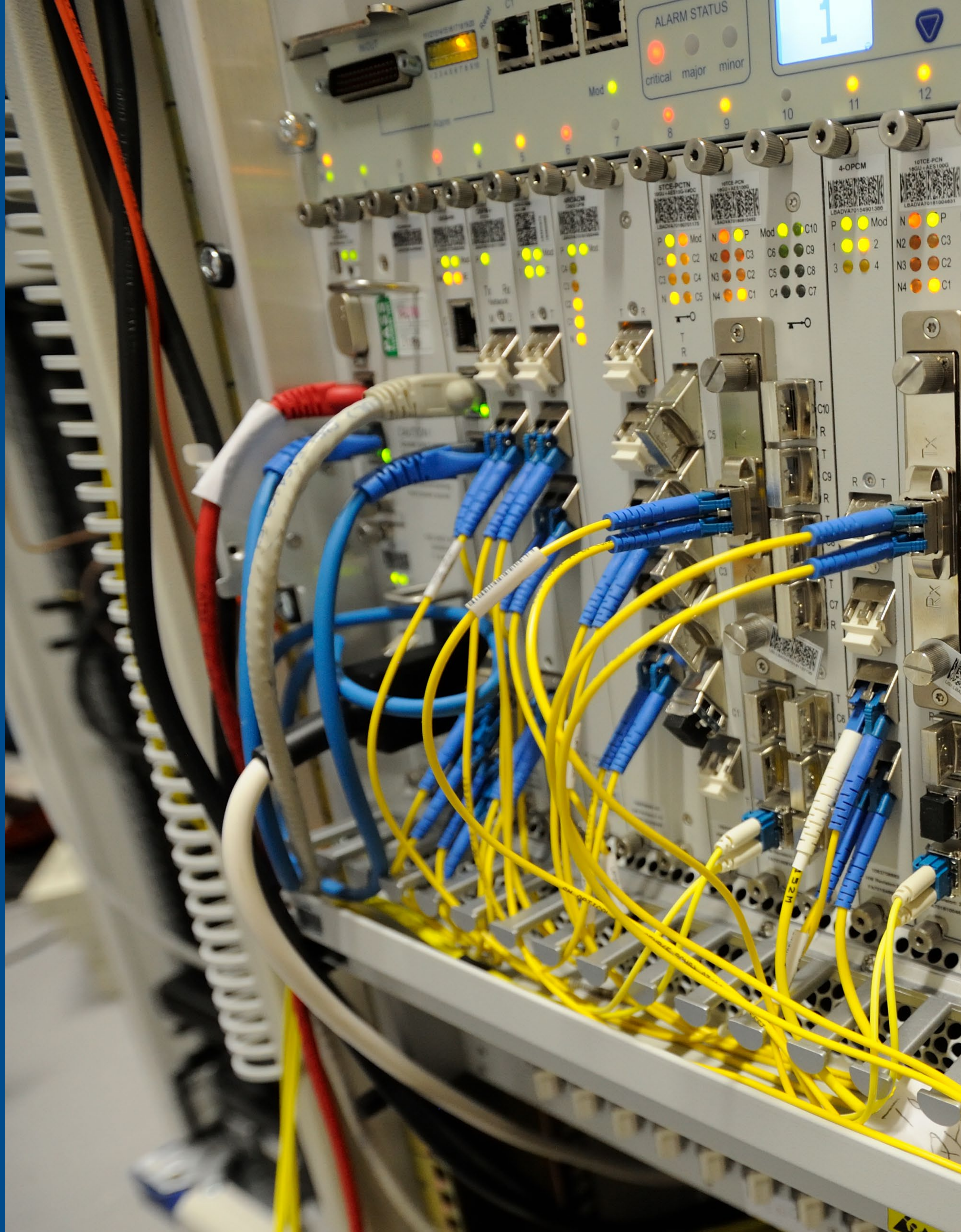
QUANTIC
The UK Quantum Technology Hub in Quantum Enhanced Imaging

Quantum Communications Hub

Current secure communications systems have vulnerabilities, some already exposed today and others that may become apparent in the future as computing power and hacking techniques improve. Secure communications based on quantum physics can eliminate some of these vulnerabilities, providing systems whose security is underpinned by the laws of Nature. The basic features of quantum physics that enable secure communications are that information encoded in a quantum system cannot be copied; and that information encoded in a quantum system is irreversibly changed when somebody reads it, so that no hacking goes undetected.

Our researchers in the UK Quantum Communications Hub are developing such quantum secure communications technologies (for example, quantum key distribution – QKD) for a range of applications and users: from government agencies and industry to commercial establishments and all of us at home. In particular Hub researchers are: miniaturising quantum systems for development of chip-based devices; securing banking apps and ATMs; creating a UK Quantum Network initially linking Cambridge and Bristol; developing prototype quantum secured approaches for digital signatures and document authentication; investigating quantum random number generators; developing ground-to-satellite quantum communications links; and undertaking cryptographic, security, vulnerability analysis and testing of all our technologies with the view to develop effective and protective countermeasures.

Included in the Hub partnership are many UK Universities (Bristol, Cambridge, Glasgow, Heriot-Watt, Kent, Queen's Belfast, Oxford, Sheffield, Strathclyde, and the lead – York), industry partners such as ADVA, BT, Fraunhofer UK, ID Quantique, Teledyne e2v, Toshiba and many more, and public sector bodies such as the National Dark Fibre Facility, National Physical Laboratory and RAL Space.



Photons are sent down optical fibres, generating a quantum key (photo by Dr Adrian Wonfor).

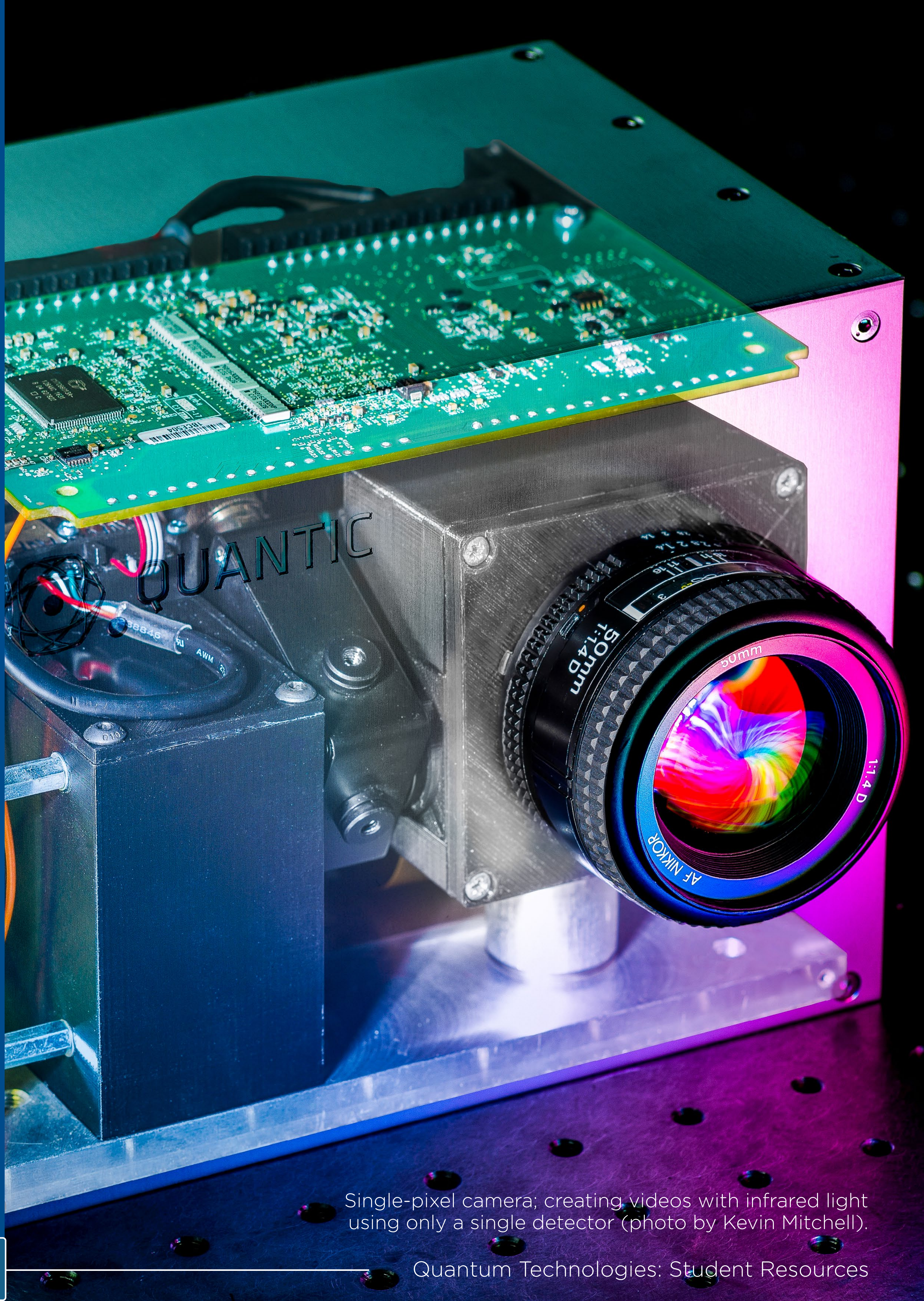
QuantIC - Quantum Enhanced Imaging

QuantIC, the UK Quantum Technology Hub in Quantum Enhanced Imaging, was formed to apply quantum theory and technology to the development of new cameras with unique imaging capabilities. Our vision is to pioneer a family of multidimensional cameras operating across a range of wavelengths, time-scales and length-scales.

QuantIC is working to create imaging systems with the ability to see directly inside the human body, the ability to see through fog and smoke, to make microscopes with higher resolution and lower noise than classical physics allows and quantum radars that cannot be jammed or confused by other radars around them.

These developments will be made possible by new technologies, such as single-photon cameras and detectors based on new materials and single-photon sensitivity, combined with our new computational methods.

Our technologies can address challenges in transport, life sciences and security.



Single-pixel camera; creating videos with infrared light using only a single detector (photo by Kevin Mitchell).

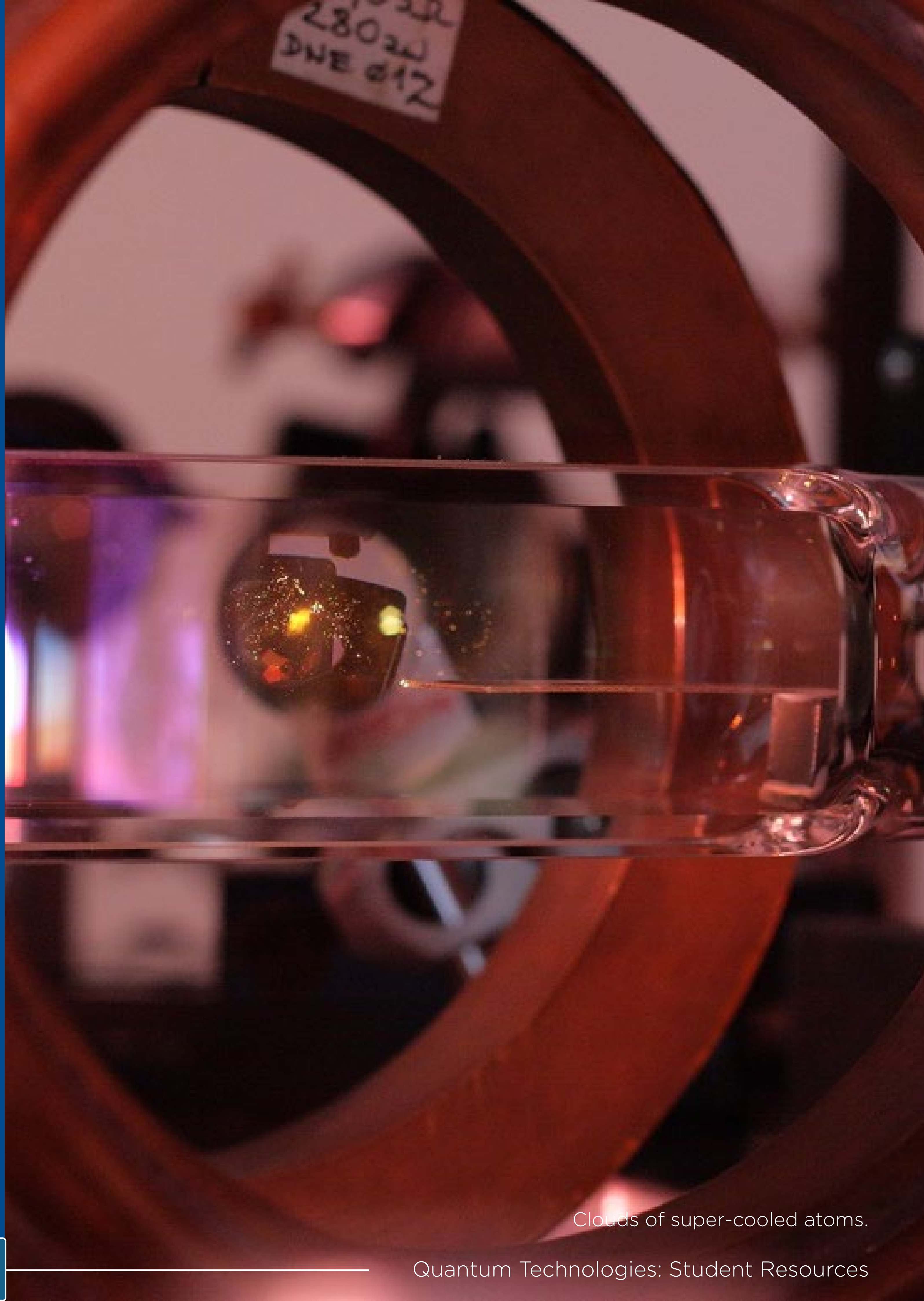
UK Quantum Technology Hub - Sensors and Timing

We are the UK Quantum Technology Hub Sensors and Timing, led by the University of Birmingham. We work with quantum experts at the Universities of Birmingham, Glasgow, Imperial, Nottingham, Southampton, Strathclyde and Sussex, and well as the National Physical Laboratory and the British Geological Survey.

We are using quantum science to develop sensor technology and highly accurate timing devices. Sensors are all around us – in the phones in our hands and even in lights in our homes and offices. However, these sensors are very limited in what they can detect.

At our Hub, we're aiming to create ultra-precise quantum sensors with extremely high detection capabilities. These sensors will be used across many different sectors, such as civil engineering, where sensors can be used to see deep underground, identifying smaller and deeper objects, such as sinkholes, boreholes and mineshafts. We are also developing extremely accurate and robust clocks which will lead to improved navigation systems; these will have improved long-term stability and reduced size and power consumption. Quantum timing devices will lead to improved navigation systems and GPS tracking devices, ultra-fast broadband internet and will be needed in banking trade environments, where buying and selling shares needs the most accurate of time stamps.

Some of our technology is based on cold atoms science - when atoms are cooled to temperature near absolute zero using finely controlled lasers and magnetic fields, an ideal state for scientists to explore and discover new quantum behaviour and new states of matter.



Clouds of super-cooled atoms.

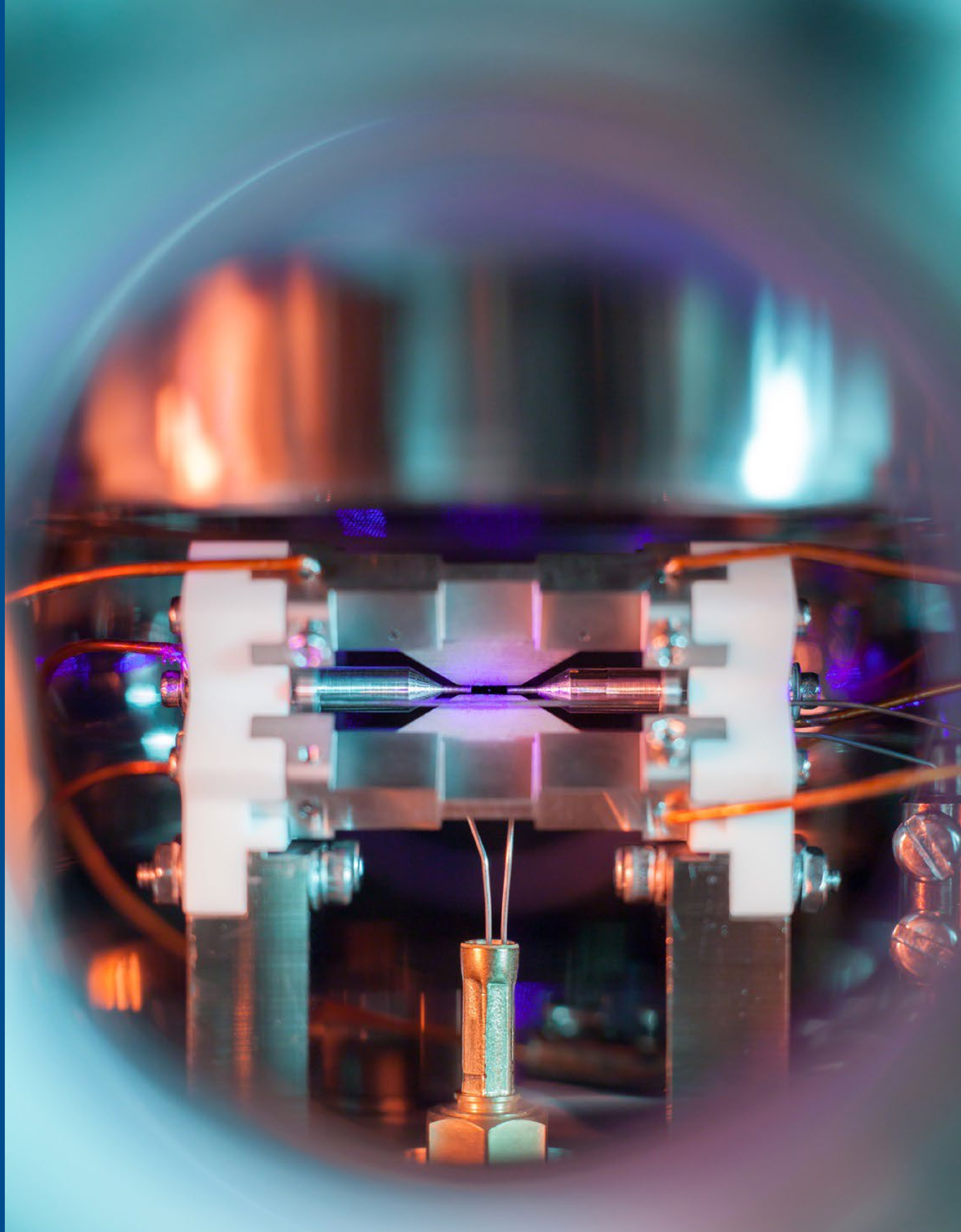
Quantum Computing and Simulation Hub

The UK's Quantum Computing and Simulation (QCS) Hub is a collaboration of 17 UK universities, working with commercial and governmental partners to put the UK at the forefront of the global race to develop advanced quantum computing. Researchers in the QCS Hub come from a diverse range of disciplines, reflecting the many different skills required to transform this area.

Quantum computers have the potential to provide answers to a vast array of real-world questions and enable new approaches to problems that classical computers are currently unable to handle. Quantum computing and simulation will, for example, accelerate the development of new drugs and materials, change the landscape of cyber security, and exponentially increase the speed of machine learning. The key challenge in quantum computing is the creation of scalable and accurate high-quality qubits (quantum bits) which are the quantum equivalent of the binary bits that form the cornerstone of classical computing.

From a hardware perspective, the Hub's activities include the development of scalable technologies for both near-term and long-term quantum computers and simulators. The Hub is working on a number of approaches, some examples of which are "trapped ion" systems, in which qubits are created using single atoms suspended in magnetic fields and stimulated by lasers, the use of artificially created defects in diamond lattices, and the adaptation of traditional silicon wafer technology.

Work on software and applications within the QCS Hub includes the development of algorithms and protocols for how such machines could be used, as well as techniques to verify their accurate operation. Researchers are also studying the architecture of quantum computers in order to develop emulation techniques that will allow future applications to be tested.



A single atom in an ion trap (photo by David Nadlinger).

Lesson structure

All four lessons are standalone; they do not need to be studied in order.

They all follow the general pattern:

- an introduction to the type of problem, and the existing approaches being used;
- an explanation of the science behind one of the quantum technologies currently under development;
- further exploration of the challenges, the current state of the technologies and the wider work of the hubs.

Most of the questions can be answered by students using the information provided, requiring knowledge from their 11-16 science studies.

In the lessons about atomic interferometry and LiDAR systems there are some questions that require that they have existing knowledge from their further education (details of these are given in the relevant sections).

Hub	Focus of lesson	Recommended for students of:
Quantum Communications Hub	**Quantum Key Distribution** is a method of creating a secure communication channel.	Physics, computer science, or maths
QuantIC: Quantum enhanced imaging	High-resolution and high-speed **LiDAR systems** that detect individual photons are being developed to create detailed depth images.	Physics
UK Quantum Technology Hub: Sensors and timing	**Atomic interferometry** can be used to create a gravitational gradiometer for measuring very small changes to gravitational fields.	Physics
Quantum Computing and Simulation	The complexities of real-life **quantum systems** cannot be modelled easily on conventional computers, but it may be possible on a large enough **quantum computer**.	Physics, computer science, or maths

Students are likely to have heard the following quote (or similar variants):

> "I think I can safely say that nobody understands quantum mechanics."
>
> Richard Feynman

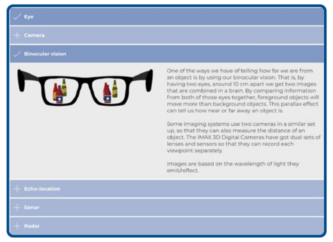
Without the full context of this quote, it is possible that this can be misleading our students. Quantum mechanics as a tool for modelling systems is well-understood by thousands of people, and it is continually being used in countless applications throughout the world. Elsewhere, Feynman says that the challenge is perhaps not that we cannot understand or describe quantum behaviour, but that we have an:

> "...utterly vain desire to see it in terms of something familiar."
>
> Richard Feynman

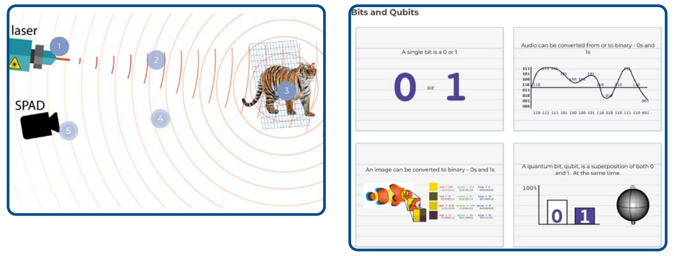
With this in mind, as well as giving students an awareness of the work of the Hubs, one of the objectives of these lessons is to help students see that quantum behaviours, no matter how surprising or unfamiliar they may appear, can be modelled, predicted and harnessed in the same way as other conventional technologies.

A variety of elements are used in the lessons to promote engagement from the students.

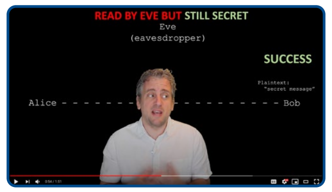
Annotated text



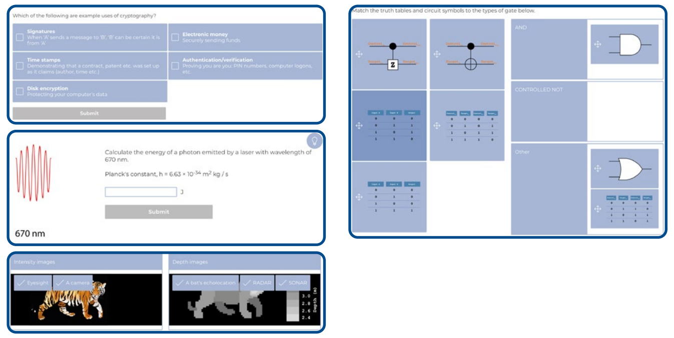
Interactive infographics



Videos



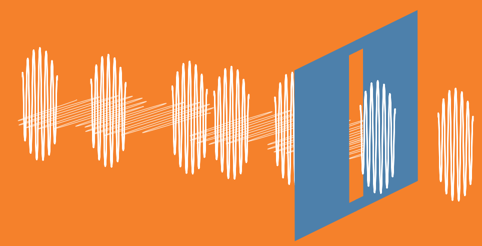
Different question styles



Lesson 1: Quantum Communication

Teaching route

The estimated time for students to self-study this module is 40 minutes, and is split up into four sections to be studied in order.



Learning objectives

The learning objectives for this student task are as follows.

1. Quantum Key Distribution (QKD) is a way of generating a secure key between two parties.
2. It relies on a natural laws of physics to create this key, rather than difficult maths.
3. During the process where this key is generated, if someone is listening-in, then they will be detected. If no-one was listening-in, then this key can be used to encrypt the message (and the key is then discarded).
4. The encrypted message can now be sent conventionally between the two parties, with a guarantee that only the other person can decrypt it.
5. One of the protocols used for Quantum Key Distribution is called BB84

Prior knowledge

Students should be happy with the idea that light can thought of as an **electromagnetic wave**, with all the associated behaviours of waves (including polarisation), and that light can also be thought of as being made up of **individual photons**.

Students should already be familiar with **polarisation**. Ideally this will have involved playing with the transmission of light for a range of polarising filters in a lab, but should also include real-world contexts (such as 3D movies, LCD screens, anti-glare sunglasses, etc.)

They should know what happens to the intensity of a polarised wave passing through a polarising filter at 0°, 45° and 90°. This is recapped during the session.

Familiarity with using **truth tables for binary logic gates** is an advantage.

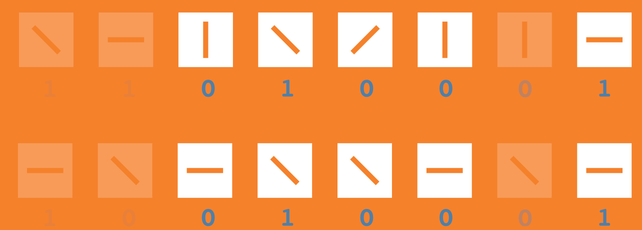
Key challenges

The following are points for discussion/emphasis that are likely to cause some confusion for students.

- The quantum key that is generated is not a message, and this is not the information that Alice and Bob want to communicate. However, it is random and it is secure, so it can then be used to encode the real message (or to share other cryptographic keys that can then be used to encode the actual messages).
- There is a profound point about the nature of light: the property of an individual photon cannot be determined without measuring that photon.
- If a photon has passed through a polarising filter then it will now have the polarisation that matches the axis of the filter (regardless of what its polarisation was before).

1 Why do we need cryptography? This explores, through videos and questions, the wide range of places that humans have historically used cryptography and how it's used in the modern world. The language and the simple models for talking about cryptographic systems are explained (for example, the model of Alice trying to securely communicate with Bob without Eve being able to listen in). It sets up the idea that modern computer networks are susceptible to attack by a third-party who is listening in, trying to work out the original message.

2 What physics do you need to know? Polarised light behaving as a wave is first considered, looking at what happens to the transmitted intensity when a polarised wave passes through a filter at 0°, 90° and then 45°. Snell's Law, used to quantify the intensity of transmitted light, is introduced as an idea. The probabilities of an individual polarised photon being absorbed or transmitted as it passes through a filter at a range of angles are then discussed. This is followed by questions about the number of photons transmitted if a large number of polarised photons hit a filter at different angles.



Message to encode	0	1	1	1	0	0	1	0
Quantum key (random & secure)	1	1	0	1	0	0	1	1
Publicly shared cipher-text	1	0	1	0	?	?	?	?

3 Can physics help us to send messages secretly? The BB84 method of generating a Quantum Key is examined step-by-step. There are questions to check that students understand that each bit of the key will only be identical for both parties if/when they were generated and received using the same randomly chosen polarisation basis (rectilinear or diagonal). If Bob chooses a different basis to Alice then that bit has to be discarded.

The task then explores that if Eve is eavesdropping then she will introduce errors into the system; it asks students to determine the size of this error. Error correction and privacy amplification are summarised as techniques that Alice and Bob can use to increase their security if a small number of errors are detected.

4 So, what is QKD and who is using it? The XOR logic gate is briefly explained, and students are then asked to use it to show how a message can be combined with a randomly generated quantum key. This creates a cipher-text that can be shared publicly, with no possibility that it can be cracked by any eavesdropper. Students then use the same XOR operation to decode the original message from the cipher-text and quantum key.

Finally, some of the challenges of building a real-world quantum network are explored, providing context for the different research areas of the Quantum Communications Hub.

Lesson 2: Quantum Imaging

Learning objectives

The learning objectives for this student task are as follows.

1. A quantum imaging system can measure the time-of-flight for individual photons sent from a laser pulse. By knowing the speed, it can work out the distances accurately.
2. It builds up an image of an object, based not on what it looks like, but upon the distance to the parts of that image.
3. Thousands (or more) of pulses can be sent every second; by looking at all of this data background interference can be ignored.
4. This enables images to be constructed that can do seemingly impossible things, such as imaging through clouds or around corners.
5. LiDAR (Light Detection and Ranging) systems are already extensively used, with a wide range of applications. As their cost comes down further, and their resolution goes up, they will be used more and more.

Prior knowledge

Students should be very comfortable with distance = speed × time so that they are able to calculate a distance using the time of flight of a sound or light wave that is bouncing off of a surface.

To work out the number of photons in a laser pulse in section 3, students should know they can use $E=hf$ to calculate the energy of a photon, and $v=f\lambda$ to determine the frequency of a photon.

Students should be able to calculate the area of a hemisphere (or sphere).

Students should be comfortable working with standard form numbers and be able to express them in the format 3.0E8.

Hints and tips for all these tasks are available to students during the online lessons.

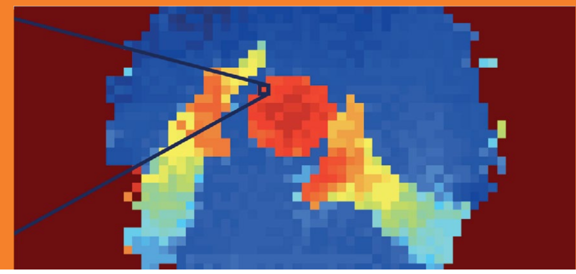
Key challenges

The following are points for discussion/emphasis that are likely to cause some confusion for students.

- When using LiDAR we are not creating an image based on colour or brightness in the same way as a photo is generated; we are only ever generating a depth image. When we add colour to one of these depth images, it is a false colour, added to help humans to interpret the data.
- When using the QuantiCAM system there may be significantly more detections that come from background light than are reflections that began with the laser source. However, this does not need to be a problem, because by creating a histogram of thousands of events, a peak can still be identified that will correspond to reflections from the laser source.
- Some students are likely to struggle with some of the steps in the calculations. Hints and answers are available as they go, and to help students there is no need for students to carry numbers forward from one part of the question to the next.

Teaching route

The estimated time for students to self-study this module is 50 minutes, and is split up into four sections to be studied in order.

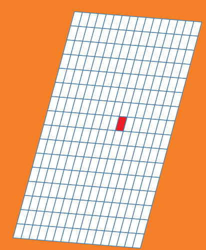


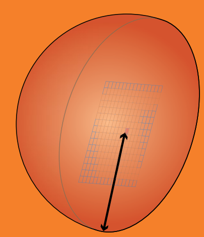
1 How do we generate images? The initial task is to compare different imaging systems that students should already be familiar with. They should know that some images are constructed using the colour and brightness of different surfaces: these are intensity images and examples include cameras and the human eye. However, some images are constructed by measuring the distance to different parts of the objects: these are depth images and examples include RADAR and a bat's SONAR.

This is followed by simple calculations to measure a distance when told the total time of flight of a sound or light wave reflecting off an object.

2 What about LiDAR? LiDAR is compared with RADAR, and raster scanning for LiDAR systems are examined. The Hub's QuantiCAM system is then explained: it uses a laser being pulsed at a very high rate (for example, ~80 000 times in a millisecond, to make up a frame) flooding the whole area on each pulse. An array of Single Photon Avalanche Diodes (SPADs) forms the sensor; each pixel on every frame may record hundreds or thousands of individual photons, with each event recording the time between pulse and detection.

The data from the histogram of a single pixel in a single frame is analysed by students, to calculate an accurate distance, whilst ignoring any background light or scattering.





3 Some calculations. This task is a series of seven calculations using plausible numbers from the QuantiCAM system. Students will calculate that 6 700 000 photons from a laser pulse head towards an object 1.5 m away, and that some will reflect off each part of that object, and then return to be counted by each individual SPAD within the sensor. Using the numbers provided in the question, the average number of photons detected at each pixel from a reflection event is shown to be only 0.0034. However, this is statistically observable compared to background light, by identifying a peak on the histogram (which represents the number of photons counted from over 80 000 pulses for each frame).

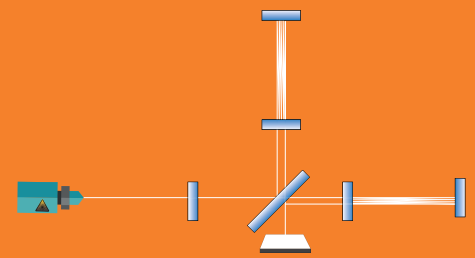
4 What about applications? LiDAR is already used in phones for face unlocking, augmented reality and improved focussing in low-light. LiDAR is also one of the technologies being used in autonomous or semi-autonomous vehicles. Both of these examples of LiDAR are described in this section.

Some exciting uses that are enabled using the powerful technology in the QuantiCAM are then explored, using the time-of-flight method of detecting individual photons. This includes the ability to image through clouds and even the ability to construct an image of an object that is hidden around a corner.

Lesson 3: Quantum Sensors & Timing

Teaching route

The estimated time for students to self-study this module is 40 minutes, and is split up into four sections to be studied in order.



Learning objectives

The learning objectives for this student task are as follows.

1. An interferometer sends beams down two separate paths; by looking at interference patterns you can measure very small changes to those paths.
2. Light interferometers have been used for years, and recently led to the first ever detection of gravitational waves from the collision of two black holes at LIGO.
3. Atomic interferometers have the potential to be even more sensitive. Supercooled atoms act as the ‘beams’, and they rely on laser pulses to act as beam splitters and mirrors.
4. Clever techniques, such as firing the atoms up into the air or running two experiments on top of each other, can be used to increase the sensitivity of the detector.
5. Practical applications include being able to measure very small changes to gravitational fields, which could enable more accurate underground imaging without needing to dig down.

Prior knowledge

Students should be familiar with the **gravitational field strength**, g, and be able to work out the **forces between two masses using G**.

They should be aware of **wave-particle duality** that both light and atoms can be thought as a wave or a particle: for example, the ideas that **photons have a momentum** and that **atoms can have a wavelength**.

It would be helpful if students were already familiar with **light interferometry**, but this is summarised in the session.

Key challenges

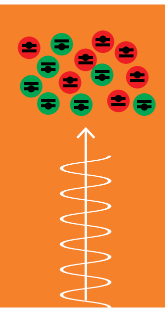
The following are points for discussion/emphasis that are likely to cause some confusion for students.

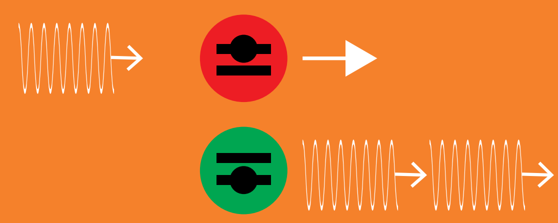
- Some students may think that the wave-particle duality is a problem that scientists cannot solve. We would like them to realise that although the behaviours may go against day-to-day common sense, they are very well understood and well described phenomena and do not represent a problem.
- Students in their studies are likely to have met the wave-particle duality for light on number of occasions: the photoelectric effect, double-slit interference, etc. There will be many different mental images, and students can struggle to swap from one model to the other.
- However, students are likely to be even less confident that atoms can behave like waves: they will have studied fewer examples, and will probably have spent many years building up a strong mental model of atoms and subatomic particles as spheres.
- In the fourth section we consider a beam of Rubidium atoms that is fired up and which are then in free-fall. It is not easy to see that this beam of atoms is undergoing free-fall on the way up in the same way as on the way down – students will tend to think of the apex as being special, but in reality, the forces are unchanged.

1 **The usefulness of measurements.** A history of how gravitational fields have been measured since the time of Newton is described in a video. This is followed by a discussion of some of the uses for research and industry that could occur if we could improve the sensitivity of our gravitational measurements. There is then a calculation to determine the very small gravitational force between two lead spheres, as were used in Cavendish’s experiment at the tail end of the 18th century.

2 **Interferometry.** This begins with a quick check that students are aware that both EM radiation and matter can sometimes be considered as a wave, but also as a particle. Some of the differences between waves and particles are compared.

Light interferometry is then summarised, through a series of annotated diagrams, highlighting that although we tend to describe the process as a wave-like behaviour, it is also possible to send an individual photon that can travel simultaneously through both arms of the interferometer, causing it to interfere with itself. The Laser Interferometer Gravitational-Wave Observatory (LIGO) is then highlighted as the example interferometer that first measured black holes merging.





3 **Atomic interferometry.** Atomic interferometry is explored by considering first a batch of atoms falling through an interferometer, and then an individual atom falling and travelling through both paths. Atomic interferometry is explained by analogy with light interferometry, making comparisons between the component parts: the beams, the mirrors, the beam splitters, etc.

4 **Interferometer calculations.** Calculations are done using information about the portable gravity gradiometer that is currently being developed by the Hub; it uses a cloud of super-cooled Rubidium atoms in free-fall. There are also discussions about techniques to increase the sensitivity of the interferometer, and comparisons between a gravitational gradiometer (which measures how a gravitational field changes spatially) and a gravimeter (which just measures the gravitational field strength).

Lesson 4: Quantum Computing

Learning objectives

The learning objectives for this student task are as follows.

1. Whilst a quantum computer still has binary inputs and outputs, they store information as qubits, which can be a superposition of 0 and 1 simultaneously.
2. When you have multiple qubits, they can become entangled; this enables qubits to affect each other.
3. The properties of superposition and entanglement mean that quantum computers solve problems in a different way to conventional computers. A sufficiently large quantum computer will be able to solve some types of problems that a conventional computer just cannot, or may be able to solve them much, much faster.
4. This quantum advantage is likely to occur around 53 qubits.
5. A major application for quantum computers is the ability to simulate quantum systems, which should eventually be used for developing new pharmaceuticals and materials virtually.
6. A large enough quantum computer will also be able to break the public-private key encryption that much of the internet relies on to keep it secure.

Prior knowledge

Students should be familiar with **simple mathematical techniques**, including probability and factorisation.

Familiarity with using **truth tables for binary logic gates** is an advantage.

It would be useful for students to be aware that the **superposition of light** can cause interference patterns, for example in a double slit interference experiment. However, this is explained in the resources.

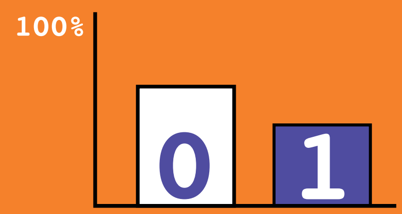
Key challenges

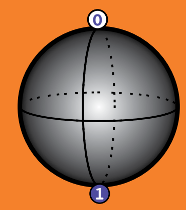
The following are points for discussion/emphasis that are likely to cause some confusion for students.

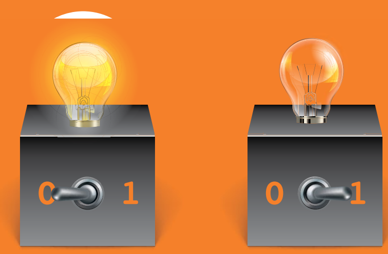
- Students may have met the term superposition several times before, but they will struggle to visualise something that can simultaneously be in multiple states, until it is observed.
- It is challenging to compare conventional computers with quantum computers because of the very different way in which they work. It is helpful for students to understand not only how qubits differ from conventional bits, but how this can affect the types of problem you are able to solve.
- There is a clear separation between the hardware and software challenges in quantum computers. Some of the challenges in constructing a quantum computer include: creating qubits that remain entangled, minimising 'noise' within the system, setting the input states and reading the output.

Teaching route

The estimated time for students to self-study this module is 40 minutes, and is split up into four sections to be studied in order.

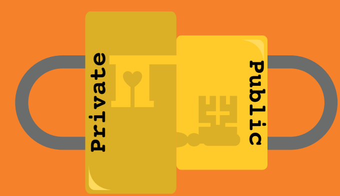


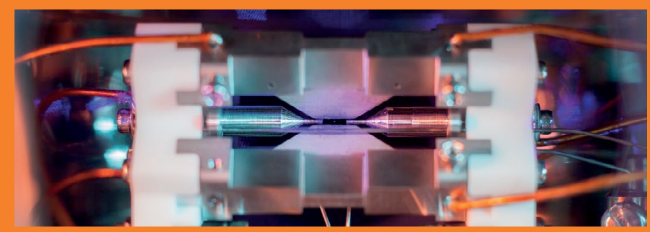




1 **What is a quantum computer?** Through analogy with a conventional computer, quantum computers are explored in a video and then through a series of questions – with a qubit being described in some detail. Truth tables are considered for an AND gate, and then for a conventional CNOT gate. The behaviour of how a single CNOT gate might behave in a quantum computer is then explained, with qubit values being a superposition of 0 and 1 at the same time.

2 **When can quantum computers provide an advantage?** Given a conventional computer and a quantum computer are both 'black boxes' that process binary inputs and create binary outputs, this section looks at why there is so much excitement about quantum computers, and the type of problems that they are good a solving. This compares the different approaches that a conventional and quantum computer would use when solving the Deutsch-Jozsa algorithm.





3 **Uses of quantum computers.** The first area considered is that real-life quantum systems cannot be easily simulated on a conventional computer, because as the system increases in size the computing power needed to model it grows exponentially. However, a quantum computer does not have this limitation, so should be able to solve problems that are impossible for conventional computers.

The second area considered is by using quantum computers to solve optimisation problems, such as factoring large primes – and the danger this has to current internet security, which is reliant on public-private key encryption.

4 **Building a quantum computer.** The final section looks at the current status of quantum computer development from some of the lead industries, and some of the hardware approaches that are being pursued. The power of these computers is compared to the theoretical quantum advantage, and questions are posed about the future of quantum computers.

Curriculum links

These lessons are being made available to students in further education. The experience of 11-16 year olds will vary; for example, some students may have never heard the term 'photon' as part of their studies. Therefore, if students are engaging with these resources at the start of their further education, they are likely to be meeting some new terminology.

16-18 years olds who are part way through their physics studies are likely to have a broader knowledge of quantum systems.

Relevant topics covered in physics by further education specifications may include:

- the polarisation of electromagnetic waves, including Snell's Law
- the photon model of electromagnetic radiation, including the energy of a photon
- the photoelectric effect
- superposition, constructive/destructive interference caused by path differences
- double- and multi-slit interference patterns
- wave-particle duality and the de Broglie equation
- electron diffraction

It may be useful for teachers and Quantum Ambassadors in any initial meeting to share information about the subjects the students are taking, and if they have already studied any of the above topics in physics.

Additional resources

Each of the lessons includes at the end a suggested reading list for extra information about the technologies involved.

Each of the hubs also maintains their own web-site with more information about their own work.

The UK National Quantum Technologies Programme
https://uknqt.ukri.org/

UK Quantum Technology Hub - Sensors and Timing
https://www.quantumsensors.org/

Quantum Computing and Simulation Hub
https://www.qcshub.org/

QuantIC - Quantum Enhanced Imaging
https://quantic.ac.uk/

Quantum Communications Hub
https://www.quantumcommshub.net/

Quantum Ambassador Visits

Quantum Ambassador visits, whether they are face-to-face or virtual, are a chance for students to meet a role model from industry or academia, and to ask questions about the quantum technologies they have been studying.

It may be some time since you have worked with students, so this section is a short summary of some things to think about and some top tips to help you prepare for meeting with students.

Please plan to talk about yourself and the work you're doing, but also ensure that there is plenty of time for students to ask follow-up questions about quantum technologies in general and your work.

Please do

- Tell the teacher in advance how long you will allow for questions, so that they give students time to prepare.
- Be clear if you're happy for students to ask you questions as you talk or if you would rather have them at the end.
- Ask the students questions – these can be a mixture of closed questions (with a single correct answer) and open questions (which need a student to explain more).
- Use any relevant vocabulary that students may need to understand your work, but take the time to explain any new terms that are crucial to understanding.
- Try to avoid unnecessary jargon, acronyms or initialisms.
- Share visuals of your work/research that you have available.

Preparing to meet the students

These following are some questions you may wish to consider before meeting the students.

- What are you currently working on? Does it relate to the work of one of the hubs?
- How did you get your current job? What did you study, and what other roles have you done?
- What is your work like on a day-to-day basis?
- What excites you about the future of quantum technologies?

Getting the balance right

It can be a challenge to know what level you should pitch your work at. It is probably better that you pitch your talk slightly above some of the students, rather than to go too low and risk patronising them. Remember, the teachers are also there to help, and can help to interpret if needed by some students.

You may wish to familiarise yourself with the four online lessons in advance, and to check with the teacher which have been completed by the students.

Role models

Further information about many of the people working within the hubs can be found on their websites and YouTube channels. This is one example of an interview from the QuantIC Hub.

The team at QuantIC caught up with Emma Le Francois to find out more about being a PhD student and what motivated her to join the UK National Quantum Technologies Programme.

Emma came to the UK from France in 2016 as an Erasmus student before deciding to embark on a PhD with Professor Martin Dawson, Director of Research in the University of Strathclyde's Institute of Photonics.

At the moment you are undertaking your PhD at the University of Strathclyde, what exactly is it that you are working on and what is a typical day like for you?
My PhD consists of developing a three-dimensional imaging technique that can reconstruct an object's surface using light-emitting diodes (LEDs) and a mobile phone. The LEDs modulation scheme was already developed when I arrived on the project, so my first task was to implement an algorithm, using Matlab, that integrates the surface normal components to obtain the surface topography of a scene or an object. Now, I am working on combining two 3D imaging methods together (Time-of-Flight and Photometric Stereo) in order to reconstruct a discontinuous scene in high-resolution.

I always start my day by checking my emails to be up to date with different tasks I might be asked to do. Then I go to the lab to take some measurements or correct the experimental setup depending on previous results. After that, I do some image processing on Matlab. When I start something new, I spend some time checking the literature or teaching myself how to code in a new language. For example, I'm currently following a course on Coursera about Deep Learning because I need to speed up the computational time of my algorithm.

Why did you decide to do a PhD in the field of quantum imaging, what attracted you to it?
At first, I wanted to work in industry in a R&D group and at an interview I was told told that a PhD would be useful in the quantum imaging area. I was already a Master student at Strathclyde when I noticed this studentship on "High-speed, ultra-low photon flux imaging". After an internship on night vision glasses, I knew I wanted to work in an area that deals with camera, imaging technique and image processing. Quantum imaging englobes a lot of interesting research which made me want to try it. On top of that the studentship was co-funded by Fraunhofer UK so that gave me the opportunity to keep a link with industry and applied research.

Can you tell me a bit more about your experience of applying for your studentship?
I remember it to be easy and straightforward. I first had an interview and a lab tour with Michael Strain. It took me a few weeks before making the choice to apply for the studentship as I was still having a look at a job opportunity in the industry. One night, I realised that I wanted to take the studentship position. The application process was easy, I needed to send a motivation letter, my CV and two recommendation letters. Two days after applying, I was granted the studentship.
I understand your studentship was sponsored by Fraunhofer UK, what do you feel you have gained from your placement with them?

The benefit from being sponsored by Fraunhofer is the support I obtain from them on a regular basis and the access to their lab if I need any specific equipment. From the beginning of the studentship, the details of the project were decided with both my supervisors and a researcher from Fraunhofer so that all the work that I achieve can also benefit them. Knowing that the work is applicable and lines up with a project plan gives a great motivation at the beginning of the PhD. Another great advantage is if you have an innovative idea that can be commercialised then Fraunhofer UK can be of a great support as they can help you get started.

Can you tell us a bit more about the career paths you are considering?
After the PhD, I want to find a job in industry as R&D engineer. The part that I like in research is developing a product that will have a specific use. Ideally, I would like to keep working in the quantum imaging area or start working in AR/VR as I heard interesting talks about this field at a conference in Washington DC.

Women in STEM subjects are unfortunately the minority, do you feel as though you have experienced any barriers because of your gender?
I personally never experienced a situation where I felt like I could not do it because of my gender. Since high school, I've always been supported by my teachers and family and I'm grateful to them. I believe that in Europe a girl who wants to pursue studies in STEM can do so. It is true that women are still in minority but I'm confident that the situation will improve, slowly maybe, but surely. Many events are hosted to support women in STEM and the word will spread to the young people that physics is fun and available to everyone. I personally work in a group where I'm the only woman and I don't even notice it! My voice is heard the same way as my colleagues' and my gender does not have to do something with it. It is important to highlight the work of women to encourage younger girls that they can do the same. However, in my opinion, it is also as important to make sure women are "selected" for their work and not for their gender. For example, we need to be careful with quotas, a woman that is selected to give a speech only because the event needs more women does not help women integrate easily in the STEM research area.

What do you feel is the highlight of your career to date and why?
A paper about my work on 3D imaging using LEDs and a smartphone has been recently published by Optics Express. I take it as a great achievement because this paper has first been rejected and it was hard to hear it first. But by listening to the different advice from the reviewers, with the help of my supervisors, the paper is now published. As a student, I sometimes wonder if I have the capacity to do it, if I have selected a career path that fits me or if I aimed too high. Seeing your work being acknowledged as innovative by other researchers gives you the confidence that you need to feel like you belong in the quantum community.

Do you have any advice for someone who might be considering a studentship in quantum imaging or quantum technologies?
Doing a PhD can be quite challenging, so I suggest that you pick a topic that sounds fun to you because you will spend a lot of time on it. Keep in mind that no matter the subject you choose, you will always be able to follow your career in a different research area if you wish. Quantum technologies is a vast topic and you don't need to be good in every theoretical aspect of it to start a PhD as you will learn everything you need as you go along.

The Quantum Technology Student Resources were designed and written by Alan Denton in collaboration with the Hubs and STEM Learning.