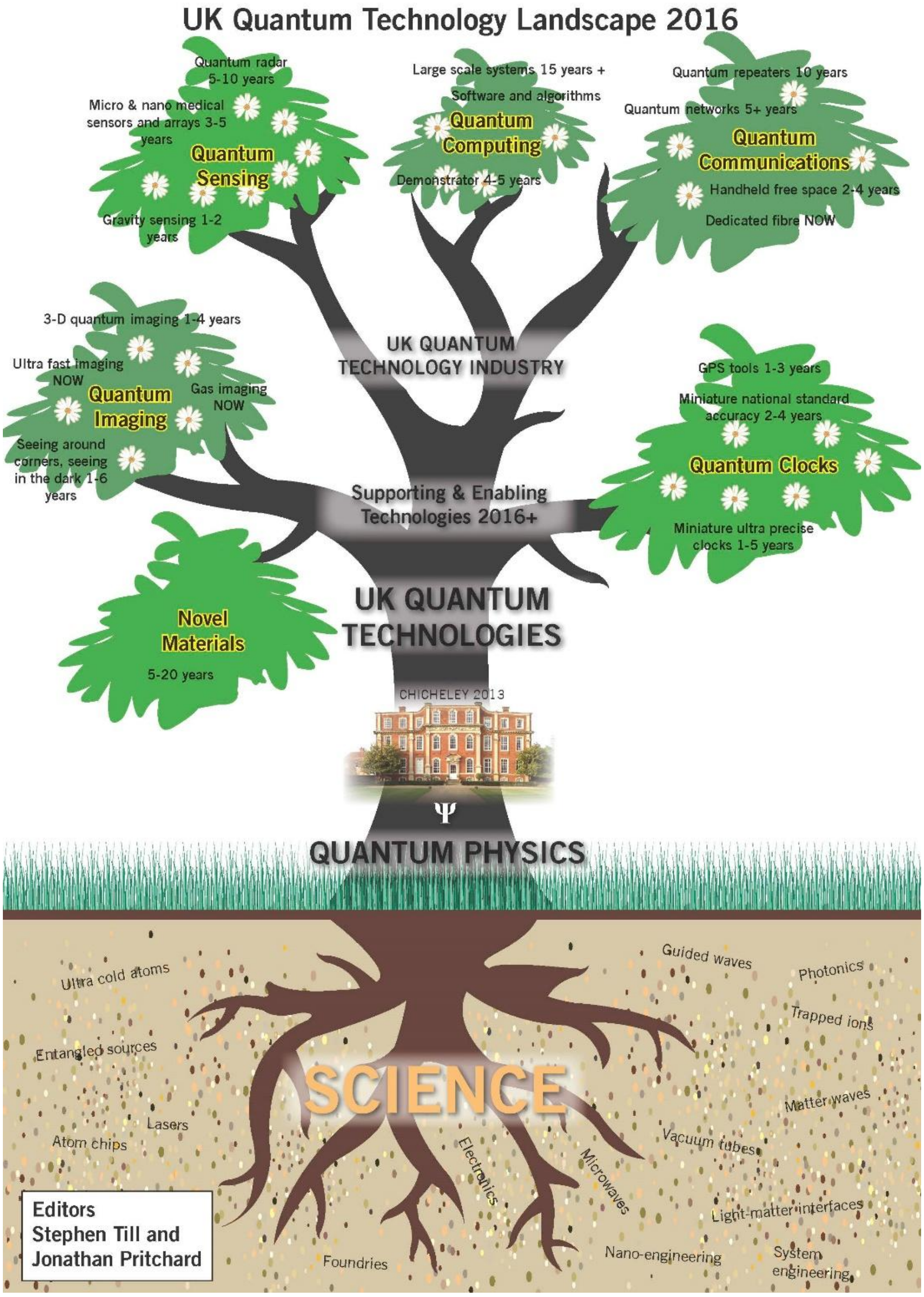
A perspective of UK Quantum Technology prepared by and for the UK Quantum Technology Community



1 Foreword

The UK has for a long time had a strong academic research base in quantum science, funded largely by the EPSRC and its predecessors. Further funding has been provided by other government agencies and departments, particularly the MoD and NPL. Indeed, the current funding for quantum science related research through the EPSRC is around £65m. However, converting this great science into generally applicable technology and products was for a long time considered to be some way off into the future. However, in 2013, largely driven by Dstl, a meeting was held at Chicheley Hall both to review the state of quantum developments, and also to map the current UK activities in these areas across academia, industry and government. That meeting and the resulting UK Quantum Technology Landscape document, resulted in a consensus across all those involved that the science was at the point where real workable technologies were practical, and that a new quantum based industry was on the cusp of being achieved. This galvanised the community, working closely together, to bid to government for a major "Quantum Technologies" (QT) initiative. This had the aim of providing a major kick start for these developments in the UK, and in particular to ensure that the UK would be a major beneficiary of a new quantum technologies industry. That bid was successful, and the government provided £270m over a five-year period for the first phase of this programme.

We are now approaching the mid-term review of the first phase. The major investments made by all the partners are already resulting in very significant progress, with industry beginning to develop the first generation of components and products based on these new technologies. However, the UK is not alone in seeing the potential of Quantum Technologies. Other countries are also now making significant investments. In 2016, with the assistance of the Royal Society, the community organised an open two-day Discussion Meeting in London. This was followed by a smaller two-day satellite meeting at Chicheley Hall at which invited participants conducted a focussed appraisal of key technological developments and examined the current UK QT Strategy. As preparation for this, Dstl colleagues, working with the UK QT community, prepared a preliminary update of the original UK Quantum Technology Landscape document. The view of the participants at that second meeting was that the UK would significantly benefit from a fully revised Landscape document, covering all UK activities, not just those directly funded by the UK QT Programme. The document should also identify the major international initiatives to provide an international context for the UK activities. The resulting document is a major piece of work and provides a unique snapshot of the rapidly developing QT field. It is an invaluable resource for the UK QT community and government. Although almost all members of the UK quantum community have been involved in its production, I must thank and acknowledge the work of Jonathan Pritchard and Stephen Till in pulling this together.

David Delpy

2 Contents

3 Executive summary

This document supersedes the UK quantum technology landscape 2014[1]. It represents the state and outlook of the UK quantum technology community, with key contributions from government agency representatives and pre-eminent workers in the field. We describe how quantum science is being harnessed for wealth creation, defence and security. We also describe the current state of quantum technology in the UK together with a brief overview of other efforts around the world, as well as the progress made in our combined national programme. The national programme, together with the complementary MOD quantum technology initiative, represent a unique team effort by academia, Industry and several government departments.

During 2013, we had established a well-coordinated team to develop new technologies. Our champions included leading academics, GCHQ[2], EPSRC[3], TSB (now Innovate UK[4]), NPL[5] and Dstl[6]. Representatives of those groups, in partnership with the Royal Society[7] and representatives from Industry met at Chicheley Hall from 10-13 November 2013 to agree the initial strategy and way forward for the UK to exploit this emerging field.

In the 20th century, our understanding of quantum physics gave rise to the quantum revolution. This represented an advance in our understanding over "classical" laws of physics, such as Maxwell's equations, thermodynamics and Newton's laws that gave rise to the industrial revolution. This new knowledge allowed us to develop for example, lasers, nuclear power, micro-electronics and solid state imagers. In our 2014 paper, we recognised that the currently emerging quantum technologies rely on the subtler, less familiar aspects of quantum mechanics. We recognised that these technologies have the potential to create a "second quantum revolution". Our mission is to create that second quantum revolution in the UK with our coordinated national initiative.

The programme is known as the National Quantum Technology Programme (NQTP). It won an initial grant of £270M of new money from the Chancellor for a first phase of five years, which resulted in the establishment and first 18 months of operation of four hubs, led by Oxford, Birmingham, Glasgow and York universities. Together with a unified community made up of a wide range of academics, government departments, the National Physical Laboratory, MOD (Dstl) and industry we have developed, and made significant progress towards, a vision of instituting a multi-billion pound industry aimed at wealth creation for the UK.

Each hub has made excellent progress, with deep engagement with industry. Over 100 companies are now involved with the initiative, with some making sizeable investments[8]. Each hub has a number of products lined up, with appropriate supply chains being constructed. Underpinning and enabling technologies are set to become businesses in their own right, with the launch of several product lines imminent. During the process of industrialisation, commitment and investment for

1 See https://www.epsrc.ac.uk/newsevents/pubs/Dstl-uk-quantum-technology-landscape-2014/
2 See GCHQ website.
3 See Engineering and Physical Sciences Research Council website.
4 See IUK website
5 NPL = National Physical Laboratory
6 Dstl = Defence Science and Technology Labs, Dstl is an Executive Agency of MOD which ensures that innovative science and technology contribute to the defence and security of the UK.
7 See the Royal Society website
8 Figures are withheld due to confidentiality issues

innovation needs to be sustained, i.e. we need to sustain and, if possible, increase, the "drumbeat" of our initiative.

The Birmingham hub is developing atomic sensors, the Glasgow hub imaging sensors, the Oxford hub quantum computing and simulation, and the York hub quantum communications. Each hub also includes a wide spread of associated activities (see section 5.3). Outside the hubs structure, there is a wealth of additional activity, in particular concerned with research and its development in complementary areas. EPSRC is also sponsoring centres for doctoral training (CDTs) and a number of quantum fellowships for both early and mid-career scientists.

The MOD, (as first adopter of substantial steps in novel technologies) is exploring complementary activities, i.e. miniaturised atomic clocks at Birmingham and NPL, atomic gyros at NPL, atomic accelerometers (for a quantum navigator) at Imperial College, and a gravity imager being built at Birmingham. The MOD is also sponsoring 46 PhD projects relevant to all of the quantum technology programmes. The MOD and National efforts are unified to maximise synergy and gearing between the two strands.

A second Royal Society meeting took place on the 9th-10th May 2016 in London, and the 11th-12th May 2016 at Chicheley Hall aimed at reviewing and updating the long term quantum strategy. As before, the meeting consisted of talks by leading physicists followed by closed sessions. The purpose of the meeting was to assess the latest progress in quantum physics and technology development, and to develop strategy ahead of the national programme midterm review. This document will become the main evidence base to support the second phase of the programme (years 5-10).

Quantum physics is still a rich and rapidly advancing field with much yet to be discovered and explained. Completely new opportunities for technological development are likely to arise over the next 20+ years or more. We are also on the lookout for new physics and its possible applications.

Strategy output from the Chicheley meeting 2016 included (paraphrased):

- Identify, develop and maintain the relevant ecosystem and its infrastructure;
- Accelerate development and exploitation where possible. Build upon and mature our new way of engagement with industry and other potential stakeholders;
- Improve further our understanding of users and markets;
- In parallel, develop quantum technology supply chains;
- Pay more attention to cross cutting technologies and enablers;
- Consider the establishment of an industry and supply chain hub, and engage with entrepreneurs;
- More innovation funds with greater focus need to be made available for technology translation to marketable products and services;
- We should not necessarily follow the TRL ladder slavishly; many products could be developed via rapid advances that do not demand every intermediate stage to be demonstrated and tested separately;

- We need to ensure a "pipeline" of new products and services through continued investment in focussed fundamental research and development;
- We need to ensure that appropriate reward, recognition and career path be made explicitly available to those physicists and engineers engaged in quantum technology translation, with a route open for them to return to academia after they have made their contribution;
- Ensure adequate funding is available for post-graduate and post-doctoral workers to maintain programme momentum;
- More time should be made available to the most brilliant, key scientists (such as the hub principal investigators) to develop more ideas (including "seed corn" ideas) for new developments as existing technologies reach maturity.
- We should benchmark our activities and successes against activities in other nations, and fine tune our approach accordingly;
- We must drive towards a virtuous circle, where some profits can be returned to academic physics to ensure that intellectual pre-eminence and competitive edge is maintained in the future.

Figure 1 Chicheley Hall - where it all happened *Creative commons attribution-share alike 3.0*

4 Introduction

4.1 Vision

The community's vision for the UK is that it becomes the world leading and world renowned centre leading the second quantum revolution. The first quantum revolution occurred in the 20th century, and gave us many of the technologies we are now familiar with. These include the laser, nuclear power, microelectronics and thermal imagers to name but a few. Now, due to recent advances in quantum physics, we are on the brink of a second quantum revolution.

The UK has many of the brightest physicists in the world. They are enthusiastically working as a single team, together with British industry and several government departments, engineering new products and services that will have beneficial consequences for many aspects of our lives.

Our key goal is wealth creation on a multi-billion pound scale within 10-20 years. Benefits are already beginning to crystallise, and will soon be felt in the areas of health, medicine, manufacturing, finance, exploitation of natural resources, defence and security to name just a few.

Our vision includes the combination of innate scientific capability with a coordinated, enthusiastic nationwide team to push our world class technology forward. As we do so, a virtuous circle will be set up, channelling money back in to research to generate more knowledge that we can transform into more technology and more wealth.

The programme[9] is a coordinated effort between the extensive UK physics and engineering communities, Department for Business, Innovation and Skills (BIS), the Engineering and Physical Sciences Research Council (EPSRC), Innovate UK and the National Physical Laboratory (NPL), in partnership with the Defence Science and Technology Laboratory (Dstl) and the Government Communications Headquarters (GCHQ).

4.2 History

During 2013, there were several initiatives, well-coordinated, to build a case for national funding to develop what were initially known as "quantum 2.0 technologies". This label was used to differentiate between the (mainly) 20th century technologies and the new opportunities which we could see emerging from the latest quantum physics research. The organisations involved in the initiative included (in no specific order) our leading academics, GCHQ, EPSRC, TSB (now Innovate UK), NPL, and Dstl. We foresaw that applications of the latest science could lead to a "second quantum revolution".

In 2013, following the Witty report[10], the MOD Defence Science and Technology Laboratory (Dstl) undertook a detailed analysis of the UK quantum technology landscape. In partnership with the Royal Society, they organised a meeting of leading academics, representatives from Industry, NPL and relevant government departments at Chicheley Hall from 10-13 November 2013. The purpose was to develop further the evidence base for this analysis. The attendees were selected to enable

[9] In this document, we generally speak of a single project as a project, and a programme as a group of projects.

[10] Encouraging a British Invention Revolution: Sir Andrew Witty's Review of Universities and Growth

the meeting to explore how the UK might exploit emerging quantum technologies for the benefit of defence, security and the wider UK economy.

In December 2013, the Chancellor approved £270M of new money for a five-year programme to develop wealth creation and advanced security from UK's world leading quantum physics research base.

In February 2014, the definitive, peer reviewed UK quantum technology landscape document was published[11].

During the rest of 2014, competitions were held for the UK national programme. Four bids were successful in the national competition and these were centred on four hubs at:

- The University of Birmingham (sensing and metrology)[12]
- The University of Glasgow (quantum enhanced imaging) QUANTIC[13]
- The University of Oxford (quantum information processing) NQIT[14]
- The University of York (Quantum Communications Hub)[15]

Concurrently, Dstl submitted ideas for novel, disruptive quantum technologies to the MOD's R&D board. In February 2014 a sum of £30M was approved, with MOD planned to be a "first adopter" for several key technologies. The sum was later increased to ~£36M with the inclusion of (initially) 42 fully funded PhDs. The Dstl programme now comprises:

- The University of Birmingham (gravity imaging sensor and ultra-stable atomic (optical lattice) clock)
- NPL (National Physical Laboratory) (atomic gyros and miniature atomic clocks);
- Imperial College (atomic accelerometers);
- 46 PhD projects at key universities, on long term, applied and system oriented projects.

The National and MOD projects are run as a mutually supportive and synergistic programme. At the end of FY 2016 / 2017, the programme as a whole will be reviewed and any necessary adjustments made.

Over the last two years, significant progress has been made. We will describe this in more detail later in this paper.

4.3 Purpose of this document

This document serves as a 2016 update and refresh of the original 2014 landscape document. It is designed to appeal to a wide audience. It will be useful as a reference for non-technical readers as well as those with some technical expertise in the field. We aim to:

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11 See UK Quantum Technology Landscape 2014
12 Known as UK Quantum Technology Hub for Sensors and Metrology
13 UK Quantum Technology Hub in Quantum Enhanced Imaging
14 NQIT = Networked Quantum Information Technologies
15 Known as UK Quantum Technology Hub for Quantum Communications Technologies

- Act as a general purpose reference for experts and non-experts;
- Provide an update on the progress of quantum technologies, since the first landscape document, particularly in the UK technology context;
- Provide a unified view of UK's integrated approach to quantum technology and its leadership;
- Provide an update of products and markets, i.e. progress of industrialisation;
- Give technically aware people an appreciation of quantum physics and what it could deliver in terms of technologies and benefits;
- Serve as an evidence base and foundation to set strategy and future direction.

4.4 Layout of the document

We start in section 3 by providing a description of our strategy and how it will lead to wealth creation, and a commentary on industrialisation and the creation of supply chains. This leads naturally to the state of enabling technologies and a top level set of development roadmaps, together with some key milestones and their expected timing.

Section 4 describes the UK national quantum technology programme and some of its recent achievements together with the major quantum activities outside the four EPSRC hubs. We include the essential enabling and underpinning technologies, which themselves represent sophisticated technology developments undertaken by our team. Finally, we summarise mainstream UK quantum technologies and, for comparison, provide a global perspective.

In section 5, we introduce quantum physics and describe what makes it so different to the familiar classical world, described by Newtonian mechanics, 19th century thermodynamics, Maxwell's equations of electromagnetism. We describe some counter-intuitive characteristics and effects, and speculate briefly on what the far future may hold.

In section 6 we describe the mainstream emerging quantum technologies in detail. The five main categories are: clocks, communications and networks, sensors, quantum imaging and computers. We include a commentary on when quantum processors are really needed for simulation, and a brief description of quantum technology in the context of materials and nanotechnology, which is a bourgeoning new field of exploration. Underpinning and enabling technology development is a very important component of the programme and will itself become a significant, indigenous wealth creation vehicle, finding markets throughout the world in the research communities as well as enabling system development. These are covered in section 6.3.

"Making it happen" was discussed in some detail in the previous document, which still serves as a useful reference and we will not repeat it here.

Where possible, we have used open source documents to act as references. This allows access to the widest possible community of readers. Throughout the document, the more technical sections are written in indented italics; these sections may be skipped by the non-technical reader.

Finally, we summarise progress and opportunities with conclusions, and draw out some key recommendations.

5 Strategy and industrialisation

5.1 Current strategy

5.1.1 The national quantum strategy

The National Quantum Technology Programme's Strategic Advisory Board (SAB) published a National Strategy for Quantum Technologies in March 2015.[16] The document recognises that to realise the benefit of quantum technologies, the UK must succeed in converting its world-leading research into innovative and marketable products. This requires a national strategy, sustained over time, to which all parties remain committed.

The strategy has been drawn up by the Strategic Advisory Board (SAB) with input from the Programme Operations Group (POG) on behalf of the UK quantum community. Its purpose is to guide new quantum work and investments over the next 20 years to help deliver a profitable, growing and sustainable quantum industry deeply rooted in the UK. The vision is to create a coherent government, industry and academic quantum technology community that gives the UK a world-leading position in the emerging multi-billion-pound new quantum technology markets, and to substantially enhance the value of some of the biggest UK based industries. Key elements of the published strategy are:

- Enabling a strong foundation of capability in the UK;
- Stimulating applications and market opportunity in the UK;
- Growing a skilled UK workforce;
- Creating the right social and regulatory context;
- Maximising benefit to the UK through international engagement.

In order to achieve these objectives, we will:

- Invest in a 10-year programme of support for academia, industry and other partners to accelerate jointly the growth of the UK quantum technologies ecosystem;
- Sustain investment in the vibrant UK quantum research base and facilities;
- Incentivise private investment, including through road mapping and demonstration, and support early adopters of these new technologies as they emerge over differing timescales;
- Enable industry to use state-of-the art UK university facilities;
- Invest in the development of a dynamic workforce that meets the needs of future industry supporting the free flow of people, innovation and ideas between academic, industrial and government organisations;
- Drive effective regulation and standards and champion responsible innovation;
- Preserve the UK programme's competitive advantage as a global supplier of quantum devices, components, systems and expertise while continuing to play a leading role in engaging globally in the development of quantum technologies.

16 See https://www.epsrc.ac.uk/newsevents/pubs/quantumtechstrategy/

The vision is not only to grow and develop a quantum technologies industry, but to ensure it remains strongly rooted in the UK and delivers long-term benefits to society as a whole. The National Quantum Technology Programme has already brought about some significant changes in the UK.

The current investment is the first step towards establishing a quantum technologies industry in the UK and creating environments and skills for early innovation and product development. Subsequent investment will secure this foothold and stimulate growth of the emerging industry, ensuring a pipeline of new ideas. Failure to invest would have meant failing to capitalise on the UK's strengths and previous investment in basic research, leaving it trailing the rest of the world.

In addition to the SAB's Strategy document, Innovate UK has published a Roadmap.[17] This shows companies where new opportunities in quantum technologies overlap with their interests and helps them to understand how these new applications could drive their growth. It also highlights the challenges and barriers that must be overcome if UK businesses are to become world-leading in new quantum technologies. We elaborate on the baseline roadmap in section 6.4.

Innovate UK has also created a Special Interest Group (SIG) as part of the Knowledge Transfer Network (KTN) to help shape the future of the emerging quantum industry, which is expected to have a major impact on the finance, defence, aerospace, energy and telecommunications sectors.

5.1.2 MOD quantum strategy

In February 2012 the UK "National Security Through Technology" white paper was published. Amongst other things, this document recognised the changing nature of the defence and security threat faced by the UK and recommended that defence and security R&D should evolve to meet the new threat. The option which was finally chosen dedicated a significant fraction, 20% - 30%, of the MOD Research Building Block (RBB) to investigate, and develop rapidly, promising technologies which have the potential to achieve game changing and disruptive advantage. The concept is similar to the US DARPA programme in which a small number of selected emerging technologies are well funded and where research is stopped if the concepts prove to be flawed or impossible to achieve ("fast to fail").

The opportunity presented by cold-atom physics has been firmly embraced by DARPA (see sections 5.1.6 and 6.4) and cold atom technologies are now believed to be subject to ITAR control.

The MOD Defence Science and Technology Laboratory (Dstl) proposed a Disruptive Capability programme to what is now the Defence Research, Development and Innovations Board. The outputs would comprise demonstrators for:

- GNSS independent positioning, navigation and timing system comprising sub-systems whose performance achieves a disruptive improvement over existing technology and available for technology insertion to upgrade e.g. timing and synchronisation across a range of platforms and military operations;
- a gravity field imager capable of detection and classification of object and voids of interest. No countermeasures to such a system are believed to be possible.

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[17] See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/470243/InnovateUK_QuantumTech_CO004_final.pdf

As the technology is developed, it is anticipated that new militarily disruptive technologies e.g. novel communications or radar modalities, will be enabled. There will also be potential for commercialisation, delivering economic benefit as well as improvements in size, weight and power through optimisation by industry facilitating access to a wide variety of markets.

The Dstl programme will benefit from gearing with projects within the National Quantum Technology Hub Network, and vice versa.

In the longer term, defence is expected to benefit from quantum communications, quantum computing and development of some of the more esoteric sensors. However, the near term strategy is to observe progress and support activities by funding PhDs where appropriate.

5.2 Wealth Creation from new quantum science

5.2.1 Introduction

This document is attempting to meet the needs of a very broad audience, hopefully without reading too much like a text book. This section is particularly aimed at a non-technical audience. This includes industrial collaborators, including their MDs and Finance directors, as well as senior decision and policy makers in BIS, MOD, Treasury and other departments. Ideally it should be read in conjunction with the first Landscape document which clearly set out a range of possible technical opportunities and its sections on "making it happen", which has been applied with great success.[18]

The first quantum revolution and an initial understanding of quantum effects led to the development of nuclear power and refinement of semiconductor electronics; subsequently the transistor had enormous world impact. All modern electronics depends on the transistor. In the form of integrated circuits, it provides phones, televisions; controls car, lorry, aircraft and train engines; and provides computers and the internet. Without the age of quantum discovery, the world would have limited communications, minimal IT and there would be far fewer options to tackle global warming in the absence of PV solar cells and nuclear energy.

Applications of recently developed quantum science will add an extra dimension of capability to optical and electronic devices, which may have a huge number of diverse applications. Some of these can be predicted, such as machine learning using quantum computers, however we are certain that there will be a large number of others that currently remain unimagined.

5.3 Economics

Our comments on the economics of the quantum technology programme will be necessarily limited. Comprehensive analysis, looking forward, of the economic impact of emerging technologies is notoriously difficult. Such analyses are usually addressed by dedicated professional teams.

"Wealth creation" draws its meaning from well-established economic models of a national economy. In its simplest form, there are two significant economic sectors, private and public. Political idealism is often aimed at achieving a balance of the two which may differ depending on the party concerned.

[18] https://www.epsrc.ac.uk/newsevents/pubs/Dstl-uk-quantum-technology-landscape-2014/

The concept key to "wealth creation" is the circular flow model[19], which describes the way that economic entities interact. There is no universally accepted single definition of "wealth creation", although two common definitions are:

- The increase in the stock of Land, Capital and Money. This can be applied to economic entities, or aggregates such as the whole Nation[20];
- The increase in the capacity of individuals to consume goods and services.

In the context of this document, wealth creation is considered at the national level of aggregation and our interpretation of the government's vision is to improve the UK's "books" significantly, well beyond the cost of investment. Wealth resulting from the UK quantum technology programme is likely to increase via the following mechanisms:

- Increased productivity leading to higher value adding companies that result in their workers earning more;
- A virtuous "success to the successful" effect where the higher volume of money flow leads to more investment in more economic assets, subsequently leading to future growth. Ideally, there will be investment in longer term assets (such as more research into ultimately wealth creating physics and other fundamental sciences);
- New or re-modelled companies which take increasing share of the circular flow of money, offering higher profit. There are already some good, early examples.
- Lagging indicators across the supply chains including:
    - High wage rates and high levels of employment
    - Increased company sales and profits
    - Increased tax returns

Many factors connected to these ingredients are inextricably linked, with many interactions across the economy. The essence of value added may be summarised:

- Increased national productivity;
- Increased volume of private sector economic activity.

This description does not capture all important factors, such as national health and happiness. That is one major reason why public engagement is important; quantum technology is likely to enable significant advances in medicine for example.

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[19] See circular flow of income, for a simplified explanation

[20] Money is a debateable part of this measure; on the one hand it can supposedly be freely exchanged for Land and Capital and so is equivalent. On the other hand, there is only so much Land and Capital available for purchase within a Nation, so adding it in is double counting. When international trading is taken into account (Land and Capital can be bought from an "infinite" external stock) it is probably correct to include money.

5.4 Economic impact

The future of the UK Quantum Technology programme up to and beyond 2019 will depend on a number of factors including successful demonstration of useful new technologies and their transfer to the emerging UK quantum industry. Sustained funding will be essential. Economic benefit at the mid-stage of our ten-year programme will include:

- Opportunity to establish sustainable and large scale manufacturing in a new and growing area where UK has strong competitive advantage;
- A new sector which is high in value and highly differentiated. We can expect turnover per employee to exceed £100K/year and margins well suited to the fuelling of growth;
- Flexibility – quantum educated workforce is highly adaptable and could be deployed to help to make up for a wide range of STEM related shortfalls;
- Highly leveraged – quantum systems and services are expected to bring major competitive advantage to some of the largest established UK industries e.g. construction, mining, oil/gas;
- New jobs created in industry as well as academia; difficult to estimate but currently in the order of hundreds and possibly thousands;
- Rapidly emerging businesses in the field of supporting and enabling technologies, such as magneto-optic (cold atom) traps, specialised lasers and laser systems, and vacuum technology. Services such as highly sensitive quantum gravitational field analysis will soon become available to prospecting, civil engineering, mining and the military and security.

Currently, "green shoots" exist in all those areas, these are most encouraging as we are less than half way through the first five-year phase.

5.5 Industrialisation of quantum technologies

Because 21st century quantum physics is providing an even deeper and more insightful view of the true nature of our universe than the early (20th century) theories, it is realistic to expect a similar global impact over the coming century. In 1947 there was little inkling of where the USA Bell Labs invention of the transistor would lead, although the team were awarded the Nobel prize in Physics a decade later, in 1956.

The exploitation plans suggested in this section will only be the start of a long journey. It is clear, however, that the more these technologies infiltrate everyday life, becoming consumer devices, the more that they become greater than mere technologies. To reach a sophisticated level of integration requires an in depth knowledge of what people want, and how these new devices are perceived. By way of an example, just ask people on the street why they own an iPhone, a car or even a simple wrist watch. For many the use is far more than just the need to make a telephone call, travel from A to B, or tell the time. These devices normally cause an emotional response, which is rarely achieved through functionality alone.

For large scale exploitation to take root, the latest quantum technologies must transition from laboratory to industry and be adopted on an ever increasing scale. This happened with transistors, integrated circuits, computers and modern communications. In addition, further development of these devices is needed if mass markets are to be created. Future devices must become less specialised, more easily used, and prices must (normally) decrease considerably.

Although development of any particular device might involve very advanced physics and cost a relatively large sum of money, the commercial fabrication of many quantum devices is intrinsically cheap as they will be made using mass production, with some eventually incorporating integrated circuit-like technology.

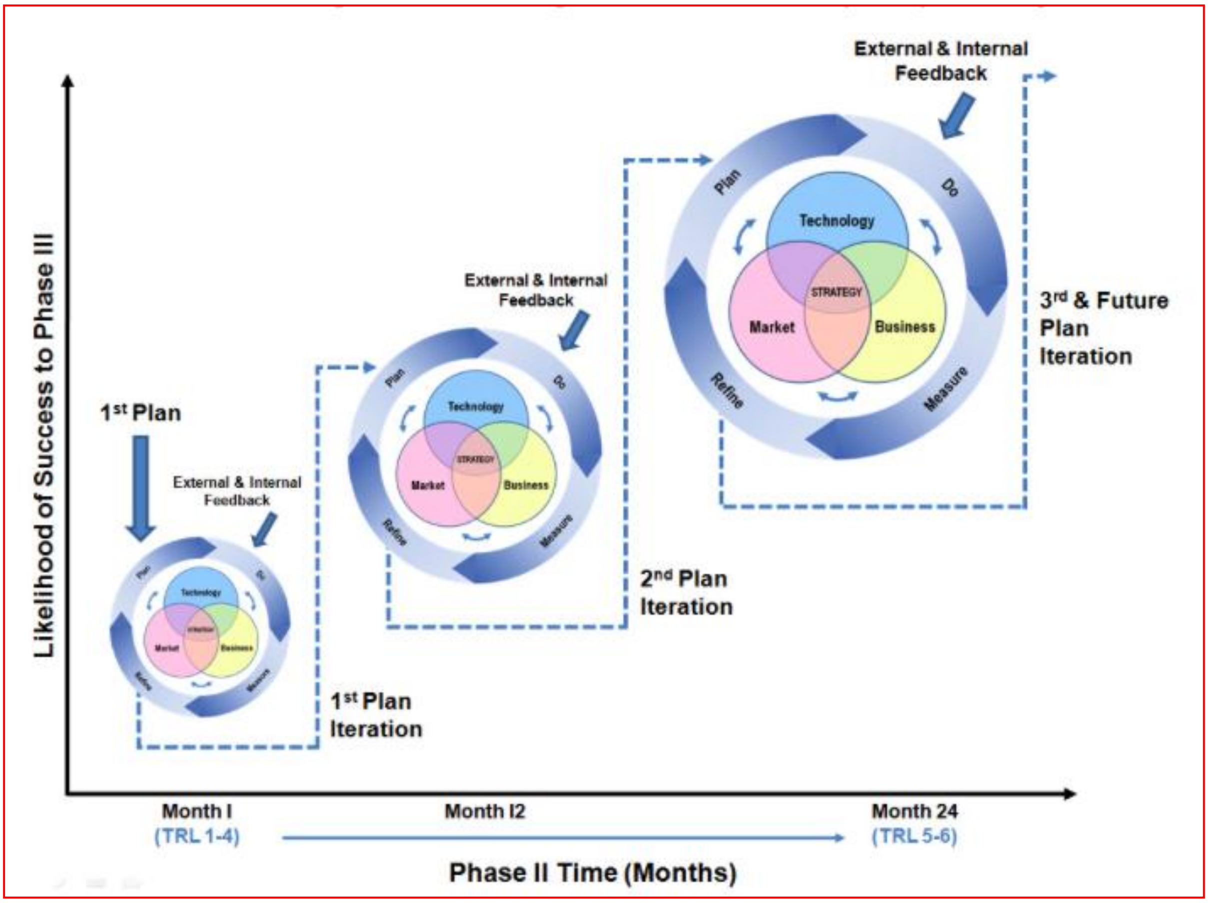

Figure 2 DARPA process for bringing technologies to market *Credit DARPA*

The path taken between an idea to a prototype, and through to a commercial product, is notoriously difficult to characterise, plot or measure. While there are a number of well-known metrics that can be applied (such as the technology readiness level, TRL); on their own these fail to accommodate the manufacturability, *and* the market for devices and systems[21] (which cannot be plotted on any one-dimensional scale). These are both important ingredients to a successful commercial device. These scales must also be taken to be a guide, as on many occasions, the actual path taken may be highly non-sequential, and non-linear.

DARPA in the US has a very well defined process for bringing technologies to market, see figure 2.[22]

[21] The System Readiness Level (SRL) and Manufacturing Readiness Level (MRL) are often used to bridge the gap between an individual technology at a given Technical Readiness Level (TRL) and its implementation in a commercial product or service. An exposition of these measures is interesting but beyond the scope of this report.

[22] Source = DARPA transition guide, model that has worked well.

5.5.1 Quantum technology Exploitation

To improve products and services in volume, our new quantum technology must be injected into the wider industrial supply chains. In this case these supply chains can be represented as illustrated schematically in figure 3.

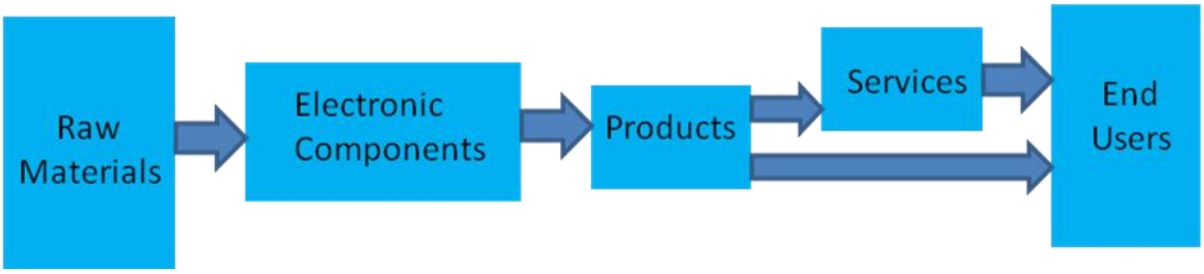

Figure 3: Simplified representation of supply chain

An end user might be a domestic consumer buying a phone containing a quantum secured ATM link, or might be a company using some quantum enabled equipment in its business. It is quite common to hire expensive products as part of a managed service, e.g. when you call a taxi. Instruments such as quantum gravity imagers for civil engineering use will probably be accessed by buying surveys accompanied by professional expertise rather than an instrument.

A product, such as a gravity imager, is made from many components only a few of which will rely on novel quantum concepts. Thus product manufacturers will demand quantum technologies in the form of subsystems (such as a gravity sensor using trapped, cold atoms). It is important to note that each stage in the supply chain depends on the pre-existence of the previous stage. There will be no products without novel quantum enabled components, and no components without supply of raw materials. It is also important to note that a simple supply chain, such as the that shown in figure 3, is rarely so simple.

If a supply chain has developed naturally, every component will often have multiple alternative uses in other similar or dissimilar industries. Each component may also have several suppliers that prevent single point failures, and provide a healthy competition that keeps costs low for the customer. Such a supply chain is difficult to engineer but will normally develop organically under the right market conditions.

Under the National Quantum programme sponsorship, UK is already beginning to establish an internationally competitive supply chain. It is initially focussed on the Raw Materials and Electronic Component space, but with industrially co-funded plans addressing Products and Services. This is the youthful start of a new, high value and sustainable industrial segment for the UK, exploiting UK's best competitive strength

5.5.2 Building a supply chain

At each stage in a supply chain, the companies who will become involved already exist. While start-ups will doubtless occur, early developments are expected to be capital intensive and suited to existing companies adapting existing capabilities. Indeed, this is one of the attractions of this emerging quantum opportunity, since existing companies are more capable of ramping up production quickly and often possess good market knowledge in quantum related areas[23].

In the context of our "second quantum revolution", the technologies are sufficiently different from current electronics that component manufacturers will need to form consortia even to build components. For example, the skill sets to construct high vacuum electronics and laser based optical subsystems tend to lie in different companies. This has been the immediate focus of the Innovate UK programme, which has stimulated and helped fund formation of industrial teams to make quantum components, and supported product and service companies in their investigation of what they could provide once quantum components become available. Further details of the Innovate UK programme can be found in section 4.1.7.

In the context of the formation of UK teams, the interests of the UK MOD and Innovate UK have proved particularly well aligned. The MOD is investing in quantum technology because it can see how particular defence and security problems can be solved by quantum technology and it wants to stimulate manufacture of suitable quantum enabled equipment. This programme of quantum component construction aligns well with Innovate UK's expectation of early quantum take-up, in particular

- Compact precision timing sources ('Clocks');
- Gravity sensing for survey and detection of hostile activity;
- Quantum enhanced navigation (especially underwater and underground).

...but that is far from the whole story. MOD has also invested over many years in other types of quantum sensing (e.g. single photon sensing and imagery) and needs the concepts to transition to manufacture before MOD can make use in volume.

The Quantum Hubs have a critical role to play in the formation of the new supply chains needed. They are providing academic support, often free of charge, to companies investigating the opportunities that the second quantum revolution might bring to their business. They are the source of the quantum skilled people that the industrial supply chain will need to expand quantum activity. Hubs and Centres for Doctoral Training also work to create superior understanding of the technical quantum opportunities which will underpin UK's exploitation of known, and yet to be discovered, quantum phenomena over the coming decades.

5.6 Enabling technology

While a generic roadmap is expected to describe accurately the mass take-up of quantum technologies, there is a special, different market already prepared to buy modest volumes of materials and partly finished components. These are the R&D purchasers, of which perhaps the most important group are university physics researchers throughout the world.

Although volumes are modest by (say) computer chip standards this market has a critical 'stepping stone' role and buys high value products. Their demand for materials and the assemblies that themselves are part of 'components' provide a 'lower risk' route to full manufacture of quantum

[23] First class examples are e2v (ultra high vacuum systems), Chronos (miniature atomic clocks) and M^2 lasers (specialist laser systems)

subsystems. For example, R&D and early development phases demand lasers and MOTs[24] for research purposes. That small volume production paves the way to engineering and cost improvements, and larger, more affordable volumes anticipated for navigation and gravimetry.[25]

5.6.1 Early manufactured quantum components and subsystems:

Novel quantum enabled systems are already available for purchase, such as QKD[26] based point to point communications links (free space and fibre) which prevent clandestine communication intercept. In a few years these will have moved from being able to operate over < 150 km range to much greater distances. However, quantum protected networks, including space satellites, as opposed to point-to-point links, are not quite yet ready. Options for network purchase are expected within 5 years.

Investment has already begun in the creation of:

- Special lasers, an essential part of many quantum sensors;
- Affordable and compact MOTS traps, providing 'laser refrigeration' down to near absolute zero;
- Internal electronic modules and software to control quantum systems;
- Precision time / frequency sources. These are best seen as a 'production line' of new technologies, with the first 'product' being 'Quantum Fibre Clocks', a form of compact electronic oscillator with superior stability to the quartz crystal but much more affordable and useable than current atomic clocks;
- Quantum accelerometers and gravimeters, for navigation and survey;
- Quantum enabled surveying equipment;
- Highly sensitive detectors able to detect at the single photon level, for a range of purposes.

All are expected to be available as manufactured products, within the next 5 years.

5.6.2 Product development roadmaps

A definitive description of technology road mapping has been described by Phaal.[27] The paper presents a framework for road mapping science and technology-based industrial emergence, in order to better understand the nature and characteristics of such phenomena and as a basis for improved strategy development. A full life cycle perspective is included and industrial emergence is mapped from various perspectives covering wealth creation, demand and supply-side factors. The framework has been extensively tested giving confidence that it might be applicable to both current and future emergence. Characteristics of industrial emergence have been identified, delineating the various phases and transitions. However, this is a complicated approach, difficult for the non-specialist to understand and use. Here, a simplified approach will be outlined.

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24 Magneto Optical Traps are high vacuum chambers that are used to hold atom clouds reduced to within a few microKelvin (i.e. µK or 0.000001 degrees) of absolute zero temperature without requiring a bulk cryogenic system. These are important in many areas of quantum technology.

25 I.e. measurements related to the gravitational field.

26 QKD = Quantum Key Distribution (not to be confused with cryptography itself)

27 " A Framework for Mapping Industrial Emergence" R Phaal, E O'Sullivan, M J Routely, S Ford and D Probert, Technological Forecasting and Social Change,78, 217-230 (2011)

The successful establishment of a market selling point to point QKD has confirmed the market demand for secure communications which has been a major driver to successfully realise secure networks and trials are beginning to be implemented.

Precision timing is poised to become a significant UK market supplied by UK technology being developed at NPL together with UK universities and industry. Telecoms need precise clocks for time based services, though not yet in huge numbers. The finance community will also need to access precise time, either from local devices or via precision time distributed over the NDFIS[28], since it is necessary for transaction timestamps to be locked to UTC[29].

The availability of new quantum based gravity sensors, offering enhanced sensitivity together with faster read out (which will shrink survey times from days / weeks to minutes / hours) has prompted the geo-surveying community to undertake careful analysis of the impact this will have on future business. Low SWAPC[30] MEMS[31]-based gravity surveying devices, even though they lack the high precision of cold atom instruments, will allow rapid survey of large areas from unmanned air vehicle platforms which, again, has major implications for future markets.

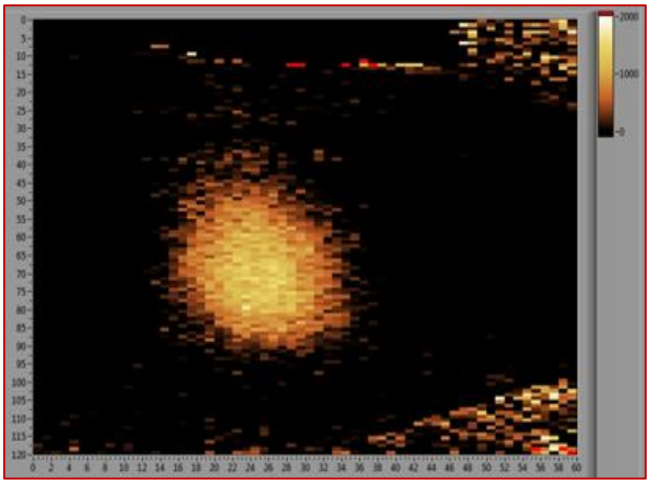

Figure 4 Picture of atoms held in a red MOT at a temperature close to absolute *zero Courtesy of Yeshpal Singh Birmingham University*

When the previous Landscape was published, we believed that the research market would be the key stepping stone to stimulating the development of sensor components (lasers, detectors, MOTs, control electronics etc.). This has been realised with a number of UK companies engaging strongly with emerging quantum technology development, although it is too early to quantify the value of this market except to note that it is potentially very large.

MOD still would like to procure resilient navigation systems (robust against denial of GNSS and human error or instrument failure) and the ability to image through ground and walls. There is also a need for single photon detectors for range finding, improved long wave IR imaging, and imaging through seawater, dust and smoke. The range of active imagers is usually limited by eye-safety considerations so more sensitive sensors will make a greater range of detailed imagery available. Precise clocks are certain to have disruptive impact for military communications and electronic warfare systems. UK requirements in terms of numbers of units are still unclear, although likely to be counted in tens of thousands with (possible) export markets many times that number.

28 NDFIS = National Dark Fibre Infrastructure Service. Loosely, a dark fibre is a fibre communications link that is not used, often laid down by companies as insurance against expected exponential growth in data traffic.

29 UTC is short for universal coordinated time, an international standard. Note that corrections have to be made due to the time light takes to travel between nodes.

30 SWAPC = Size, Weight, Power and Cost.

31 MEMS = Micro-Electrical Mechanical Systems

In many instances there is close alignment between MOD's requirement's and early civil exploitation. This has been deliberately highlighted across many of the quantum technology areas. Unless prototypes transition to manufacture, MOD is unable to procure the systems it needs in a cost effective manner.

Finally, it is noteworthy that "old" (i.e. 20th century) technologies are contributing significantly to the worldwide efforts to tackle global warming. For example, photovoltaic cells, nuclear power and integration of wind and wave generated power transmitted into electrical distribution systems through semiconductor reformulation[32]. It is likely that many will look to new quantum technologies, such as thermoelectric generators based on heat transport via coherent media, to mitigate global

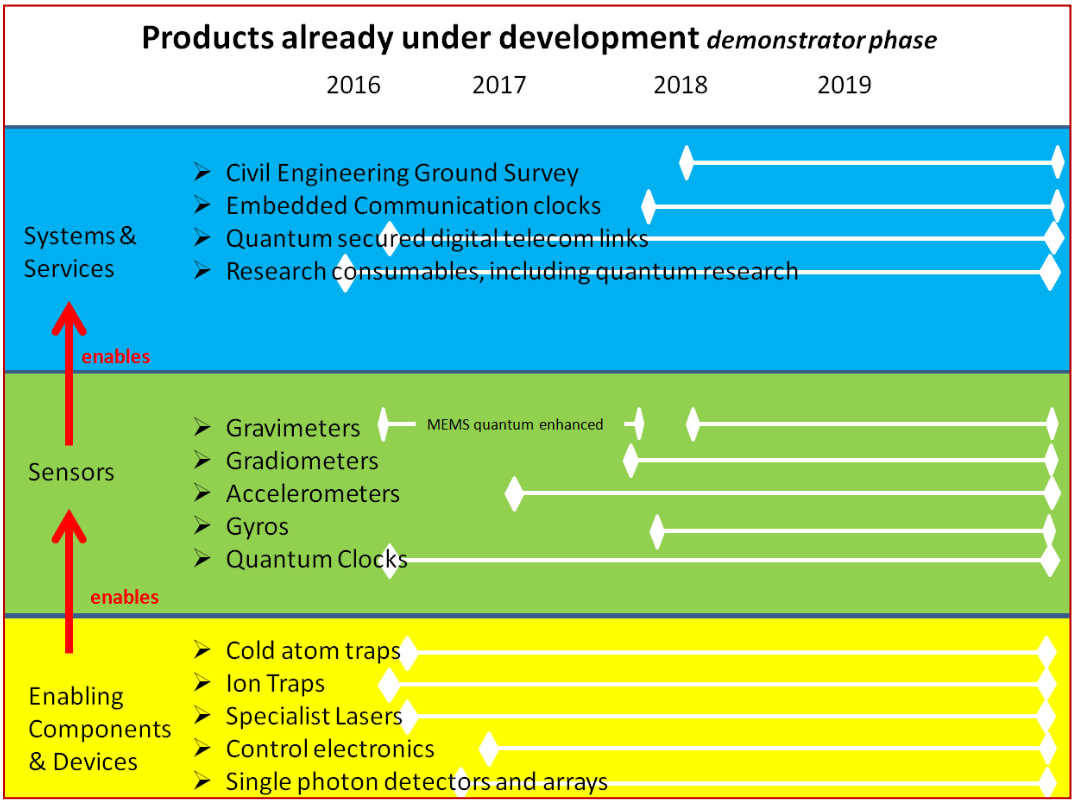

Figure 5: Quantum products in the programme already under development

warming.[33] These technologies are still at an early stage of development. The greatest gain might be to utilise quantum coherence to harness the production of an electric current using low grade heat.[34]

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32 I.e. reliable, solid state power conversion using grid tie inverters and even ultra-high voltage grid inter-tie systems.

33 The impact may be limited due to general efforts to improve efficiency. However, it is unlikely that major thermal cycle based plant will achieve much greater than 50%. The most important factor is ultimately the cold "sink". Large mechanical to electrical systems such as hydroelectric or tidal are exceptional and can exceed 90%.

34 The maximum efficiency of a heat engine depends on the initial and final temperatures of the working gas (or fluid). The "quality" of the heat sink is as least as important as the source and this point is often overlooked.

Much as Bell Labs had no concept of the revolutionary potential of their post war development of solid state transistors it is not fanciful to assume that the new quantum technologies will become similarly transformative.

Very approximate product development roadmaps, as anticipated in mid-2016, are shown below for the short, medium and long term. together with a view of progress in the rest of the world (figures 5-8).

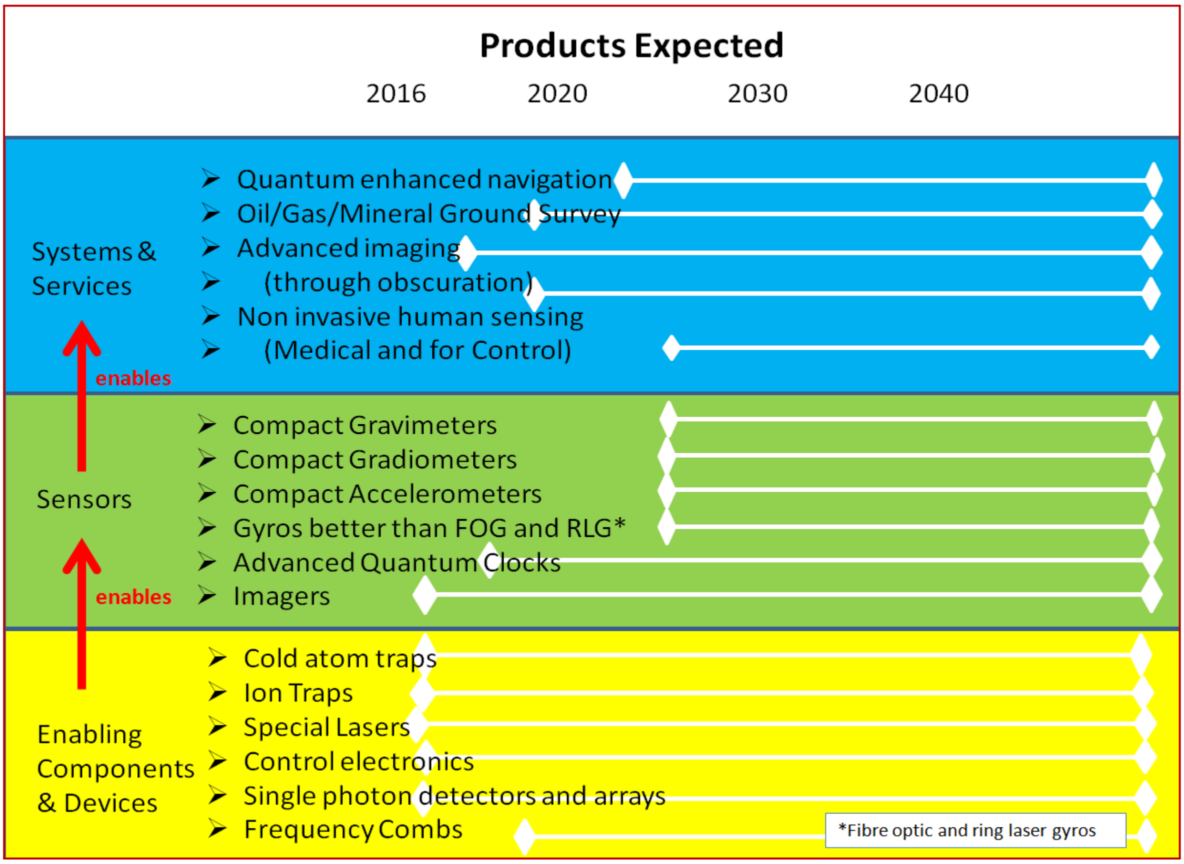

Figure 6: Timelines for QT products expected in the UK

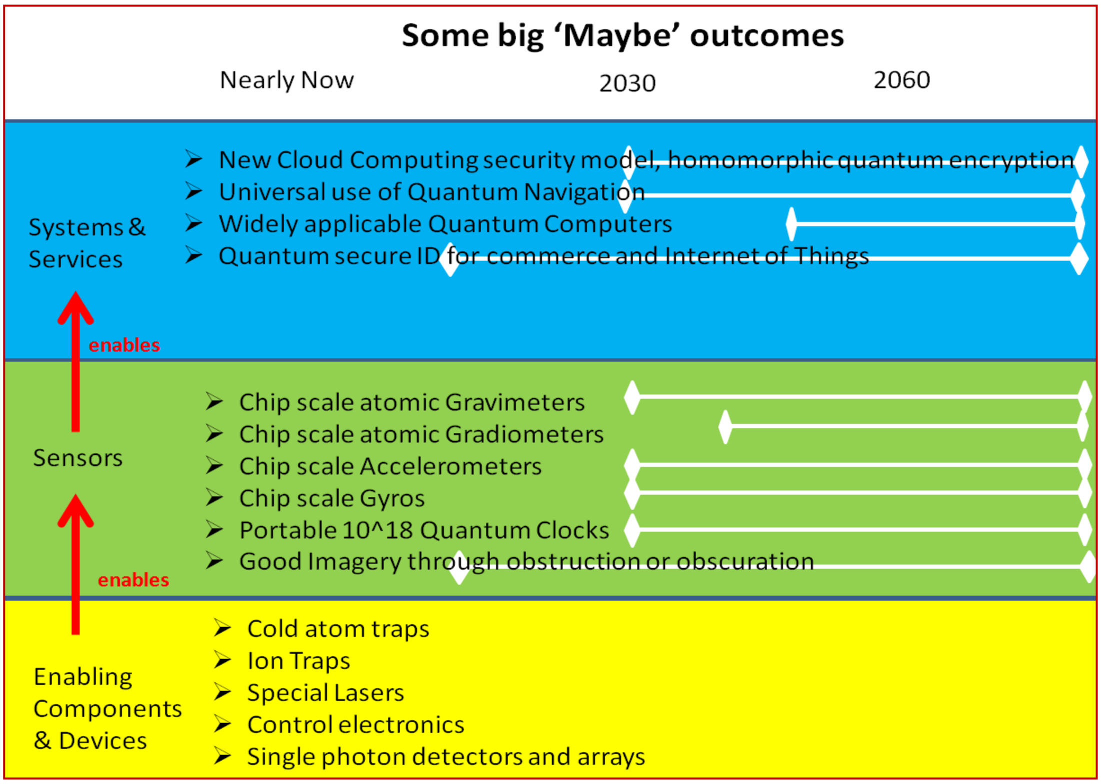

Figure 7: Timelines for possible "big" outcomes in the UK QT programme

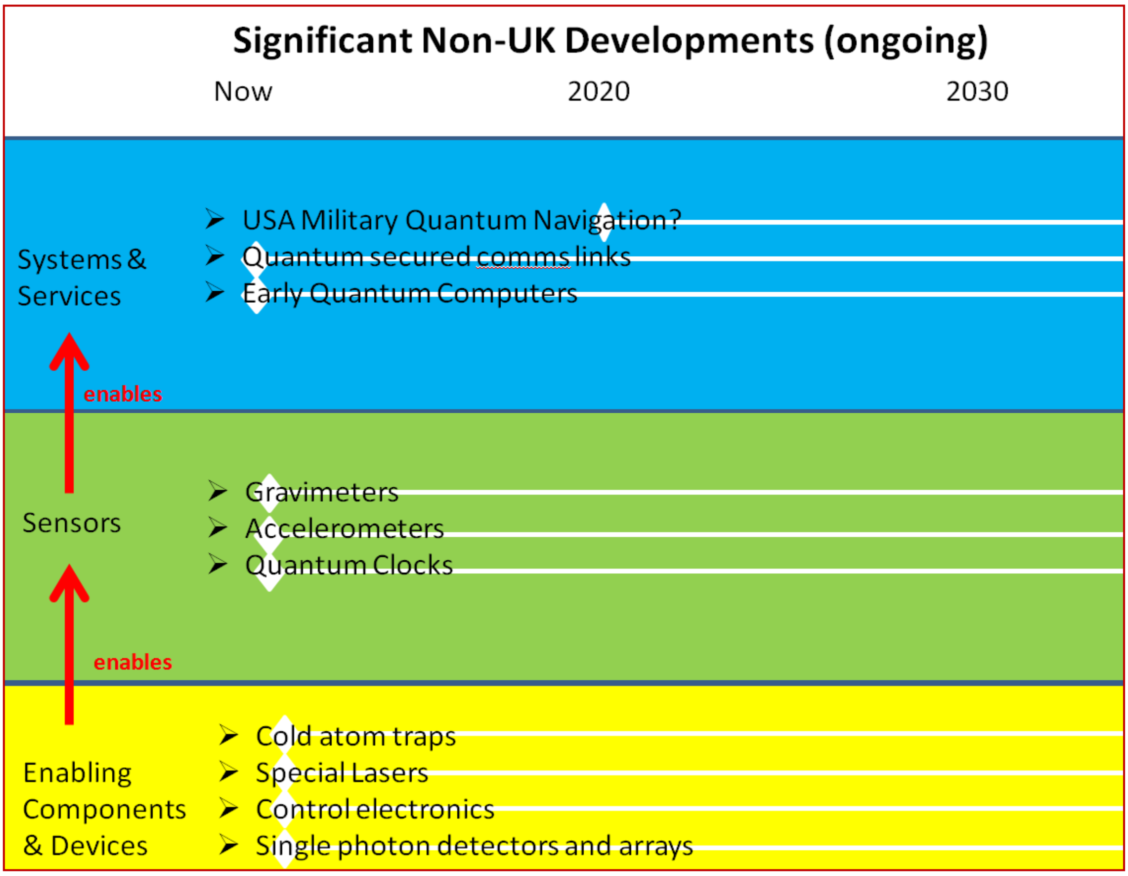

Figure 8: Significant non-UK QT future products

5.6.3 Some key technical milestones

Some more detail is provided below (lists not in chronological order). Estimated time to demonstrator figures are shown for some:

Key milestones for quantum clocks

- 1 in 10^{11} – 1 in 10^{12} atomic clock "paperback" size by 2017;
- 1 in 10^{14} miniature atomic clock "shoebox" size by 2019;
- 1 in 10^{16} small "suitcase" size by 2020;
- 1 in 10^{18} portable by 2025.

Key milestones in Quantum communications

- Point to point QKD systems are commercially available (present situation);
- Greater testing verification and standardisation on key issues, such as denial of service attacks, leads to greater trust, and possible adoption by government installations (2018-2020);
- Cost reduction of QKD systems, and continued understanding and familiarity leads to wider uptake (2018);
- Free space QKD is demonstrated over long distances (2020) which leads to QKD connected satellites (2025) and QKD protected ATM machines (2030);
- The "envelope" of systems is widened to include solutions to authentication, digital signatures etc.;
- Device independent QKD systems are commercialised giving greater trust, particularly within secure nodes (2019);
- Quantum repeaters are developed, extending the range of QKD links (2020);
- A quantum computer with the ability to run Shor's algorithm[35] is developed, increasing the threat to worldwide encryption, creating a greater demand for post-quantum cryptography solutions (2030+) (but note the effort being put in to design "post quantum cryptography").

Key milestones in Quantum imaging

- Practical ghost imaging[36] demonstrated;
- Covert range finding demonstrated;
- Baseline gravity imaging demonstrated (2019);
- Gravity maps developed;
- Time of flight imaging yields cm accuracy 3-D imaging at long (hundreds of metres) distances;

[35] Shor's algorithm is a quantum algorithm that makes factorisation of large integers tractable via a process of solving discrete logarithms; this makes RSA cryptography relatively easy to break and will reveal legacy data that has so far been unreadable.

[36] Ghost imaging is a method of forming an image that is out of sight of the detector. It may be implemented using classical correlations, although the quantum version offers better performance. The Quantic hub has developed a form of ghost imaging that can interrogate an object at one wavelength and image using detectors working at another. A thorough technical article covering most aspects may be found here.

- Chemical analysis at a distance (at least tens of metres);
- Electric and magnetic field imagers;[37]
- Low cost volume production begins, which opens up more mainstream applications.

Key milestones in Quantum sensors

- Quantum inertial sensing devices operate in challenging environments;
- Incremental adaptations to quantum gravity sensors increase the functionality of devices (such as continuous measurement, noise rejection (2016-2018);
- Components and better system integration reduces the cost, size and durability of devices. (2016-2020);
- More complex set-ups and sequences are used to give additional functionality (higher sensitivity, gyroscope measurement);
- A range of general quantum sensors used for niche applications (2020-25), such as oil and gas, geosurvey, space, defence and security;
- Imagers using information and image fusion techniques.
- Inertial sensors for GNSS free navigation

Key milestones in Quantum computing

- A greater range of quantum algorithms are developed for new applications (2018-2025), and in particular for machine learning (2022);
- Superconducting qubit systems are proven to speed up the processing of a niche, but ‘real’ computational problem (2020);
- Oxford 20:20 system delivers a baseline demonstrator that allows evaluation of the potential of a larger system (2020);
- A universal quantum computer is realised (analogous to a universal Turing machine) - capable of undertaking any computation that may be addressed by a quantum machine;
- A key milestone quantum computer system is developed which has 100-200 fault tolerant qubits which allows quantum algorithms to start to solve problems which normal computers are unable to solve (2025);
- A ‘few’ qubit topological computer robust against errors is tested, and shows evidence of quantum “gain” in the speed of finding solutions to problems (2025);
- A wide variety of disruptive, high utility quantum applications become available;
- Large scale universal quantum machines become available (2035+).

[37] These already exist in classical form, although their nature is somewhat different to photonic imaging. However, a more sensitive "quantum front end" could well boost performance and facilitate a wider range of applications.

Key subsystem milestones

- Standard electronic control systems to manage MOTs and the intricate operation of quantum enabled sensors (2017)
- Wavelength converters, such as PPLN,[38] used to make a wide variety of tuneable laser sources (2017-2020), ghost imaging (2018), quantum information networks (2020);
- Diamond NV centre[39] devices used in magnetic sensors (2017) and quantum computer memory (2020);
- Continued miniaturisation of cryogenic and cryogen-free coolers allows portable superconducting devices (e.g. high efficiency photon detectors, & longer wavelengths) (2018-2025);
- Single photon sources and entangled sources increase in quality and speed, to be used in quantum imaging devices (2016-17), quantum communications devices (2018-2020) and optical quantum computers (2020) Solutions are developed with a fidelity which is close to 1. This may be a full heralded single photon (2023), or an ion or quantum well in an optical cavity (2020);
- Plug and play ion traps allow faster technology development, and improved performance (2018);
- Miniature and self-stabilised laser systems (e.g. narrow line width DFB lasers) greatly increase the stability of quantum sensors (2020);
- Integrated circuit (analogous) to electronics available for matter waves (2030+), speculative.

[38] PPLN = Periodically Polled lithium niobate ($LiNbO_3$), a crystal with an engineered fine pattern of alternating crystal domains

[39] An NV centre in diamond is where two carbon atoms have been replaced by a nitrogen atom plus a vacancy. Often these are called “colour centres” as in higher concentrations they bestow a characteristic colour upon the crystal. These impurities have interesting and useful magnetic properties. See section 6.4.7

6 Progress since 2014 and state of the art

6.1 The UK national quantum technology programme

6.1.1 Introduction

Progress in the first 18 months of the programme running[40] has been excellent, and has exceeded the expectations of most people.

Since the beginning of the programme, and as confidence in our vision grew, investment has increased to over £360M for the first five-year phase. A key component has been the joined up nature of government departments and their investments, shown below in figure 9:

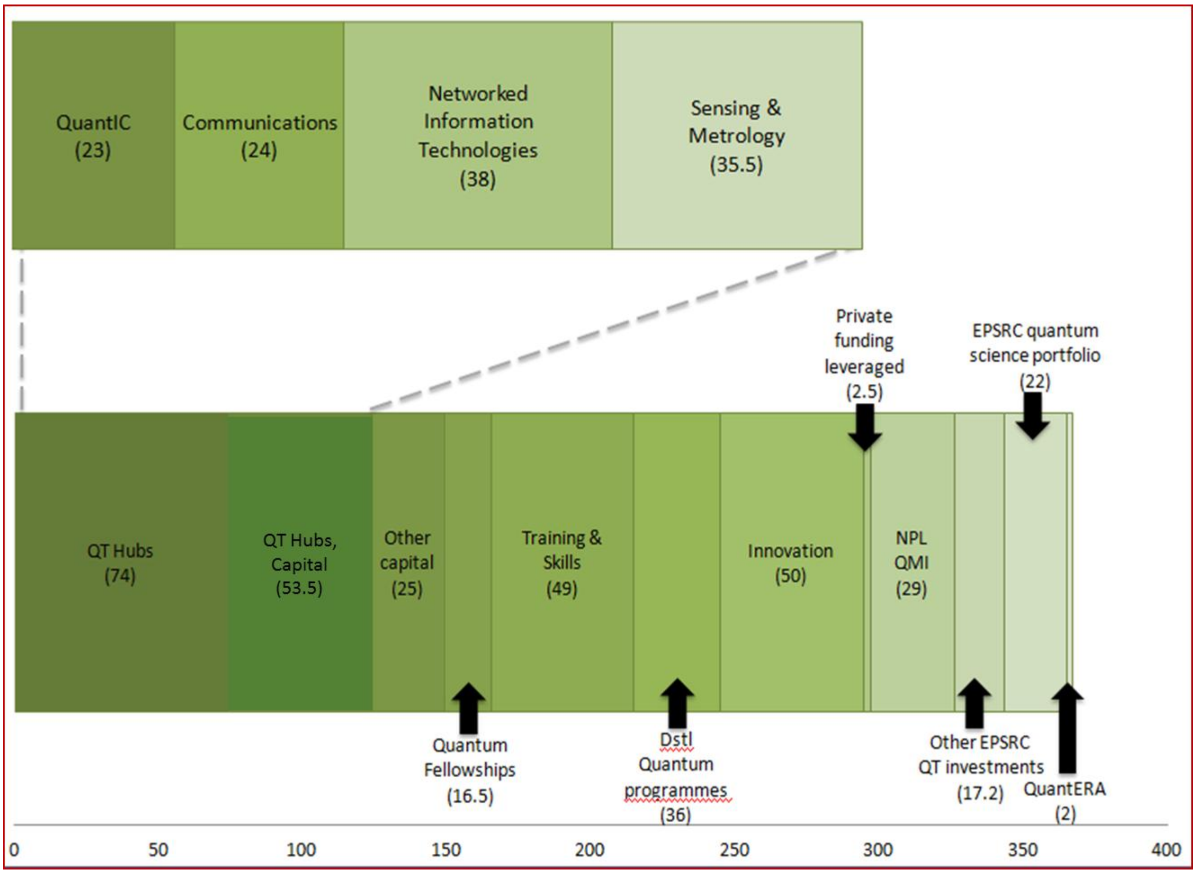

Figure 9: Value of combined UK quantum programmes *courtesy of Richard Murray IUK*

The programme builds on a strong base of EPSRC quantum physics and other research across a number of areas. It supports investment in applied research, innovation, skills and technology demonstration to help UK industry commercialise these new technologies. At first, UK industry will produce devices for niche applications in defence, secure communications, information technology and oil and gas, before evolving into more mainstream consumer markets. The programme encourages this evolution by funding grants to UK companies to help them identify and develop uses, applications and markets for new technologies which will impact their business.

40 Most of Year 1 was taken up with a competition.

The bulk of the UK quantum technology effort is based on a hub and spoke model that accelerates the development of quantum technology. It is closely linked to funding for industry-led projects, providing an easy entry point for companies interested in unlocking the potential of emerging quantum technology markets. All four of the Hubs have funds to support projects of different sizes and duration to develop enabling technologies, demonstrators and translation to market in the short, medium and long term.

In April 2015, Innovate UK, with the assistance of EPSRC and Dstl, successfully conducted the first round of grant funding for industry led projects. These projects were aimed at developing the technologies or understanding potential market opportunities.

Centres for Doctoral Training (CDTs) in quantum technology are ensuring the next generation of researchers in this field are supported, and the recently opened Quantum Metrology Institute at the National Physical Laboratory (NPL) also forms part of the programme.

The UK National Quantum Technologies Programme is being delivered by the hubs and underpinned by EPSRC, Innovate UK, BIS, National Physical Laboratory (NPL), Government Communications Headquarters (GCHQ), Defence Science and Technology Laboratory (Dstl) and the Knowledge Transfer Network (KTN).

6.1.2 UK quantum technology hubs[41]

There are excellent descriptions of the UK national programme available on the internet. Here, we present a short summary of the hubs' activities together with appropriate references.

Programme strategic guidance is provided by the Strategic Advisory Board[42] (SAB) and operations guided by the Programme Operations Board (POG). These will be described below.

6.1.3 Hub overview

The four hubs are led by the Universities of Birmingham (Sensors and metrology), Glasgow (Quantum Enhanced Imaging), Oxford (Networked Quantum Information Technologies) and York (Quantum Communications) selected after a competitive peer review process. The network started in December 2014 and initially involved 17 universities and 132 companies with a common aim of harnessing recent advances in quantum physics for use in technology.

6.1.3.1 Quantum communications hub[43]: Director Professor Tim Spiller

This hub is led by the University of York. The principal investigator is Professor Tim Spiller with academic partners[44] at the universities of Bristol, Cambridge, Heriot Watt, Leeds, Royal Holloway, Sheffield and Strathclyde. There are also many non-academic partners such as NPL, innovate UK and Industry e.g. Toshiba and BT.[45]

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41 A summary, together with the latest news, can be found at and a video summary can be found at [UK quantum technology programme]

42 The national strategy for quantum technologies can be found at: https://www.epsrc.ac.uk/newsevents/pubs/quantumtechstrategy/

43 http://www.quantumcommshub.net/

44 See http://quantumcommshub.net/people/

45 See http://quantumcommshub.net/partners/

Quantum communications technologies have potential use in a wide range of functions and applications where security is vital: from encryption of communications, passwords and identification, to financial transactions.

The hub has a particular focus on quantum key distribution (QKD) - one of the most mature quantum technologies, and one which is considered especially promising for early commercialisation. It is working towards market-ready technologies, exploring ways of making smaller, lower-cost devices which can be integrated into existing systems and infrastructure. Initial developments include the chip-scale integration of QKD. This will facilitate QKD modules for use in a range of devices where quantum-secure communications are desirable. One such application would be for secure mobile banking, where a device, e.g. a suitably enhanced mobile phone, would undertake secure transactions with a service provider – e.g. a bank through an ATM via a free space link. The principal goals of the hub are currently:

- Practical, affordable hand held devices;
- UK quantum network (UKQN): a network test bed for integration of quantum and conventional communications;
- Exploration of theoretical approaches and applications, protocols and services for the next generation quantum communications beyond Quantum Key Distribution (QKD).

The quantum network will provide access to quantum secure communications on different scales: within buildings, within cities, and between cities. The network will be a test-bed, enabling researchers and companies to develop, trial, and demonstrate technologies and applications.

Key technological enablers for the hub are:

- specialist photon emitters and detectors;
- lightweight, low-cost, low-power optical chips and components;
- fibre optic systems including switches and other components;
- high-power, compact processors;
- underpinning theory and security analysis.
- Interoperability and standardisation

6.1.3.2 Sensors and metrology[46]: Director Professor Kai Bongs

The UK quantum technology hub for sensors and metrology[47] is led by Birmingham University. The Principle Investigator is Professor Kai Bongs who leads a large, world class team.[48] The other academic partners in this consortium are the universities of Glasgow, Nottingham, Southampton, Strathclyde and Sussex, and the National Physical Laboratory (NPL). There are also a large number of industry participants. Trevor Cross from e2v is a member of the hub leadership team.

It aims to develop a range of quantum sensor and measurement technologies that are ripe for commercialisation by UK businesses, by translating the output of state of the art physics

46 See http://www.birmingham.ac.uk/generic/quantum/index.aspx
47 See http://www.birmingham.ac.uk/generic/quantum/index.aspx
48 See http://mpa.ac.uk/muarc/ and http://quantumsensors.org/

experiments and knowhow from the lab into practical, deployable devices. Alongside this, it is also training a cadre of people working within the UK quantum technology community.

Figure 10: Portable atomic gravimeter demonstrator (right) and together with engineering test harness during field trials (left). A portable gradiometer is expected by the end of 2016. *Courtesy of Mike Holynski, Birmingham University*

There are several work packages[49] arranged to realise an integrated plan and based around the following topics:

- Gravity sensors;
- Rotation sensors;
- Magnetic sensors;
- Clocks;
- Imaging;
- Atomics (value added enabling subsystems);
- Laser subsystems;
- Single chip lasers;
- Systems (additive manufacturing);
- Applications of gravity sensors (civil engineering and geophysics);
- Industry links and future supply chains.

The key technological enablers for their activities are:

49 See: http://www.birmingham.ac.uk/generic/quantum/workpackages/index.aspx

- advanced specialist lasers, including specialised components such as switches, femtosecond frequency combs and integrated optics;
- optical delivery systems and computer control including application-specific integrated circuits;
- atomics "physics packages" – vacuum cell technologies including gratings, atom chips and finely controlled electric and magnetic-field generation;
- packaging expertise, including functional materials and additive manufacturing. Experience in miniaturising atomic measurement systems.

Quantum sensors have the potential to be cheaper, lighter, smaller, more sensitive and more energy-efficient than existing, classical sensors. Advances in this area have many applications. Examples include healthcare, navigation, archaeology, data storage, network timing, civil engineering and defence. The Hub also has technology translation and prototyping centres where industry can work alongside academics; sharing ideas, expertise and facilities to accelerate technology transfer.

6.1.3.3 Quantum enhanced imaging[50] (QuantIC): Principal Investigator Professor Miles Padgett FRS FRSE; Director Professor Steve Beaumont

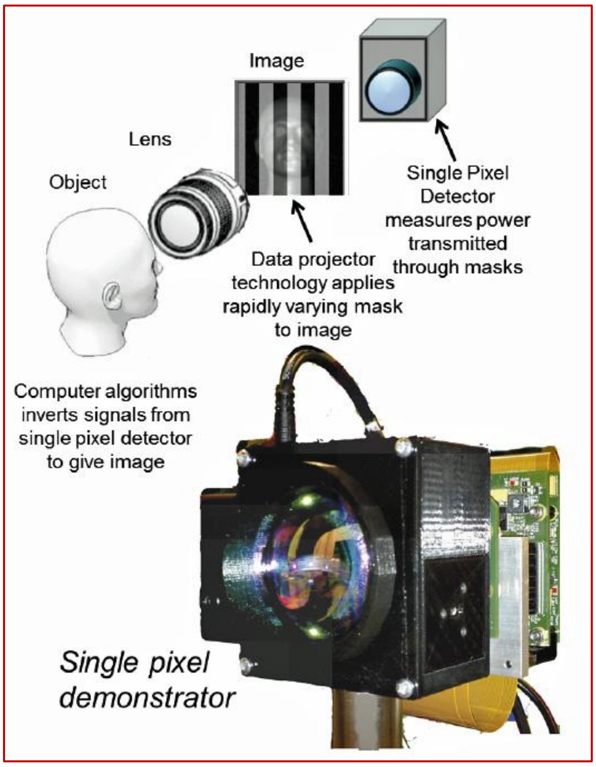

Figure 11: Demonstrator of single pixel camera developed by Quantic

Courtesy of Professor Miles Padgett, Glasgow University

QuantIC is the hub developing quantum enhanced imaging from the output of 120 full time researchers engaged in basic physics i.e. "discovery" science. The principal investigator is Professor Miles Padgett FRS, FRSE. Professor Beaumont manages the hub, which is centred at Glasgow University. The hub brings together the expertise of Glasgow and the universities of Bristol, Edinburgh, Heriot-Watt, Warwick, Oxford and Strathclyde. There are also more than 30 industrial partners engaged in technology translation.

The hub is working closely with industry to develop new types of ultra-high sensitivity cameras with capabilities far beyond the current state-of-the-art. The work also includes improving existing imaging systems through quantum technologies. Applications of quantum cameras include visualising gas leaks, seeing through smoke, and even looking around corners or underneath our skin.

These are techniques that industry partners have helped identify as being of potential commercial use. Their requirements include single-photon visible and infrared cameras, single-pixel cameras,

50 See https://quantic.ac.uk/

extreme time-resolution imaging, 3D profiling, hyper-spectral, ultra-low flux covert illumination, imaging beyond line-of-sight, and low cost imaging of local gravity fields[51].

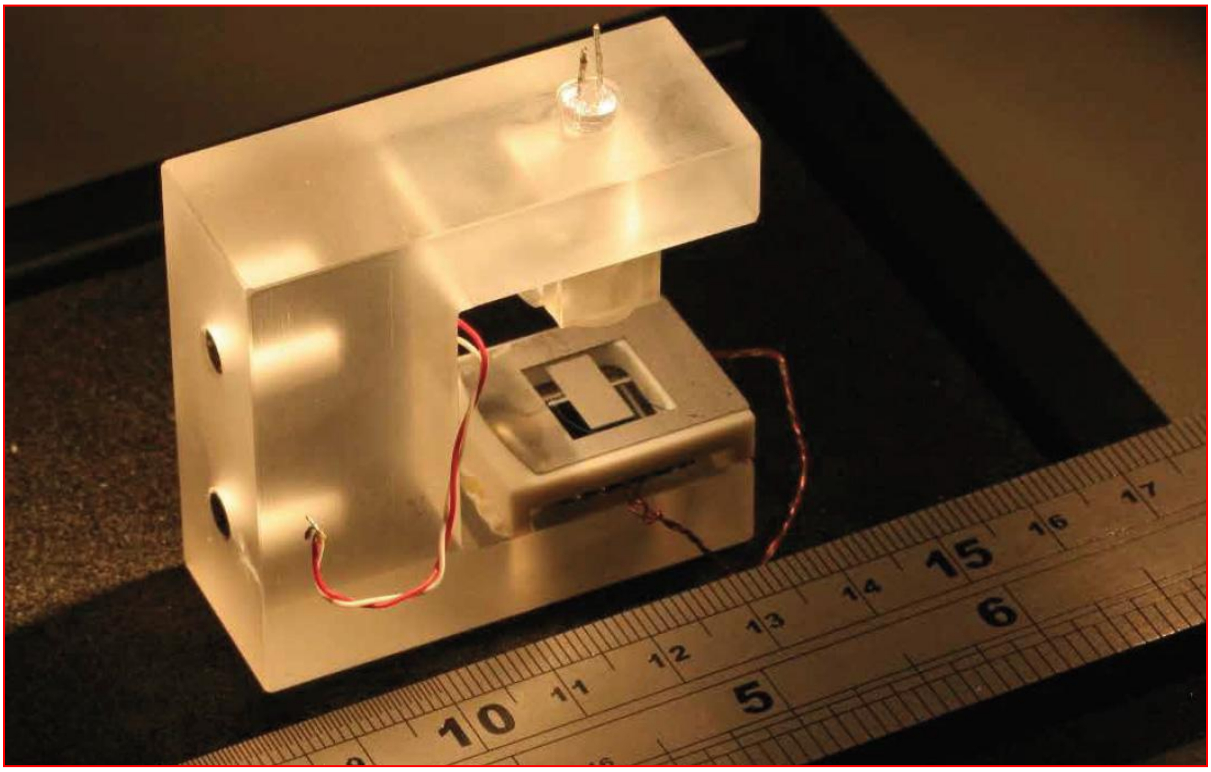

Fig 12: Prototype of MEMS gravimeter mounted in test harness. Although unlikely to reach the sensitivity of an atomic system, this is capable of sensing Earth tides and is a good benchmark against which to compare the more sensitive atomic sensors ***Courtesy of Professor Miles Padgett Glasgow University***

A summary of the principal outputs from the hub is cast as four work packages as follows:

- Imaging with correlation. This work package seeks to use quantum correlations to exceed limitations brought about by wavelength, noise characteristics etc.;
- Imaging with timing. Novel, fast, single photon detectors will enable covert, 3D imaging, the ability to see around corners and imaging of short light pulses while in flight;
- Imaging with squeezing. This will exploit a trade-off in the quantum world that permits the use of a number of quantum effects to overcome noise limits in certain types of sensor;
- Sensors and source technology. This package will deliver leading edge underpinning technology to feed into the three packages above. It will consist of a suite of novel detector and source technologies capable of operating from the far infra-red and through the visible spectrum.

Key technology enablers include:

- MEMS, NEMS, general state-of-the-art fabrication and solid state, for example complementary metal–oxide–semiconductor and III-V semiconductors, detectors and micro-LED arrays including specialist packaging;

51 This work is centred on MEMS technology and is complementary to the atomic sensors at Birmingham. It was originally sponsored by a Dstl PhD project to provide a baseline against which to compare the performance and sensitivity of the atomic (quantum) sensors.

- Specialist lasers and high-power parametric sources; specialised optics and cameras, optical switches;
- specialist data processing equipment including FPGA[52]s.

Within this hub an "innovation space" has been created through which businesses can physically work alongside academic teams to develop demonstrators into prototypes. This initiative is supported by a £3 million Scottish Funding Council grant.

6.1.3.4 Networked Quantum Information Technologies[53] (NQIT): Director Professor Ian Walmsley, FRS

The NQIT hub incorporates the universities of Bath, Cambridge, Edinburgh, Leeds, Southampton, Strathclyde, Sussex, and Warwick. Its principal goal is to engineer networked quantum information technologies that will outperform existing supercomputers in important tasks of high computational complexity. NQIT is focussed on creating interconnecting systems which can form flexible, scalable solutions for a wide range of applications, such as accelerating drug development, analysing "Big Data", ultra-fast generation of quantum random numbers, secure communication between many parties (with the York hub), and enhanced distributed sensing.

The principal technical outputs are stated as:

- Ion trap engineering;
- Atom-photon[54] interfaces;
- Photonic network engineering;
- Solid state node (qubit) node engineering;
- Secure communications;
- Networked quantum sensors;
- Hybrid classical / quantum computing;
- Quantum digital simulation;[55]
- Architectures, system integration and standards.

Key enablers include:

- Specialist "physics packages", including vacuum systems and infrastructure needed for ion-trap architectures;
- Specialist engineering including integrated optical waveguides, configurable circuits components and interfaces; fibre optic technology and specialist lasers and LEDs; NEMS and MEMS;
- Engineered solid state materials such as diamond with precisely controlled impurities;
- A strong theoretical and modelling community.

[52] FPGA = [Field Programmable Gate Array](). These are microelectronic chips whose structure may be programmed using software and are thus extremely versatile.
[53] https://nqit.ox.ac.uk/
[54] A photon is the smallest possible unit of light, i.e. a "quantum" of light
[55] This is a study to investigate how a quantum computer could be used as a co-processor in the context of partitioning algorithms into classical and quantum parts.

The technical effort (summarised in figure 13) is built upon a wide variety of world class technical expertise. Workers in the hub hold world records for achievement using light, matter and their interaction at the quantum (smallest) level. The aim is to realise their vision of a 400 qubit quantum computer in 2020. This ambitious objective, which when delivered, will represent a breakthrough that will lead to a proliferation of novel quantum technologies.

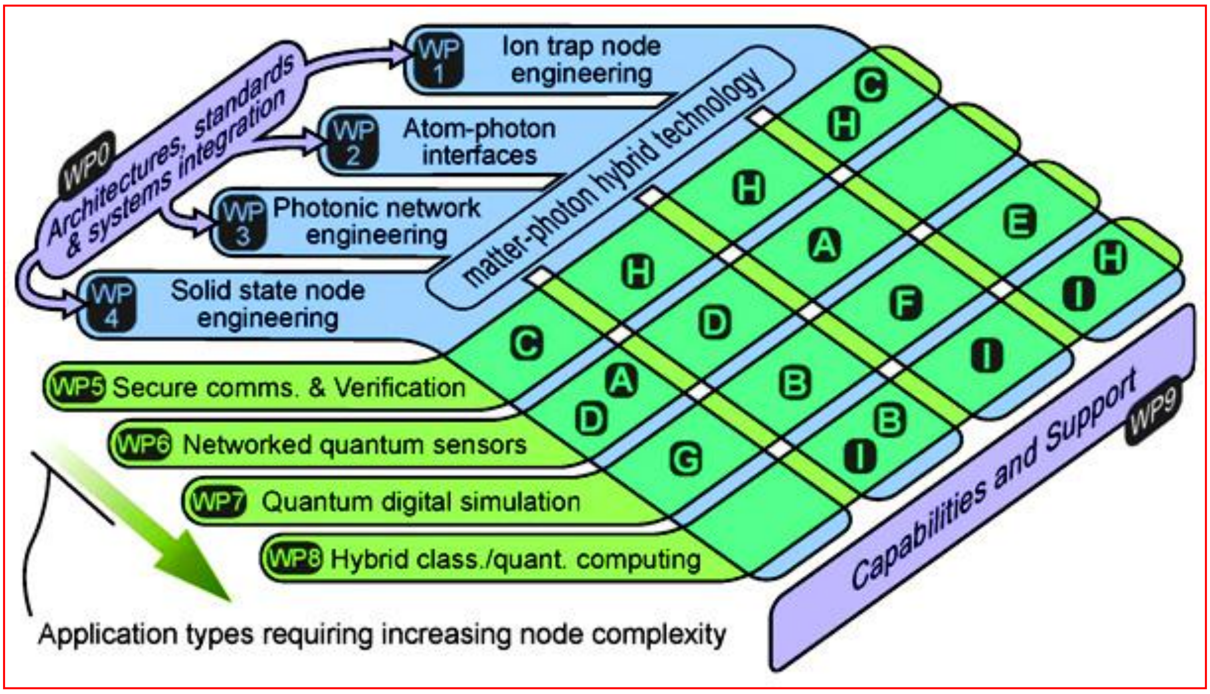

Figure 13: representation of NQIT programme ***Courtesy of Professor Ian Walmsley FRS Oxford University***

The Q20:20 quantum engine is the flagship project within this hub. It will be a network of 20 quantum processors (each processor contains 20 matter qubits) that share information via light. It is a hugely complex and powerful design that the hub is confident will put the UK at the very forefront of quantum computing and simulation. Scientists working within this hub hold world records for best quantum control, both in matter and in photon systems (99.9999% fidelity[56] ion qubit manipulation; single photons of the highest purity).

6.1.4 Governance of the National Quantum Technology Programme

Two groups were established to facilitate the coordination of effort in the UK Quantum Technologies programme with the aim of enabling the successful delivery of the programme and development and coordination of a longer-term strategy for quantum technologies in the UK.

6.1.4.1 Quantum Technology Programme Operations Group

The Quantum Technology Programme Operations Group (POG) focuses on the implementation of the UK National Quantum Technologies Programme. That includes coordination of efforts by the various government agencies and key organisations. It facilitates the effective and efficient delivery of the publicly funded Quantum Technologies investment in the UK as a whole and identifies scope for collaboration and co-funding R & D and joint calls. The group meets monthly.

[56] See section 6.5.9. High fidelity implies less errors (100% implies no errors) and thus a lower requirement for error correction. Resources required for error correction rise very sharply as fidelity decreases.

The group contains representation from the Engineering and Physical Sciences Research Council (EPSRC), Innovate UK (IUK), National Physical Laboratory (NPL), Defence Science and Technology Laboratory (Dstl), Government Communications Headquarters (GCHQ), Department for Business, Innovation and Skills (BEIS) and the Knowledge Transfer Network (KTN).

A key role during 2016 will be the design and oversight of the Hub midterm review.

6.1.4.2 Strategic Advisory Board

The Quantum Technology Strategic Advisory Board (SAB) was set up to provide a visible focus for strategy and to act as a co-ordinating body for UK interests. It has a top level oversight of the UK National Quantum Technologies Programme and has drawn up a strategy for the initiative. The Board meets quarterly. See Appendix 8.1 for board members' bios.

6.1.5 Performance metrics

The UK quantum technology national programme will be reviewed at the midterm at the end of 2016. The output must measure parameters and be cast in a form that will be understood by economists, financiers and politicians. It needs to be pragmatic and describe progress toward wealth creating technologies. Although there will be some scientific advances, these will represent a by-product as the UK quantum initiative is not a research programme.

At this stage, success will be difficult to quantify. A POG team has generated a proposed set of programme level indicators that are comprehensive, covering key strands of activity. These include jobs created, interest and investment generated in the commercial sector and creation of intellectual property.

6.1.6 Strategic Capital Investment

On the 1st March 2016 Strategic Capital investment was announced. This will contribute to the aims of the UK's National Quantum Technology strategy by expanding the UK's underpinning technology base for quantum. There will be investment at seven universities focused on four areas:

1. Building technical capability;
2. Manufacturing tools;
3. System/subsystem design;
4. Acceleration of innovation

See Appendix 8.2 for more detail on strategic capital investments.

6.1.7 Training and Skills

6.1.7.1 Introduction

Skills and training are essential to a long-term plan for the UK to be a world leader. Their application must take account of societal as well as economic impact. The national programme is one of the largest investments in a science and technology area in recent times. There is now an opportunity to develop and implement a strategy that allows the general UK economy to acquire a deep understanding of quantum technology. This is needed to make best use of fundamental (i.e. curiosity driven) research output.

Skills development goes far beyond the provision of university training, although the doctoral training centres (DTCs) (see below) are key to the successful exploitation of new quantum opportunities.

There are four broad themes to consider – how to provide industry and academia with an expert quantum knowhow, how best to address multidisciplinary training, and how to establish interest and familiarity with quantum science prior to university. Last but perhaps most important is the point of view of the trainees, who may not produce as many papers and other conventional markers of achievement. These PhDs, post docs, university staff and engineers need a clear system of recognition and career advancement. Their post training opportunities need to be balanced between academia (with applications and practical engineering experience), and newly emerging posts in industry.

6.1.7.2 Centres for Doctoral Training

The 2013 call for EPSRC's Centres for Doctoral Training created over 70 new EPSRC Centres with a total value of over £350 million. Within this group of Centres, a number of awards were made that support doctoral training within the field of Quantum Technologies, including:

- EPSRC Centre for Doctoral Training in Quantum Engineering at the University of Bristol;
- EPSRC Centre for Doctoral Training in Controlled Quantum Dynamics at Imperial College London;
- EPSRC Centre for Doctoral Training in Delivering Quantum Technologies at University College London.

The first student intake of these new EPSRC Centres for Doctoral Training took place in the latter half of 2014.

On 1st March 2016 three new Training and Skills hubs for Quantum Systems Engineering were announced by the Universities and Science Minister, Jo Johnson. The Hubs will be nodes within the national network of quantum technology hubs. They will deliver a package of skills training, co-working (including mobility), and career development initiatives to develop high-level skills in quantum engineering.

The Hubs in Quantum Systems Engineering are led by Professor Myungshik Kim at Imperial College London, Professor Andrew Fisher at UCL and Professor Mark Thompson at the University of Bristol. They will focus on training the next generation of quantum engineers through research programmes. These programmes will equip them to function in the complex research and engineering landscape where quantum hardware meets real devices, real applications and real customers. Relevant themes include challenges in cryptography, complexity and information theory, devices, materials, software and hardware engineering)

At Imperial graduates will be trained in a skill set that allows them to understand cutting-edge quantum research, with a mindset geared towards practical implementation and entrepreneurship. The UCL Hub will build on the existing expertise that rests with the EPSRC Centre for Doctoral Training in Delivering Quantum Technologies and Integrated Photonic and Electronic Systems. This will be coordinated with the UCL Centre for Systems Engineering and their commercial and governmental laboratory partners. The University of Bristol Hub's ambition is to build upon the already successful Quantum Engineering Centre for Doctoral Training (QE-CDT) at the university. They will partner with Cranfield University's Bettany Centre for Entrepreneurship to create a world-leading Hub to train entrepreneurially-minded quantum systems engineers ready for a career in the emerging Quantum Technology (QT) industry.

6.1.7.3 Quantum Fellowships

A total of ten Quantum Technologies Fellowships are funded by the Engineering and Physical Sciences Research Council. These support both the individuals and their teams to help realise rapid advances in quantum technology and the realisation of demonstrators. The Fellowships were granted to both early and established career stage academics whose research focuses on the direct exploitation of quantum phenomena to address the challenges of translation to application.

The fellowships complement the other components of the national programme and investment in the hubs and centres for doctoral training. The fellows represent some of the *crème de la crème* of our world class thinkers and will conduct transformative research in areas that contribute to the aims and aspirations of the national programme. See Appendix 8.3 for a description of extant quantum fellowships.

6.1.8 Innovate UK programme

Innovate UK has been working closely with EPSRC, Dstl and the Quantum Hubs to develop a national programme which coordinates academic and industry interests, and which encourages industrialisation of our quantum technologies. The aim is to deliver high value added, manufactured devices that matches a well understood market need. The goal is to deliver products and services that will, in aggregate, produce a large scale economic return to the UK taxpayer.

To enable this initiative, £50m out of the initial £270m investment had been planned for IUK to encourage innovation. This was to be a joint initiative by EPSRC (£18m) and Innovate UK (£32m) over 4 years. The plans are outlined in the 'National Strategy for Quantum Technologies', released in March 2015[57], and the document 'A roadmap for quantum technologies in the UK' released in November 2015[58]. These documents describe a need to identify technologies and market opportunities. This would be achieved by providing public funding for demonstrators and feasibility studies. The initiative would encourage effective communication and co-working, networking, road mapping, identification of market opportunities, implementation of standards and identification of early adopters.

The high level of activity in the national programme has encouraged many to explore the benefits of Quantum Technology in a number of areas. Initially, these have been timing, defence, communications and geosurvey. The number of areas continues to expand. However, due to the immaturity of products, key information, such as precise end customer needs and performance specifications still need to be gathered. As a result of this, valuation of new opportunities is challenging. This in turn presents a challenge to persuade companies to commit resources and investment to undertake development.

[57] National Strategy for Quantum Technologies
[58] A roadmap for quantum technologies in the UK

To help companies to discover the answers to these important questions, IUK with support from EPSRC and Dstl ran a Feasibility Study, together with a collaborative R&D competition. The competition was successful in attracting projects to explore possibilities and to develop components which make up quantum devices. These were primarily to supply an immediate market for research and academic use. A small number of projects were funded to develop, test and calibrate full quantum systems, such as clocks and gravity sensors. In total £4.7 million was allocated, across 22 projects.

In 2016, a follow on competition offered the opportunity for these projects to win extensions to their funding, in order to allow them to bring the results closer to market. Out of the 22 projects which were funded in the first round, Innovate UK received 16 applications for follow on funding (some projects decided to wait for the subsequent rounds, which would have different rules), and of these 16, 12 projects were funded, allocating a further £2.1m.

The recently announced IUK competition (summer / autumn 2016) will continue the momentum initiated in the previous competition, to allow for continued, and increasing level of company engagement with quantum technologies. This is resourced at the level of £9M from IUK and £9M from EPSRC, together with a capital top-up fund of £1.5M (amounting to a total of £19.5M).

It will be split into two streams: Feasibility Studies, and Collaborative R&D. Feasibility Studies will help companies with early interests in quantum technologies either to develop new ideas which are important in the make-up of quantum systems, or companies who are new to the sector, and are perhaps looking to build a business case for internal investment. Collaborative R&D projects will help companies who have a clear plan for commercialising a quantum technology; it will encourage ‘challenge-led’ projects to produce commercial prototypes and/or demonstrators, principally in one of the following areas:

- Clocks;
- Sensors;
- Imaging;
- Communications;
- Computing.

Consideration will also be given to devices that rely on "novel" quantum effects.

In 2017 and 2018, Innovate UK has plans to run further competitions. These are intended to help academics to form spin out companies, and continue to help companies to develop quantum technologies, and link them to realistic and profitable use cases. There had been a plan to use some of the funding to assist engagement with the EU but this is now uncertain.

To help Innovate UK deliver these competitions successfully, they will continue to work very closely with the networking and connecting activities of the Knowledge Transfer Network (KTN), and their quantum technology special interest group (SIG). See section 4.1.14 for more details of the KTN.

6.1.9 Department for Business, Energy and Industrial Strategy (BEIS)

The Department for Business, Energy and Industrial Strategy (BEIS) is the UK government department that brings together responsibilities for business, industrial strategy, science, innovation, energy, and climate change. The department invests in skills and education to promote trade, boost innovation and help people to start and grow a business. BEIS also protects consumers and reduces the impact of regulation.

BEIS is the parent Government Department for EPSRC and Innovate UK. The University's Minister has responsibility for the National Quantum Technologies Programme. In March 2016, the Minister announced a £167 million investment in Doctoral Training Partnerships and a further £37 million investment in the National Quantum Technologies Programme. This additional sum will provide extra impetus to our initiative and underline UK's political will to lead in this field. BEIS is also raising awareness of the national quantum programme with other departments through a number of mechanisms, briefing ministers and senior officials, including visits and other engagements, and steering international strategy/activity.

BEIS also works closely with the Government Office for Science (GO-Science) which is collocated with BEIS. GO-Science provides scientific advice to the prime minister and members of the cabinet to ensure and improve the quality and use of scientific evidence and advice to government. Included in its remit is to ensure that government policies and decisions are informed by the best scientific evidence and strategic long-term thinking. It seeks to achieve this by addressing infrastructure, efficiency and effectiveness; jobs and skills; communication and public engagement and science diplomacy. The latter plays an important role as part of the UK's influencing capability. The aim is to catalyse and promote science investment and international growth opportunities by working with the Foreign and Commonwealth Office and the Science and Innovation Network (SIN)

A recent report from the Royal Academy of Engineering[59] prepared for GO-Science about exploitation of the "Eight Great Technologies[60]" (now expanded to Ten with the inclusion of Quantum Technology and the Internet of Things) has highlighted cross-government opportunities to exploit quantum technologies. These are listed by Department. The report emphasised that many departments have limited their ideas to computing and communication. This is missing out on opportunity for significant impact that could become available through application of quantum technology. The report suggested that more work is required in other government departments to assess the potential impacts of quantum technologies. The report also emphasised the importance of encouraging systems thinking and cross-departmental consultation. It recommended that government should encourage continuing interdepartmental dialogue between analysts such as the EmTech panel and initiate awareness raising discussions with policy makers (at departmental and cross-government levels).

6.1.10 The National Physical Laboratory (NPL)

The National Physical Laboratory (NPL, figure 14) is one of the UK's leading science facilities and research centres. It is a world-leading centre of excellence in developing and applying the most

[59] http://www.raeng.org.uk/publications/responses/emerging-technologies (may have to paste this link into browser)
[60] See https://www.gov.uk/search?q=eight+great+technologies, and in particular quantum technologies.

accurate standards in science and technology available. NPL occupies a unique position as the UK's national measurement institute. It occupies the intersection between scientific discovery and real world application, and has been closely involved with the UK National Quantum Technology Programme from its first inception.

The National Physical Laboratory manages the UK's timescale, UTC(NPL), with a suite of atomic clocks. They also hold the realisation of the SI second; their caesium fountain CsF2, accurate to 1s in 158M years. UTC(NPL) is disseminated to the nation using a range of techniques. Their latest solution is NPLTime®, a certified and resilient time service delivered to the Financial Sector.

Figure 14: NPL main building, home of the QMI (Quantum Metrology Institute) ***Courtesy of John Christensen NPL***

Precise and accurate timing plays a critical role in financial markets: underpinning the time stamping of trades; synchronisation of systems and the measurement of network latency for process optimisation. The rapid expansion of computer-based trading has increased the need for synchronisation of trading systems and traceability to UTC (Coordinated Universal Time), in order to help prevent trading irregularities and to aid forensics.

NPLTime® is delivered entirely over fibre, from UTC(NPL) via their hub in London to the customer rack. The authorised distributors provide the time on managed links to a managed end point device at the client's rack/premises, where the time is certified by NPL, and consumed as a 'trusted time'. Their development of miniaturised atomic clocks as part of the quantum programme could result in a portable version of NPLTime® being made available commercially.

NPL's quantum technology activities have recently been crystallised in the Quantum Metrology Institute (QMI). This brought together all of NPL's quantum science and metrology research in one area and provided the expertise and facilities needed by academia and industry to test, validate, and in certain circumstances commercialise new quantum research and development. By bringing together industry engineers, academic researchers and NPL scientists in a highly collaborative environment, the QMI is playing a key role in the creation of a UK quantum industry.

NPL's vision for the QMI is a leading centre for quantum metrology in Europe, collaborating with academic partners, government and industry to advance scientific discovery in quantum physics and materials. NPL delivers world-class research based on quantum phenomena for future generation SI standards. The QMI research areas currently comprise Time & Quantum Frequency Standards, Solid State Quantum Detection and Graphene. It is also engaged in development of atomic interferometers

Figure 14 View of the main NPL building housing the new Quantum Metrology Institute (QMI)

The Time & Quantum Frequency group carries out a broad programme of research in time and frequency metrology. This includes the development and characterisation of a new generation of optical atomic clocks based on laser-cooled trapped ions and atoms. This is predicted to lead to a future redefinition of the SI second. Envisaged applications of these clocks range from improved satellite navigation systems to sensitive tests of fundamental physical theories. Other areas of research include the development of compact and user-friendly frequency standards for industrial applications and unique algorithms for processing clock data to generate the most stable reference time scales achievable.

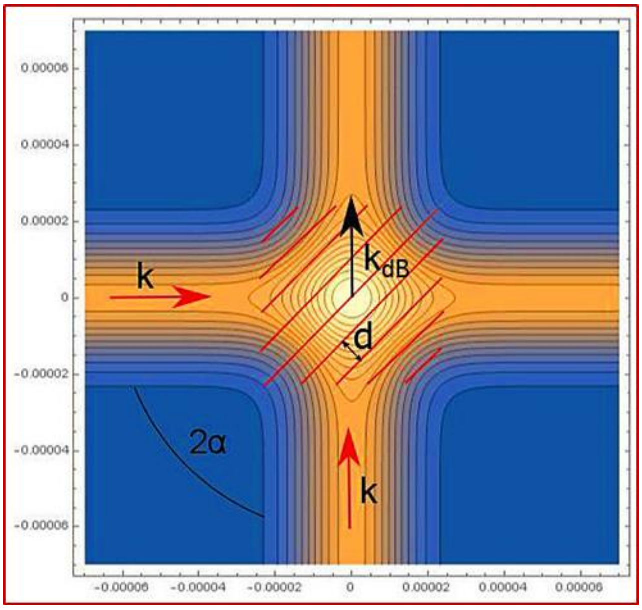

Figure 15: Guided atomic wave directional coupler ***Courtesy NPL***

The Solid State Quantum Detection group research and develop new devices for generating and detecting single quanta such as phonons or magnetic spins, develop new techniques for characterising quantum-mechanical state evolution, and using quantum coherence and entanglement to enhance measurement precision. New, high speed devices for manipulation of electrical current at the single-electron level are also studied. The Graphene group use a range of quantum metrology techniques, including functional scanning probe microscopy, and nano-analysis to advance understanding of quantum effects in graphene and thereby support the development and application of graphene based electronic devices to develop new capabilities not possible using conventional technologies.

The QMI is also studying the potential of guided wave devices to produce a new generation of atomic interferometers.

6.1.11 GCHQ

The Government Communications Headquarters (GCHQ) is one of the UK Intelligence and Security Agencies. Along with other government departments, GCHQ aims to protect the UK and its citizens from a range of threats to national security. These include terrorism, serious and organised crime, and cyber-attack. NCSC (formerly the Communications Electronics Security Group) is part of GCHQ and is the national technical authority for Information Assurance (IA) within the UK. It provides a trusted, expert, independent, research and intelligence based service in the field of information security on behalf of UK government. It also advises a wider variety of organisations on how to protect their information and information systems against the latest threats.

NCSC has been conducting its own research into "post-quantum" security. Following the National Quantum Technology Initiative, it has allocated further funding to build capacity in UK academic research in quantum algorithms and cryptography. After a competition, funding of £500,000 has been allocated to the University of Oxford to support a new research group. NCSC has released some of its own research[61] into the public domain to stimulate the growth of this area. GCHQ/NCSC is also active in promoting post-quantum computing research in the UK, for instance by supporting events such as "Post-Quantum Research – Identifying Future Challenges & Directions" held in May 2014 at the Isaac Newton Institute, Cambridge, UK.

6.1.12 Dstl

The Defence Science and Technology Laboratory (Dstl) aims to maximise the benefit of science and technology for the defence and security of the UK, supplying sensitive and/or specialist Science and technology services for the Ministry of Defence (MOD) and wider government. It is responsible for delivering the UK Ministry of Defence R&D programmes, including the MOD Chief Scientific Adviser's Disruptive Technology Programmes in Quantum Technologies, see section 5.2.12.

Dstl has been prominent in the use of its specialist quantum technology team to support and encourage the national programme.

6.1.13 The UK MOD quantum technology programme

During the twentieth century and still today, the defence industry was and is a pioneer in the development of new technologies. MOD has extensive experience developing and industrialising complex systems, built from high tech components. These have to perform to exacting specifications under a wide range of operational conditions. Given that the new platforms brought into service are likely to remain in the inventory for many years, and are increasingly complex, it is little use investing in cutting-edge science unless systems engineering capability and vital long-term knowledge is maintained. New technologies have less benefit if the knowledge of how they might best be exploited and inserted into existing equipment has been lost. This demands a high level of systems engineering skills, at all levels of the supply chain.

MOD's Quantum Technology Programme is a result of the decision announced in 2014 to change radically MOD's approach to R&D. Today about 20% of the MOD Chief Scientific Adviser's R&D budget is devoted to investigation of emerging disruptive technologies and, where appropriate, rapid development and deployment of systems with new, powerful capabilities[62]. The model is seen to be similar to that of the US Defence Advanced Projects Research Agency.

Under this new initiative, Dstl is delivering a programme whose value is about £36 million over 5 years. It has become part of the coordinated national programme, complementing activities in key areas. It comprises two demonstrators: a quantum navigation system, and a quantum gravity imager, and (as at July 2016) 46 PhD projects. The navigator is aimed at permitting certain

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61 see S07_Groves_Annex.pdf at https://docbox.etsi.org/Workshop/2014/201410_CRYPTO/S07_Systems_and_Attacks/. This describes SOLILOQUY which was a suggested basis for a quantum resistant key exchange protocol with very good efficiency properties, both in terms of public key size and the speed of encryption and decryption. Research on SOLILOQUY was abandoned after demonstrating vulnerability to quantum attack. The work concluded that designing quantum-resistant cryptography is a difficult task and recommended thorough and independent assessment of any new proposed protocols.

62 Fast track research and development and insertion into service is known as a Urgent Operational Requirement (UOR) and has an upper time limit of two years from start to finish. Typically, such projects are completed within a few months.

operations when GNSS[63] is unavailable or denied, and to provide precise time. The imager will be able to "see" a wide variety of objects or voids at various length scales by measuring components of the local gravitational field. Unlike electromagnetics, gravity effects cannot be shielded.

Specific threads of development are:

- Atomic gyros;
- Atomic accelerometers;
- Gravity gradiometer arrays;
- Miniature low size, weight, power and cost atomic clocks.

The 46 PhD projects are addressing the development of enabling technologies (such as vacuum chambers, lasers and integrated optics), enhancing or de-risking projects comprising the demonstrators and investigating new sensing modalities for possible further development in the future. There is also a system engineering component. The projects are based at 16 universities across the UK and align closely with work ongoing in the Hub network.

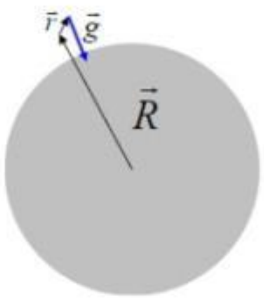
6.1.13.1 Applied physics demonstrators

The Dstl Quantum Technology Programme comprises two large scale development projects designed to provide early demonstrations of the advantage of some of the novel quantum technologies over classical physics-based techniques. The Quantum gravity imager project seeks to develop a standalone; portable system being delivered by Professor Kai Bongs' group at Birmingham University. The Quantum navigator project is more complex and technically challenging and is being delivered through work in the groups of Professor Ed Hinds at Imperial College London, Professor Patrick Gill at NPL and Professor Kai Bongs at Birmingham University.

6.1.13.2 Quantum gravity imager

This project will use atom interferometry readout of laser cooled, cold atom ensembles to sense the gravity and gravity gradient of fields local to the gravity sensors.

Consider a measurement point at $\vec{r}$ relative to the centre of the Earth defined by $\vec{R}$.



The Taylor expansion of the gravity potential is:

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[63] GNSS = Global Navigation Satellite System, the earliest system is the US GPS, or Global Positioning System.

$$U(r) = -\frac{GmM}{\left|\vec{R}+\vec{r}\right|} = C - m\overrightarrow{\cdot g} - \frac{m}{2}\vec{r}\cdot\overleftrightarrow{T}\cdot\vec{r} + O(r^3)$$

The first (constant) term is the absolute local gravitational potential; the second is the first derivative (gradient) of the potential where $\vec{g}$ *is the local acceleration due to gravity. The third term is the second derivative of the potential where* $\overleftrightarrow{T}$ *is the gravity gradient tensor. These terms individually can be measured by clocks*[64]*, accelerometers and gravity gradiometers respectively.*

The current state of the art classical devices for measuring acceleration and gravity gradient[65] *are the falling corner cube instrument, with absolute accuracy ~ 1 µGal (10^{-8} m s^{-2}), and the Lockheed-Martin Niagra instrument, with absolute accuracy ~ 3 Eo (3 x 10^{-9} s^{-2}). Such instruments are limited in accuracy and stability by issues arising from mechanically moving parts, wear and repeated calibration. Both are heavy, bulky devices difficult to miniaturise, restricting deployability. The (atomic) clocks required to measure absolute potential to a practical degree of accuracy have only been realised as complex devices in laboratories.*

Two foci of the Gravity imager project are to increase the instrument sensitivity and stability while simultaneously greatly reducing SWAP (size, weight and power) requirements to facilitate the engineering of man portable devices.

The third focus of the project is to design and engineer arrays of gradiometers to produce an image of the local mass field. The aim is to identify buried structures and artefacts, e.g. subterranean voids, pipes and hidden objects such as heavy machinery or fissile materials within containers.

The resolution of such an imager is expected to be limited by the number of nodes in the sensor array, the distance of the array from the target and the integration time used in making measurements. Figure 16 shows a preliminary model for imaging tunnels, 1 m x 1 m, buried 1 m and 4 m below the surface for a sensor 1 m above the ground. The left side of both pictures shows the effect of clutter resulting from Gaussian autocorrelated surface roughness with a 1/e radius of 1 m, height standard deviation=1 cm.

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64 An absolute measurement of gravitational potential is not possible. The *difference* between two potentials can be measured by comparing the rate at which clocks run in each locality.

65 The Gal (Galileo) is a measure of gravitational field strength and is equivalent to acceleration. So 1 Gal represents an acceleration of 0.01 m s^{-1} or ≈1/1000 the value of g. The Eotvos (Eo) is the unit of gravity gradient, equivalent to 10^{-7} Gal per meter. The vertical tensile gradient at the earth's surface is approximately 3,000 Eo, leading to the counter-intuitive conclusion that one's feet are accelerating at a different rate to one's head (by the equivalence principle). In fact, this phenomenon manifests as a phenomenon known as spaghettification in the vicinity of a black hole. These are both extreme examples of tidal forces.

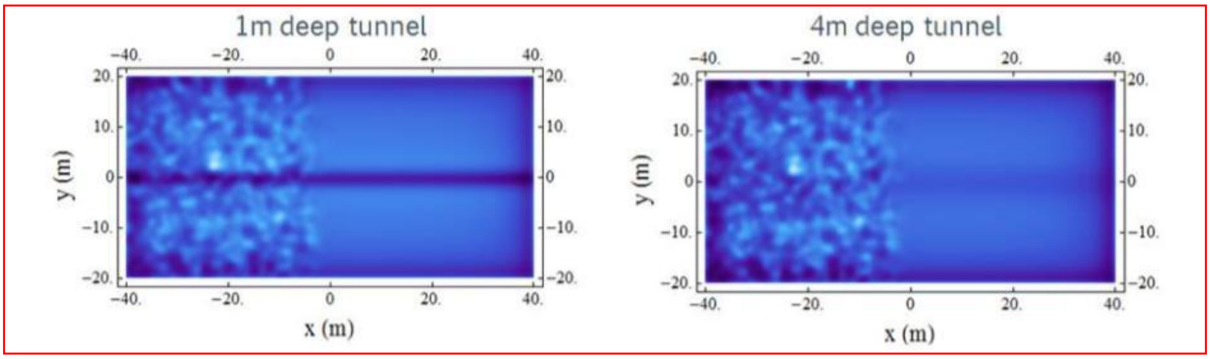

Figure 16 Simulated image from tunnels (see text above)

6.1.13.3 Accelerometers and gyros

Atomic quantum gyros and accelerometers deliver zero bias and drift, and are expected to exhibit perfect linearity. In free space, they could theoretically achieve a navigation error of about 1 metre per month. However, perfect sensors must be complemented by accurate measurement of the local gravity (to differentiate effects due to inertia and gravity) and dynamic effects which go beyond the simple models of gravity. The most commonly used is WGS84[66] which describes the Earth's size, shape, and gravity, and its geomagnetic fields. It is currently used in inertial navigation systems. Because of this, the gradiometers being developed for the Gravity imager project are important to the Quantum navigator project and may, in fact, be key to the accurate operation of the navigator.

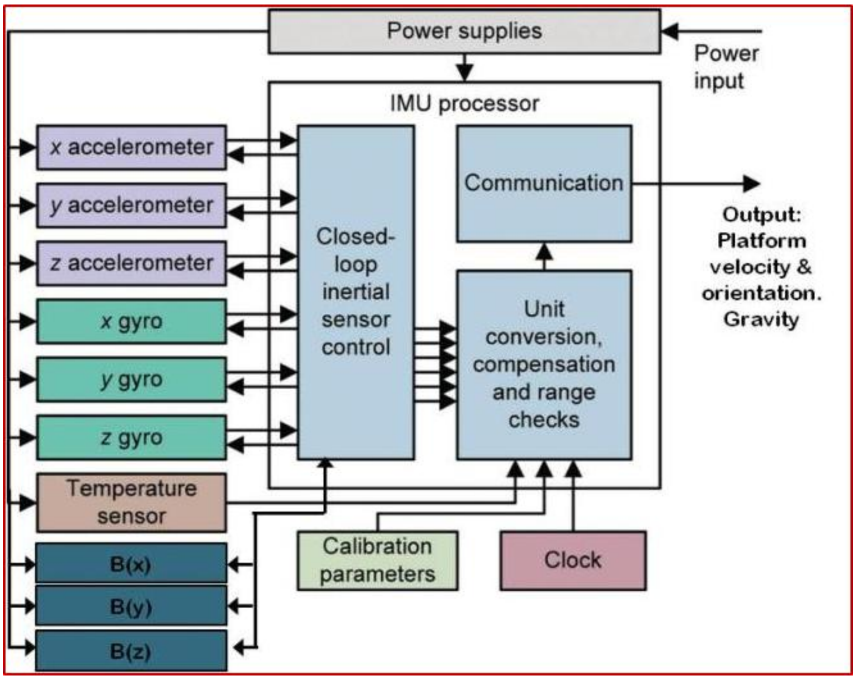

Figure 17 Block diagram of typical inertial navigation system

Deployable cold atom accelerometers and gyros are under development at Imperial College London and NPL. The initial demonstration is for a 1 axis accelerometer technical demonstrator in 2017. This is planned to be followed by a 3 axis device in 2019.

The potential for the sensor to be used in a rotation sensing mode will be assessed as will the potential for realising guided matter wave devices. If the latter devices can be realised, the impact on cold atom sensors could be comparable to the effects of integrated circuits on electronics in the 1960s and 70s, and the immense miniaturisation which was achieved compared to valve based electronics.

66 For a thorough explanation of WGS84 please see here.

A functioning quantum navigation system presents huge challenges in systems engineering which are currently being studied through a combination of mathematical modelling and numerical simulation. We expect it to be possible to achieve navigation errors of a few hundred metres per month. A simplified inertial measurement system is shown in figure 17.

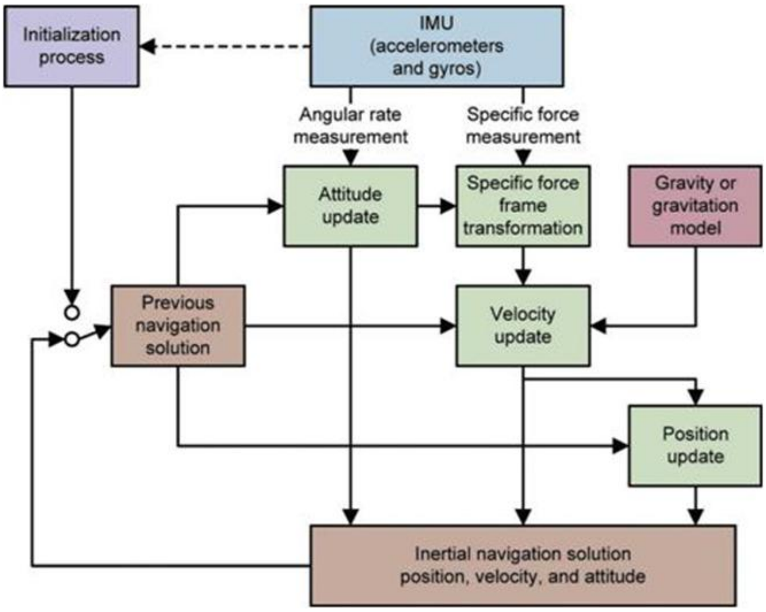

Figure 18 Typical compensation scheme for rotation and gravity

Compensation for the Earth's gravity and rotation is also required. An example of how this might be achieved is shown in figure 18. Compared to classical systems, improvements of 10^3 or more may be achieved. Demonstrator models will not achieve the lowest SWAPC possible, but with further development cycles, significant improvements will take place.

6.1.13.4 Miniature atomic clocks for precise time

The MOD programme is developing 3 miniature low power atomic clocks, each exhibiting a different trade-off between accuracy / stability and SWAPC[67].

A caesium filled hollow core filled clock is under development at NPL. The device, in its prototype form requiring ~ 1.5 W, will be the size of a cigarette packet and achieve GPS-like timing. Such a device will allow 3-day holdover. A pre-production prototype is expected to be demonstrated during 2016. Strathclyde University are developing a laser cooled, cold rubidium CPT clock with an expected Allan deviation of $10^{-13}/\sqrt{Hz}$ (at 1 Hz sample rate) and a form factor of a few cm3. These specifications make such a device a step change in portable cold atom devices (clocks and inertial sensors) and a strong candidate to be a commercially affordable occupying the middle ground between the CSAC and commercial beam clocks on the one hand and the primary standard clocks on the other.

67 SWAPC = Size, Weight, Power and Cost

Figure 19: Enclosure, physics package and electronics of hollow core clock
Courtesy Professor Patrick Gill NPL

NPL is developing an ytterbium (Yb) ion[68] microwave clock due in prototype form by 2017. The device will be teapot sized and provide GPS-like timing holdover for periods in excess of 1 year. The underlying technology uses Yb^{+} trapped in a linear blade trap initially although the design is expected to evolve to a vacuum system and optics within a 5 x 5 x 5 cm cube weighing a few hundred grams. A 29 mm square industry standard chip carrier will provide vacuum feed-through connections, electrically connected via wire-bonding. The vacuum would be provided and maintained from a custom-made non-evaporable getter.

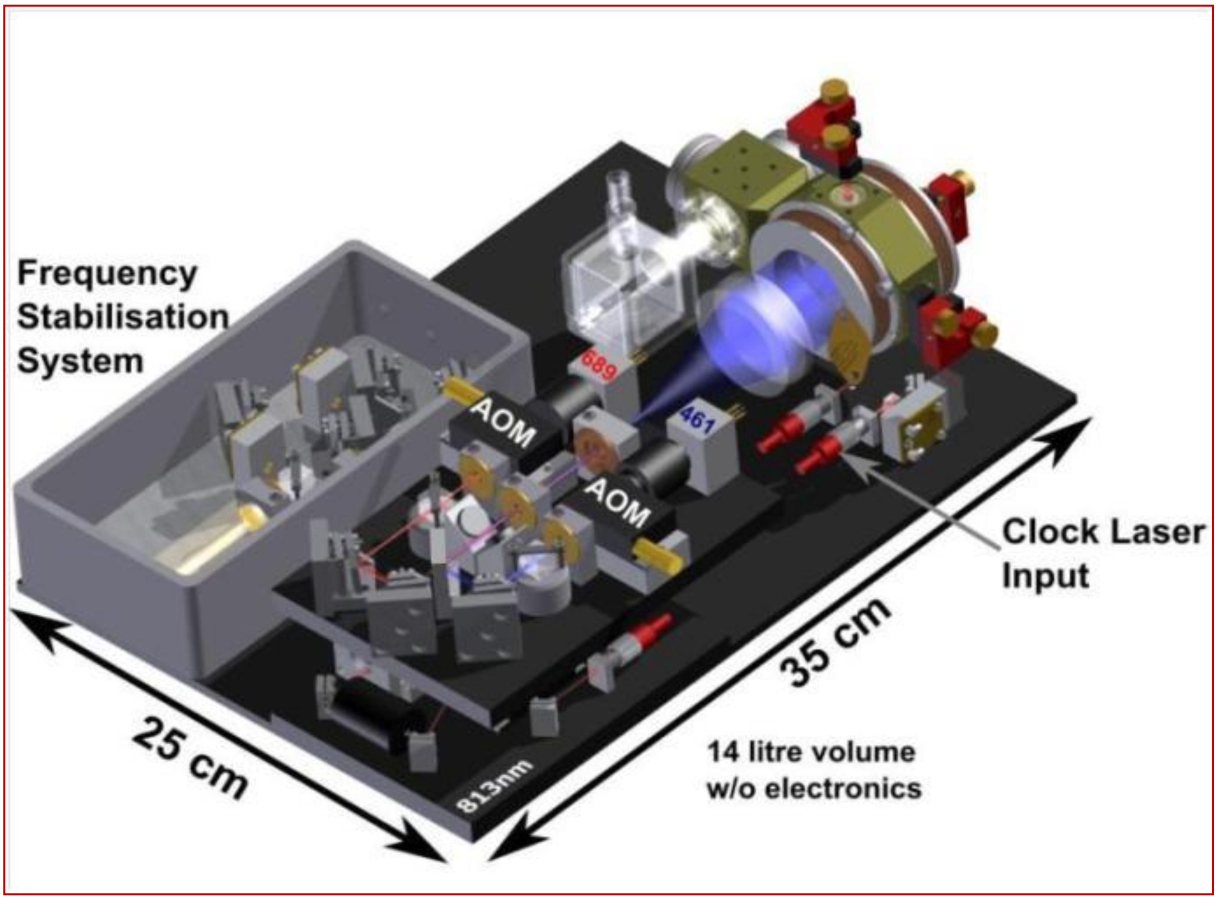

Figure 20: CAD for the physics package of the optical strontium lattice clock
Courtesy Yeshpal Singh Birmingham University

68 a ytterbium (Yb) ion is a charged atom of the element ytterbium. You will notice that various elements are used as the timing mechanisms for atomic clocks. Each have uses dependent on their excitation spectra that are optimum for different apparatus configurations and stabilities / accuracies.

Birmingham University are leading on the development of a compact strontium based optical lattice clock. This should be available as a prototype by 2019 with a stability of 10 ns in 3 years. The atomics package is illustrated in figure 20.

NPL will provide the clock laser and cavity. The approach is to have a miniaturised laser system based on the force-insensitive Fabry-Perot etalon technique patented by NPL. NPL expect to achieve stability of 1 part in 10^{15} floor or better after 100 seconds. The clock laser is designed to be an alignment insensitive 698 nm compact interference filter extended cavity diode laser (IFECDL). It will have an integrated thermal controller, be vacuum sealable and weigh less than 100gms. The IFECDL will be stabilised against the NPL patented passive vibration insensitive cavity housed in an evacuated enclosure pumped to ~ 10^{-6} mbar by an ion pump.

Separate work is in hand at NPL to develop a miniature optical frequency comb which will convert the frequency standard into a true clock. With such a comb, a form factor for the complete clock equivalent to a small travel case is anticipated.

6.1.13.5 PhD portfolio - Fundamental and applied research

Dstl currently has a portfolio of 45 projects (the 46th is due to start June 2016) spanning sensors and photonics plus a project developing approaches to quantum systems engineering. In general terms a common theme is the development of low SWAP systems with the potential to deliver, or facilitate the delivery of, disruptive capability for defence and security.

Some projects are "blue skies" in nature, others directly support, enhance or de-risk the demonstrator projects and a third group are developing enabling technologies. There is one PhD investigating specialist systems engineering. See figure 21.

The enabling technology projects include the development of miniature, high performance vacuum cells, novel miniature lasers, integrated optics and cold atom sources and traps.

In terms of sensors, the portfolio includes projects developing novel approaches:

- inertial sensing (acceleration, rotation and gravity);
- electric and magnetic field sensing;
- range sensing, including covert range-finding and quantum radar;
- sub-diffraction limit imaging;
- ghost and 3D imaging;
- miniature clocks.

The Dstl quantum programme PhD research portfolio is summarised below:

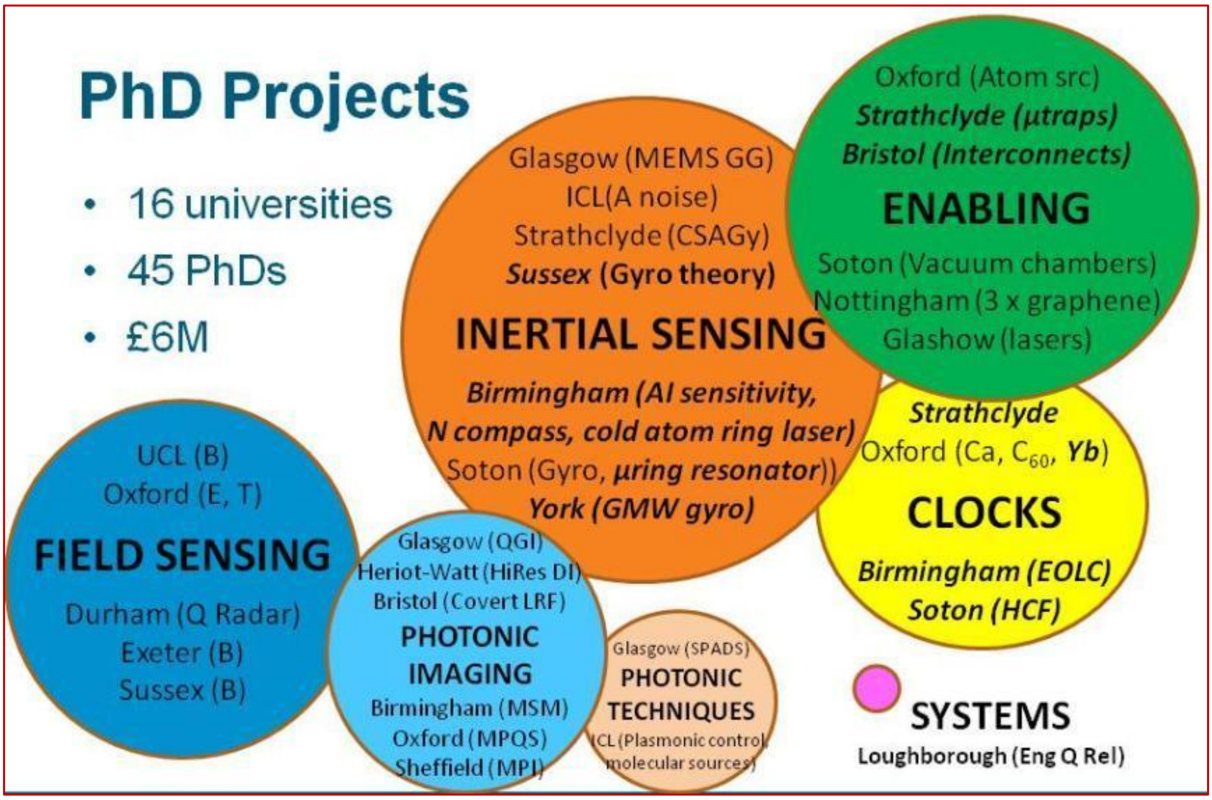

Figure 21: MOD PhDs by subject

Oxford	7
Birmingham	5
Glasgow	5
Southampton	5
Imperial	3
Nottingham	3
Strathclyde	3
Sussex	3
Bristol	4
Durham	1
Exeter	1
Heriot-Watt	1
Loughborough	1
Sheffield	1
UCL	1
York	1

Figure 22: MOD PhDs by universities

6.1.14 Synergy between the MOD and national programmes

Perhaps unsurprisingly because of the engagement of university quantum physics groups with the emerging National Quantum Technology Programme, there was a high correlation of successful proposals with universities which became part of the National Network of Hubs, see figure 22.

The two programmes were designed to be mutually complementary. The MOD programme benefits by a 9:1 gearing from the Hub and other components of the National Programme, while the civilian activities benefit from the focus on early demonstrators. These are a key driver in the MOD programme; the intention being for MOD to act as an early adopter for certain large systems.

6.1.15 KTN

The Knowledge Transfer Network (KTN) is the UK's innovation network. It brings together business, entrepreneurs, academics and funders to develop new products, processes and services.

KTN has set up a Special Interest Group[69] (SIG) for everyone interested in quantum technologies including industry, academia, suppliers, end-users, entrepreneurs and investors. The aim is to unite communities to exploit commercial opportunities for quantum technologies. The QT SIG explores market opportunities and is helping build vital supply chains to promote a thriving UK industry. Markets addressed include finance, communications, computing, defence systems, space, mining, position, navigation and timing and medical physics.

Recently, the quantum KTN has begun to hold a series of market focussed innovation workshops to help define applications areas. Areas suggested for commercialisation are:

- Pricing of complex financial instruments
- Secure cloud/low latency networks
- Fraud/anomaly detection, surveillance and monitoring
- Authenticated (distributed) time
- Secure identity/ID protection
- Quantum random number generation (RNG)
- Distributed ledger and stock management
- Risk Modelling and crisis recognition

The KTN recently held a workshop to establish industry priorities and recommendations for quantum technology development. A summary is shown in section 7.2.2. Additional detail is available from the KTN SIG website.

6.2 Major quantum activities outside the hubs

There are substantial academic quantum physics activities outside the hubs; these continue to be active in exploiting their output technologies, either independently, or with the hubs as partners. Some are members of one or more hubs, some are not. Some hubs have wide ranging quantum physics research activities that extend beyond, and complement, their technology development

69 https://connect.innovateuk.org/web/quantum-technology

activities[70]. Significant research activities are described below. Some of the material necessarily has a significant technical content in order to provide a sufficient explanation of the activities.

6.2.1 Centre for Photonics and Photonic Materials and Centre for Advanced Sensor Technologies, University of Bath

The principal focus of the research, which is an enabler for wider quantum technologies, is to develop a deeper understanding of photonics, photonic materials and photonic devices. They are also engaged in exploring their exploitation in real world applications.

Hollow-core and multi-core photonic crystal fibres (PCFs) have applications in wavelength conversion, high power pulsed laser delivery, endoscopy, and fibre lasers. Properties of the fibres are also studied to increase understanding of pulse propagation. Post-processing of conventional fibres or PCFs allows the profile and dispersion of optical fibre modes to be controlled with applications in astrophotonics[71], biomedical imaging, and mode division multiplexing for optical communications. New sources of single photons are being developed to transmit and process information for secure communications, enhanced precision sensing at low light levels, and simulation of complex quantum systems. Numerical simulation and analytical theory is used to understand nonlinear optical effects in tightly confining structures, where the light fields are far from the plane wave approximation, and also in graphene where the nonlinearity is strictly a surface effect. Nonlinear and time resolved spectroscopy is used to study the properties of resonant plasmonic[72] devices and the transient electronic states in organic photo-electric devices.

The Centre for Advanced Sensor Technologies brings together expertise in microelectronics, optoelectronics and novel materials. The Centre's interdisciplinary research focuses on highly accurate sensors, devices and related technologies, including electronic circuits and systems, wide bandgap semiconductors, LED[73]s, devices for medical applications, implantable systems, sensor and actuator materials, nanotechnology and biosensors and chemical sensors. The Centre has well-equipped optical and electronic test laboratories, including a full suite of industry-standard circuit design software, an electronics test and measurement laboratory, a materials laboratory suite, a micro fabrication laboratory, a chemical sample preparation and electrochemistry laboratory and access to the David Bullett nanofabrication facility, which is dedicated to nanotechnology research.

This nanofabrication facility comprises a range of equipment within a suite of clean rooms of ISO Class 6. E-beam, photo- and nano- lithography machines are available plus thin film deposition, etching and deposition to create custom structures. The facility also has surface characterisation capability using stylus profiling, optical and electron beam microscopy. Structures with feature sizes as small as 20 nm can be fabricated.

6.2.2 Queen's University, Belfast

Quantum technology related research at Queen's University, Belfast, comprises:

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70 For an excellent exemplar website see the Oxford Quantum core at http://oxfordquantum.org/overview/

71 Astrophotonics lies at the boundary of astronomy and photonics. An introduction may be found here.

72 A plasmon is a quasiparticle, see section 5.1.2 for a brief explanation. A quasiparticle is an aggregate of parameters that behaves like a particle but which cannot exist outside its substrate.

73 LED = Light Emitting Diode

- Quantum Optics: cavity quantum electrodynamics, all-optical implementations of quantum information schemes, strong optical nonlinearity in coherent atomic media, quantum opto-mechanics and the hybridization of mechanical-optical devices;
- Quantum Information Theory and Processing: the theory of quantum correlations, the design of protocols for the exploitation of correlation, quantum state transfer to and quantum statistics in quantum-spin chains;
- Laser cooling and spectroscopy: atomic and molecular laser cooling, Sisyphus cooling[74] and evaporative cooling;
- Ultra cold quantum gases, quantum many-body theory and quantum phases, Bose-Einstein condensation (formation of BECs[75]), vortex-dynamics in distributed systems, the physics of cold atomic ensembles and general networks, quantum mechanical properties and their simulation in systems of cold and ultra cold atoms;
- Foundations of physics: Bell's inequality, Leggett-Garg macro-realism tests, non-local realism and multipartite quantum non-locality[76]. Implementation of these tests in atomic, optical and solid-state systems.

6.2.3 Centre for Quantum Photonics (CQP) and EPSRC CDT for Quantum engineering, University of Bristol

Bristol is additionally teamed with both the Glasgow and York Hubs.

Whilst offering post graduate training in quantum engineering, the CDT, together with the CQP, aims to exploit the fundamental aspects of quantum mechanics in photonic quantum technologies. Generation, manipulation and measurement of single photons is a key focus as well as the quantum systems that emit these photons. Scalable technologies are being developed via cutting-edge engineering processes to form practical devices and technologies. Areas of technology focus include quantum communication, quantum metrology and quantum computing and simulation.

For real world applications of quantum cryptography and quantum teleportation, the extension of quantum-entanglement-based protocols to global distances is important. The group has experimentally demonstrated free space quantum key distribution over 144 km. This was achieved by measuring a photon locally at the Canary Island of La Palma while a second is sent over an optical free-space link to Tenerife, where the Optical Ground Station of the European Space Agency acted as the receiver. This exceeds previous free-space experiments (using entanglement) by more than an order of magnitude in distance, and is an essential step towards future satellite-based quantum communication and experimental tests of the limits of quantum physics.

Precision optical phase measurements can be used to measure distance, position, displacement, acceleration, and optical path length and are a focus of the group's research. Quantum

[74] "Normal" laser cooling using the Doppler has a limited lower temperature. Sisyphus cooling uses polarisation gradients in light fields and was discovered by accident during temperature measurements.

[75] A Bose-Einstein Condensate (BEC) is an aggregate of atoms that are exceptionally cold (~100nK) and which are indistinguishable. They have special properties and are being studied intensively. A more technical story.

[76] These are some of the so called "weird" effects of quantum physics that we perceive as counter-intuitive. They are mainly concerned with what we (incorrectly) see as action at a distance or over time. A detailed explanation is beyond the scope of this document, however a Google search on the individual terms will lead to suitable references.

entanglement enables higher precision estimates than would otherwise be possible and an optical phase measurement has been demonstrated with an entangled four-photon interference visibility greater than the threshold required to exceed the standard quantum limit.

Quantum information science (including quantum computing) brings together experiments and theory. The ultimate aim is to develop quantum devices that successfully compete with, or outclass, any classical devices. The areas of theoretical and experimental subjects covered are:

- Theory - Quantum algorithms, Quantum computational models, quantum "Shannon" theory[77], entanglement, quantum non-locality and fundamental aspects of quantum mechanics;
- Experiments - quantum key distribution (QKD), Single photon sources and non-locality demonstrations.

The interdisciplinary aspects of the research have led to significant advances including "The integrated quantum chip" and the "Quantum in the Cloud" resource including an open-access quantum processor.

Underpinning the experimental work is the development of novel quantum photonic technologies. The group has adopted an integrated optics architecture for improved performance, miniaturization and scalability. They have demonstrated high-fidelity silica-on-silicon and silicon integrated optical realisations of key quantum photonic circuits, showing that it is possible to directly "write" sophisticated photonic quantum circuits onto a silicon chip. Applications are expected to include information processing, communication, metrology and lithography as well as the fundamental science of quantum optics.

Bristol has a large research programme in the area of network switching in partnership with their High Performance Networking (HPN) group[78]; this is one of the world leaders in next generation optical networking. They are pioneering Software Defined Network (SDN) for optical implementations which actually turn out to have some of the same problems and constraints as QKD signals flowing through the networks. If one has to convert from optical to electronic to read packet headers for switching, most of the speed and capacity advantages of (classical) optical communications is lost.

The HPN group has developed novel additions to SDN and the OpenFlow standard to allow software reconfiguration of an optical network while keeping all of the traffic in the optical domain. Quantum signals face similar challenges, so the Bristol teams are exploring how to generalise this work using their Open Network test bed to explore how quantum security can be deployed in network scenarios.

6.2.4 Quantum Systems and Nanomaterials Group, Exeter University

Exeter has more than 200 researchers working in areas related to quantum technology, e.g.:

- The theory of quantum computing, quantum transport and quantum thermodynamics;

[77] See here for an excellent technical book on the subject that shows how quantum aspects can be derived from the classical.

[78] See their web pages here: http://www.bristol.ac.uk/engineering/research/hpn/

- Experiments that uncover the electrical, magnetic and optical properties of materials;
- The development of single photon and electron devices;
- The fabrication of nanomaterials. These are expected to provide the toolkit needed for the downstream construction of nanotechnologies. "Functional materials" is one of the five principal themes of the University of Exeter's science strategy.

Exeter is particularly strong in gaining new understanding of the physical properties of nanoscale materials and systems in which quantum behaviour emerges. Research within the departments of Physics and Engineering includes 2D materials such as graphene, phase change materials, nanomagnetic and spintronic materials, and metamaterials that strengthen light-matter interactions at the nanoscale.

The University of Exeter is home to one of three UK Centres of Graphene science and the UK's largest CDT in metamaterials. Research foci include the interaction of electromagnetic radiation with matter spanning from the microwave to the X-ray region of the spectrum, integrated optics, magnonics[79], spintronics, plasmonics and terahertz optics. Applications and industrial collaborations include data storage systems, wireless communications, displays, cloaking, security, tagging and imaging.

The quantum non-equilibrium theory group works on the interface between quantum information theory, quantum optics and quantum thermodynamics. The group has developed ancilla-driven quantum computation, a feasible model for quantum computation suitable for hybrid realisations involving a single fully controlled ancilla[80] that mediates between a large set of register qubits with very limited control. Current research addresses the extension of thermodynamics theory to the quantum regime, an essential step for harnessing quantum dynamics for practical applications in the future. Quantum thermodynamics research underpins nanoscale technology with applications expected in nano- and quantum machines, data storage, quantum computation and communication, and diagnostic healthcare devices.

The University of Exeter has state-of-the-art equipment for device fabrication, including a $500m^2$ clean room facility equipped with a wide range of nanolithography, etching and deposition systems. Three main characterisation facilities cover the analysis of electrical transport, and magnetic and optical properties over a wide temperature range (1000 K down to 50mK) and external magnetic fields (up to 17.5 Tesla). Exeter's condensed matter research includes:

- Modelling prototype structures for optical computing components, next generation light sources and energy conversion systems;
- Quantum electronic transport in mono- and multi-layer graphene for quantum-enhanced sensing technologies;

[79] Magnonics is a subset of modern magnetism that combines waves and magnetism, and its aim is to investigate spin waves in nano-structured elements.

[80] An ancilla bit is an extra bit used for convenience in a quantum logic circuit. Its analogous use in a classical circuit is to store "rubbish" components of a computation such that, in principle, the computation could be made thermodynamically reversible. Reversible computing is a large, sometimes controversial subject that is outside the scope of this document. The core of true, universal quantum computers is *de facto* reversible.

- Electronic and optical properties of graphene and carbon nanotube structures with applications to terahertz optoelectronics;
- Bandgap engineering and transport in functionalised graphene structures;
- *Ab-initio* and phenomenological theories of solids, surfaces and nanomaterials and first-principles investigations of clusters and supercells of atoms using spin-polarised self-consistent local density functional pseudopotential techniques;
- Nanomagnetic systems for data storage and their interaction with optical and microwave radiation;
- Active spintronic systems powered by spin current and spin torque for embedded memory and microwave electronics;
- Magnonic devices and materials for new approaches to information processing.

6.2.5 EPSRC CDT for Controlled Quantum Dynamics and Centre for Cold Matter (CCM), Imperial College London

The EPSRC CDT for Controlled Quantum Dynamics addresses the theoretical and experimental developments in quantum mechanics that allow exquisite control over the dynamics of small numbers of quantum systems. Quantum phenomena such as entanglement, teleportation, nonlocality and interference are exploited for applications including:

- Quantum cryptography and quantum "coin" flipping;
- Quantum computers;
- Improved high precision metrology for space and time measurements;
- Non-classical aspects of field-matter interaction;
- Quantum aspects of attosecond dynamics;
- Quantum plasmonics.

Experimental work includes trapping and manipulating ions and ultra-cold atoms. The applications include chip scale atomic clocks, coherent control of ultrafast processes in molecules and investigation of quantum matter-field interactions in nanoscale structures. Theoretical work spans quantum entanglement in many-body quantum systems, modelling quantum dynamics in biological systems, modelling quantum decoherence and studying light-matter interaction.

In addition to the CDT, there is a significant activity in Professor Ed Hinds's Centre for Cold Matter. The main focus of the group is on cold molecules and "Atom Chips" where experiments are shrunk down on to specially fabricated microchips.

Atom chips combine cold atom physics with microfabrication techniques to create and manipulate electric, magnetic and optical fields to trap and manipulate atom clouds. In prototype devices (on the mm scale), these atom chips are being used to make Bose Einstein condensates and also for applications including clocks, atom interferometry, and quantum information processing. These have potential applications for building extremely high-precision sensors as well as being tools for the future evolution of "quantum computing".

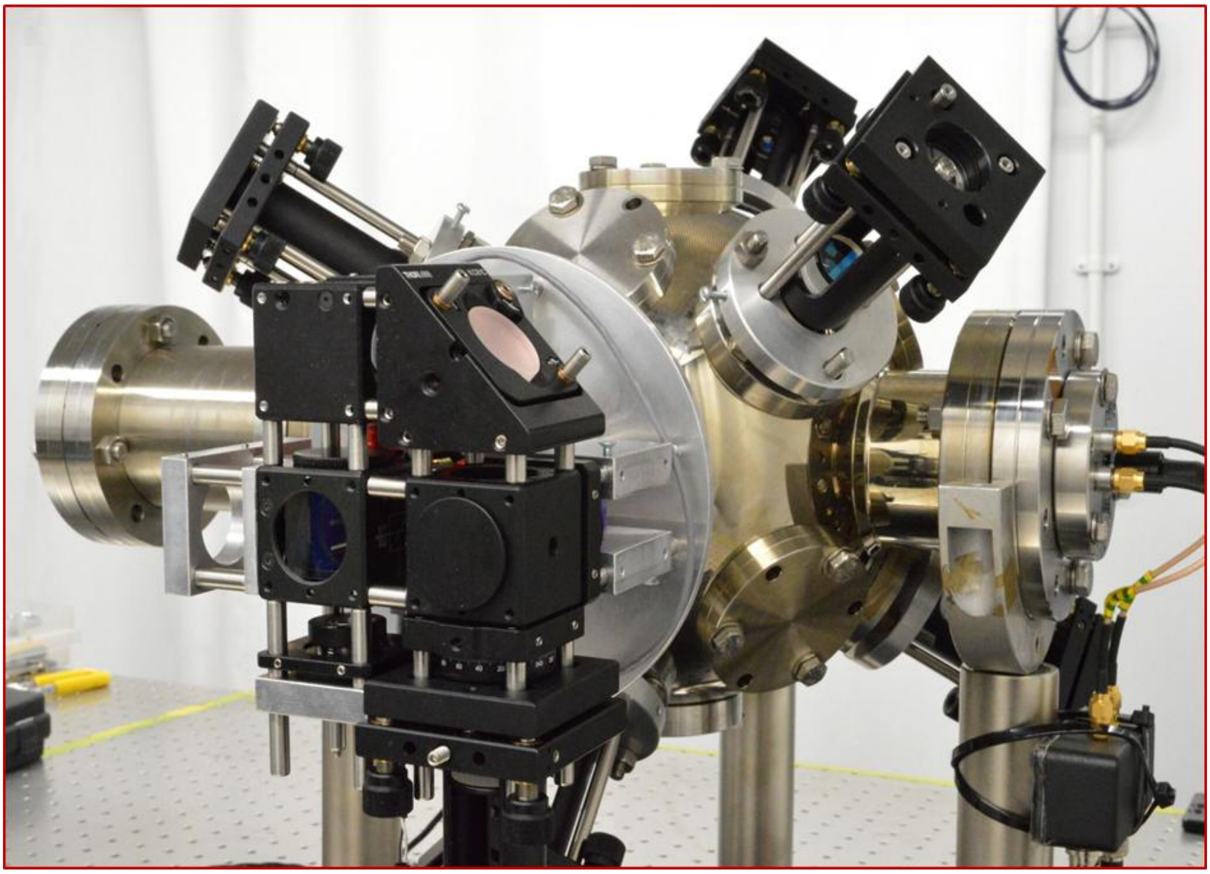

Figure 23 Miniaturised cold atom chamber developed by Professor Hinds and his team for Dstl, a *tour de force* of engineering as well as a world leading example of applied quantum physics *courtesy Professor Hinds Imperial College*

Using these atom chips, light pulse atom interferometers are being developed as atom accelerometers for force sensing and to explore the potential of matter-wave interferometry. Using the same technology, the group is funded by Dstl to build a 3-axis cold atom quantum accelerometer which is expected to be at ~ TRL 4/5 by 2019. (see section 5.2.12.3)

6.2.6 University of Lancaster Quantum Technology Centre (LQTC)

The University has created a world class facility which consists of new class 100 and class 1000 clean rooms, state-of-the-art measurement equipment and dedicated technical support. As such the LQTC represents a significant technology presence in the north west of England.

The LQTC contains state-of-the-art nanofabrication facilities, supported by molecular beam epitaxy[81] reactors for atomic layer-by-layer growth of semiconductor nanostructures and devices. Fabrication techniques available include electron-beam lithography using a dedicated electron-beam writer, plasma processing and thin-film deposition. Electronic structures are measured at temperatures down to 10 mK and below by means of DC, microwave and pulse techniques. Photonic structures are characterized using a variety of specialist (0-17 Tesla) magneto-optics and (4-300 K) spectroscopy techniques, x-ray diffraction, and electron and atomic force microscopy methods.

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[81] Epitaxy is a material deposited in a controlled environment to form a crystalline overlayer from a gaseous or liquid precursor.

A particular focus is the pull-through of science into the market place. Access to the facilities is provided to industry and academic users, enabling the translation of quantum technologies into new products and processes. The LQTC mission statement is to bring economic benefit to the region and accelerate the pull-through of science into the marketplace.

Research focuses on quantum technologies at ultra-low temperatures, including superconducting quantum circuits, semiconductor nanostructures and devices including quantum nanomechanics, low dimensional materials, quantum information theory and modelling.

Lancaster has a worldwide reputation for providing ultra-low temperature environments with accompanying expertise in ultra-sensitive measurement techniques and specialised instrumentation. Record-breaking milli- and micro-kelvin refrigerators[82] are designed and constructed in-house. LQTC's facilities are a key infrastructure and access site for the European Microkelvin Platform consisting of the 13 academic institutions and 7 industrial partners across the EU.

Superconducting quantum circuits are based on Josephson junctions and utilise charge or flux degrees of freedom, or energy level quantisation in a local minimum of the potential profile. Devices are fabricated using electron-beam lithography, dry etching and thin-film deposition techniques. Areas of applications include quantum computing, quantum metrology and quantum sensing. The group collaborates widely with academics in Europe, the far east and the US as well as industrial partners (and NPL) to develop microwave single photon sources and detectors.

The semiconductor nanostructures and quantum devices group studies self-assembled and site-controlled epitaxial growth of new semiconductor nanostructures and their application in quantum devices, using droplet epitaxy of quantum dots[83], nanowires and graphene-like 2D materials. Materials and methods used include mid-infrared LEDs, GaSb and InSb quantum dot lasers for telecommunications and remote gas sensing; interface misfit epitaxy of low noise nBn photodetectors for focal plane arrays and thermal imaging; solar cells and thermo-photovoltaic devices for renewable energy generation. The group also studies fundamental quantum phenomena including spectroscopy of GaSb quantum dots in high magnetic fields, the hydrogenation of semiconductors and materials such as dilute nitrides for single photon sources and materials with atomically abrupt interfaces on GaAs and silicon substrates. Industry collaboration is a strong focus within the group.

The quantum information group focuses on developing solutions to the practical application of quantum information systems, by combining the growth of semiconductor nanostructures with nano-scale device processing, and novel optoelectronic control and measurement schemes. The group is pioneering a solution to the problem of dephasing in quantum information components in scalable technologies such as quantum dots using the GaSb/GaAs material system. This system shows promise for achieving telecoms wavelength compatibility and room temperature operation.

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[82] These are "bulk" cooling engine systems using cryogenic techniques.

[83] Quantum dots, sometimes known as artificial atoms, are tiny, nanoscale particles that have properties intermediate between the bulk semiconductor material in which they are usually embedded and single atoms. As light emitters, they promise higher peak brightness and better colour accuracy (and saturation) for advanced displays. They also have potential for other uses, such as quantum repeaters.

2D materials include graphene and transition metal dichalcogenides (MoS_2, WSe_2, etc.). These allow the creation of the multilayer structures with a huge potential for quantum technology applications and studying new physics. Research is primarily focused on the fabrication and transport properties of encapsulated, ultra-high mobility graphene devices and the graphene superlattices. For example, double-layer graphene structures with unprecedentedly small (~ 1 nm) layer separations allow the electron-electron interaction in strong coupling regimes to be studied. New types of tunnelling field transistors, fabricated by stacking 2D materials, are being developed for fast and low power electronics.

Quantum nanomechanics explores nanoscale mechanical systems such as nano-electromechanical systems (NEMS), carbon nanotube resonators and membranes made of two-dimensional materials such as graphene. With only a few mechanical energy quanta excited, the displacement in NEMS devices are usually much smaller than atomic dimensions. Special optical, superconducting and electronic quantum systems (such as single electron transistors) are needed both to excite and to detect quantum states. The applications are expected to range from ultra-sensitive sensors to memory elements of quantum computers.

The condensed matter theory group uses quantum-mechanical methods (theory and simulation) to identify novel phenomena in low-dimensional systems and devices, and has extensive expertise in determining the characteristics of novel and artificial materials. Complex combinations of components can be modelled to understand phase-coherent transport and dynamics and design devices with specific functionality. The Nanoscale Dynamics group has expertise in the modelling materials and phase-coherent electronic transport, in low-dimensional materials as well as hybrid systems with multiple components. Capabilities in materials modelling include first-principle Monte Carlo methods (beyond Density Functional Theory) and whole-system modelling of molecular electronic devices. Quantum transport in low-dimensional materials and devices, 2D materials including graphene and transition metal dichalcogenides, conventional and topological superconductors, topological insulators (including hybrids that interface with quantum optics) are also studied.

6.2.7 Joint Quantum Centre (JQC), Durham and Newcastle Universities

The JQC is a Joint Research Centre, dedicated to a wide range of topics within quantum science and technology. The Centre was founded in 2012, and comprises members from Durham Physics and Chemistry Departments and Newcastle Applied Mathematics, and Mechanical and Systems Engineering Departments. Currently there are about 90 students, post-doctoral researchers and staff. Experimental work spans the study of Bose-Einstein condensates, ultra-cold molecules, interacting Rydberg atoms, and slow light. Most of this work is supported by closely related theoretical research.

Experimental groups cover:

- Blockaded quantum optics (entanglement of single photons via a dipole blockade using interacting Rydberg atoms);

- Bright soliton[84] dynamics (using interacting ^{85}Rb Bose-Einstein condensates);
- The effect of Rydberg blockade upon the emission of ions and electrons from an ultra cold gas;
- Creation of dense ensembles of trapped ground-state polar molecules at ultra cold temperatures;
- Ultra cold CsYb molecules for the quantum simulation of lattice spin models;
- Magnetic nanowires as sources of magnetic fields to manipulate cold atoms;
- The formation of ultra cold ground state polar molecules of Rb and Cs;
- Interactions between Rydberg atoms formed in dense thermal vapours;
- The properties of slow light propagating through thermal atomic vapours;
- Van der Waals interactions in laser-cooled gases of excited Sr_2 molecules.

Theory work includes:

- Studies of the properties of quantum gases modified by long-range, anisotropic dipolar interactions;
- Stochastic theoretical models of trapped ultra cold gases;
- The interactions of ultra-strong and ultra-short laser pulses with atoms and heavy ions;
- Quantum Chaos exhibited in classically chaotic dynamical systems;
- Matter wave soliton properties, including scattering in BECs, superfluid turbulence in liquid helium, structure and turbulence of RB/Cs BECs and vortex dynamics in BECs.

6.2.8 Quantum Systems Engineering Research Group (QSERG), University of Loughborough

The QSERG brings together a multi-disciplinary group from diverse backgrounds - including quantum technologists, scientists, engineers and end users - in order to develop the methodology that will become Quantum Systems Engineering. Interests span the engineering of quantum-systems and the systems-engineering approach to quantum technologies. The objective is to realise the benefits of quantum technologies in real systems and devices as efficiently as possible. This implies additional considerations of end of life cycle and life cycle costing, support, risk and the impact of requirement changes cost, etc.

QSE is analogous to systems engineering, which projects from a high level understanding of the user's requirements a detailed design of individual components. QSE eventually will comprise a set of tools and techniques to enable the successful design of novel quantum technology products that rely on non-classical phenomena such as non-locality and entanglement. To develop such technologies, considerations of entanglement, decoherence and non-locality will impact significantly on the design process.

In order to ensure proper performance of quantum devices, consideration must be given to appropriate testing at the design stage (Design for Test [DfT], performance requirements and Design

[84] A soliton is a self-reinforcing solitary wave. These can occur in the classical wave on a large scale. The Severn bore is a soliton.

for Reliability [DfR]). Unlike laboratory science which can afford bespoke solutions, products will also need to be designed with the manufacture process in mind (Design for Manufacture [DfM]). Additional considerations of concern to quantum systems engineers include: end of life cycle and life cycle costing, in-service support, risk management, and the impact of requirement changes etc.

The group currently comprises 7 research students, 19 academics drawn from 4 Departments and 6 external consultants.

6.2.9 University of Manchester

The Photon Science Institute is a multidisciplinary organisation with research interests spanning fundamental photon-matter interactions, photonic materials and devices. This includes photovoltaics for solar energy conversion and LEDs for low energy lighting, laser fabrication and patterning, and optical / electron spectroscopy and imaging. The work is strongly applications led across aerospace, healthcare, instrumentation and telecommunications. Recently, new research has begun on ultra-fast processes in materials, laser-mass spectroscopy and optically generated x-ray emission. Of greatest relevance to the UK quantum technology initiative is research into controlling ultrafast laser-material interactions to produce custom micro- and nano-structures on metal, polymer or semiconductor surfaces, or within bulk materials. This permits the development of novel processes to fabricate devices eg. for integrated optical components.

The Quantum Systems group in the Department of Physics and Astronomy studies quantum systems. In the thermodynamic sense these are open systems, meaning that they evolve under the influence of their surroundings rather than in isolation. Research is focussed on understanding the interplay of quantum coherence and noise that exists in such situations. Innovative theoretical methods are being developed to model open quantum systems beyond the usual common approximations, with a particular interest in cases in which system-environment interactions are strong, resulting in the generation of substantial mutual correlations. Starting from the idea of redrawing the boundary between system and environment, methods are being developed to give an efficient framework to study both the equilibrium and non-equilibrium dynamics of many-body open quantum systems which go beyond the perturbative regimes usually studied. Applications in many areas from solid-state quantum information processing to quantum biology are expected.

6.2.10 Manchester Metropolitan University

A small group in the School of Computing, Mathematics and Digital Technology carries out research in quantum algorithms and has recently devised a knowledge transfer partnership (KTP) sponsored project which developed a quantum annealing optimisation algorithm for logistics companies to calculate the most efficient routes and times to send vehicles by road. The University is transferring the technology to a company which specialises in providing (classical) software for logistics firms. The aim is to deliver goods located at a central depot to customers who have placed orders for those products – with the optimiser minimising the total route cost thereby growing sales, reducing operational costs and improving customer service levels.

6.2.11 University of Sheffield

Research groups at the University of Sheffield have substantial activities in the fields of Quantum Science and Technology based primarily around self-assembled quantum dots in III-V semiconductor systems. This work is funded by two EPSRC programme grants (Semiconductor Integrated quantum optical circuits, 2012-2017, £5.1M, and Semiconductor Quantum Photonics, 2016-2021, £5.4M) plus two Innovate-UK grants under the Quantum Technology Programme. A major overall goal of these grants is to realise new quantum-dot-based quantum science, and to translate the findings to a circuit-based scalable quantum technology, for example to form the basis of photon-mediated spin networks or quantum relays for communications.

The goal of scalability is further enhanced by a £2.1M capital grant from the Quantum Technologies programme of EPSRC for a dedicated Molecular Beam Epitaxy (MBE) cluster tool for the growth of very high quality quantum dots with controlled site placement. The cluster tool will be placed in the National Centre for III-V Technologies at Sheffield, providing a strong boost to Sheffield activities but also to national programmes in this field where there are a number of internationally leading academic groups. The new cluster tool will complement the existing three MBE and two MOVPE reactors of the National Centre, much of whose output already impacts strongly on quantum science and technology, for example providing laser sources over wide wavelength ranges, avalanche photodiode detectors and single photon sources to over 20 UK academic and industrial groups.

Altogether in Sheffield there are more than 40 researchers engaged in crystal growth, device fabrication and fundamental or applied physics towards quantum science and technology goals based on semiconductor devices.

6.3 Underpinning and enabling technology

In this section we define *underpinning* technologies as general capabilities and facilities that are required to realise quantum technology, and *enabling* technologies as specifics required to deliver particular systems and applications. These lines of technology will develop alongside the *quantum* components and systems and become new or enhanced business streams in their own right.

There are a large number of underpinning technologies required to realise quantum technology. Different combinations of these are required depending on the mix of physical principles used in each case. Important examples are:

- Specialist materials;
- A wide range of micro- and nano- fabrication facilities;
- The ability to produce specialist semiconductors and heterogeneous microstructures
- Cryogenics;
- Ultra-high vacuum techniques e.g. small, lightweight UHV cells;
- Specialist laser technology, integrated photonics, fine tolerance optical components, possibly including plasmonics and metamaterials;
- Electromagnetic shielding;
- Theoretical analysis, mathematical modelling and computer simulation;
- Inversion algorithms e.g. to enable the operation of sensors correctly within systems;
- High power computing, e.g. the ability to simulate quantum states as dynamic entities;
- Enabling systems and test beds;
- Packaging technology for systems and subsystems.

Many enabling technologies are shared with "underpinning" but are more specialised in nature. Some quantum technologies are themselves building blocks that enable more complex *systems,* and these may even contribute to *systems of systems*. For example, quantum computing will enable advances in quantum technology by emulating quantum systems. Quantum repeaters will enable long range quantum information transmission and quantum networks.

In many areas of science and engineering, advances in materials have enabled technological innovation. The innovations have been of two types: advances in processing known materials (see below) and the development of new materials that may have completely novel properties.

Materials relevant to new quantum technologies are likely to include semiconductors, metals, alloys, dielectrics, polymers, molecules, low dimensional and spin materials (such as graphene), and may incorporate materials with specific mechanical characteristics.

Quantum materials, and new physical insights derived from them, are likely to make a significant contribution to quantum technology. An example is high temperature superconductors. So called "cold atoms," i.e. Bose Einstein condensates,[85] offer the opportunity to explore how electrons display exotic and unusual properties and self-organise, at surfaces of materials and in the bulk. Novel states of "quantum matter" may become possible, leading to properties and applications as yet undiscovered.

Functional materials with carefully designed properties (eg. light-emitting materials, electro- and magneto- optical materials, semiconductors, ferroics, piezo- and pyro-electrics, superconductors, etc.) are also very important to R&D. Devices can also be critical enablers. For example, true photon counters as photon-number resolving detectors based on quantum dot gated field effect transistors, or single photon avalanche detectors, are critical enablers of quantum optical metrology. One of the key blockers for large scale quantum photon technology is the sensitivity (conversion efficiency) of detectors (currently 60-70%) and simple technology to produce photon ensembles with desired properties reliably on demand.

Micro- and nano- fabrication techniques are essential for many instances of quantum technology. For example, single electron transistors, photon emitters and detectors, waveguides, mechanical resonators, quantum dots etc. Some are very sophisticated, e.g. methods of lowering the fundamental quantum "noise floor"[86] locally. Materials with novel properties, and methods of exploiting their characteristics, are reported every week.

The UK has well-funded national facilities that are world class and cover an immense range of technologies suitable for realising quantum technologies. These are probably the most important constituents of infrastructure and include Si, SiO_2, III-V semiconductors and integrated photonics, oxynitride, polymer, glass, lasers, resonators, photon detectors etc.

There are at least 28 UK university clean rooms including (for example):

[85] NB cold atom clouds do not have to form Bose-Einstein condensates to be useful. Bose-Einstein condensation can even be undesirable, e.g. when internal collisions spoil the operation of interferometers.
[86] See http://www.eurekalert.org/pub_releases/2013-08/ciot-ctp080613.php

- James Watt Nanofabrication Centre, University of Glasgow;
- Southampton Nanofabrication Centre and Quantum Technology Centre;[87]
- Lancaster Quantum Technology Centre;
- Scottish Microfabrication Centre University of Edinburgh;;
- Cambridge nanoscience centre, CAPE, physics
- EPSRC National Centre for III-V Technologies (III-V epitaxy) University of Sheffield;
- Nottingham advanced clean room facility (shared with e2v).

In addition, there are 22 UK commercial foundries, including Texas Instruments, Semefab, Plessey, Oclaro, CSTG, Raytheon, NXP, IR, Compound Semiconductor, Seagate, Raytheon and Huawei.

It is important for us to build on our substantial strengths in this area and make sure that there are appropriate facilities to support speculative directions of research. Equally important is the training infrastructure required to remain at the forefront; we estimate this to be 50-100 PhDs in the area.

Ultra-high vacuum techniques have improved and are now miniaturised to the point where "knapsack" sized systems that require small volume evacuated cells with a pressure of less than 10^{-10} Torr are possible. The UK has a leading presence in this area. Small cells for special purposes can even be built using only getters[88] that will function efficiently for a long period of time. The principal problem with this configuration is the gradual penetration of helium atoms through or around the glass envelope or other connectors needed to pass laser beams, however, novel techniques using graphene (which forms a barrier impermeable to helium) are being considered. The move to non-pumped systems will require a reduction in helium diffusion of at least 10^4.

Lasers of specific wavelengths, powers and configurations are required for cooling and trapping particular species of atoms or ions. For simplicity and miniaturisation, specialised gratings need to be fabricated to form lattices (i.e. cages) that can trap ions using a single driving laser. Purpose-designed integrated photonics networks are required to miniaturise the large optical bench configurations used as proof-of-principle, or to construct more sophisticated systems (such as boson[89] (e.g. photon) sampling computers). A number of detailed techniques will be required, such as directional couplers with adjustable coupling strengths. To increase accuracy and sensitivity beyond state of the art, advances in basic component technology will also be required.[90]

By virtue of their inherent sensitivity, many systems are susceptible to stray electromagnetic fields. These need to be eliminated by shielding or compensation applied within the system. For example,

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87 Dr Matt Himsworth is already working on the application of planar fabrication and packaging techniques to the miniaturization and integration of cold-atom devices, supported by a fellowship from the Royal Academy of Engineering, see http://phyweb.phys.soton.ac.uk/atomchips/load.php?page=index.xml

88 Getters are materials that metaphorically act like sponges, mopping up stray atoms in the cell thereby maintaining the vacuum.

89 *A boson is a particle with integer spin, i.e. it maps on to itself after a rotation of n X 360 degrees (2π). A fermion (e.g. electron) wave function needs to rotate 720 degrees before it maps on to itself. This seems counter-intuitive to us as its phase behaves like a Riemann surface in our three-dimensional space.*

90 See for example http://www.sciencedaily.com/releases/2013/07/130721161723.htm

the D-Wave machine[91] is exceptionally sensitive to magnetic fields and requires extensive shielding, together with sophisticated setup procedures that can take weeks. Some systems using species of atoms used for clocks and trapped in optical lattices or magneto-optic traps can benefit from laser light of so called "magic wavelengths" where undesired effects cancel out.[92]

Quantum technologies are defined by quantum mechanics, a deeply mathematical subject that has evolved into a very sophisticated and specialist skill base over the last few decades. Although elegant descriptions of systems comprising ensembles of atoms and their constituents can be written down and manipulated, to obtain quantitative predictions about the behaviour of systems it is usually necessary to resort to computational simulation. Occasionally a change in perspective, such as the use of symmetry to effect transformations of the problem space, can yield significant insights and simplify the calculations needed.

Meanwhile, the theoretical framework necessary to support the development of quantum technology (including practical software development for quantum computers) is a key ingredient of progress, and needs to advance in collaboration with experimental and engineering development. This will be a unique fusion of mathematics, physics and engineering. For this, sufficient computing power (i.e. conventional high performance computer) will need to be available.

Enabling systems and test beds will form essential ingredients of advanced technological development. One example is the proposed UK quantum test bed, which would form a field test for QKD systems. This is potentially a "quick win" for advancing quantum technology if it used existing (dark) fibre infrastructure[93]. It would have the following benefits:

- A test of utility and reliability;
- Resolution of security issues and tests of hacking;
- Development of standards and tests of interoperability;
- Test bed available for developing applications:
- Engagement of system integrators;
- Engagement of higher levels of supply chain;
- Integration of other quantum technologies.

An early version of a quantum computer i.e. an analogue system (possibly realised using cold atoms in an optical lattice) could be used in the form of a service model to support a number of quantum technology developments by emulating transport effects in various geometries. We have described some of the applications in section 4.6.

Packaging forms an important part of the engineering infrastructure required to industrialise quantum technology. Packing components and subsystems, and suitably ruggedising equipment to meet environmental specifications, will be important. That will include thermal management,

91 See section 6.9.4.5 for a description of the D-wave machine.

92 See for example http://www.nist.gov/pml/div684/grp04/finding-magic-wavelengths.cfm

93 Dark fibre is a fibre optic cable that is not “lit”, i.e. not currently carrying data. Such dark fibres are often laid concurrently with those scheduled to carry data as insurance against future increased capacity demands.

control of magnetic fields and electromagnetic interference, shock and vibration management, and resistance to moisture, chemicals etc. There are many considerations in this category such as cost engineering, diagnostics, serviceability, user training and interface specification and standardisation.

6.4 UK commercial capacity enabling emerging quantum technologies

The UK is already in a strong position in emerging quantum technologies, with a number of companies heavily engaged in supplying technology to world leading groups in research and development.

Core technologies where the UK already excels include:

Fibre technology that is integral to transmission of quantum information and is likely to be essential to any choices of implementation. Companies such as Fibercore (based in Southampton) making speciality fibre, used in parametric photon production, for polarization preserving transmission, SPI lasers and Fianium (also Southampton based, producing laser sources), Phoenix Photonics (Birchington, Kent) making fibre based polarisers, Gooch and Housego, etc.

Lasers that are essential for providing coherent light for many quantum technology systems including quantum communication, atomic clocks, quantum navigators, quantum imaging, quantum sensors and photonic based quantum computers. UK companies providing lasers to quantum technology systems include MSquared Lasers, Coherent, Chromacity, Laser Quantum, CSTG, Oclaro and Gooch and Housego.

Nonlinear crystals for generating heralded photon pairs, for up-conversion detection, and comb sources, for example, Covesion Limited (Southampton, Hampshire) produces periodically poled devices supplied to many top labs (eg NIST, Stanford, Harvard, NASA, etc.).

Optical waveguide devices – used for linear optical quantum computing, particularly based on silica-on-silicon platform, companies include Huawei / CIP (Ipswich), Kaiam Corp (Livingston – previously Gemfire / Kymata) and Stratophase (Southampton).

Deposition and etching technology for thin film materials (eg quantum wells, superconducting detector layers, etc.), companies such as STSP (Newport, Gwent), Oxford Instruments Plasma Technology (Yatton, Bristol).

Semiconductor wafers and other materials: devices which are core to many semiconductor laser technologies, key company IQE (Cardiff), Helia Photonics for optical coatings (Livingston) and diamond materials (Element 6, Harwell and Ascot).

Cryogenic technology essential for superconducting detectors, for low temperature operation in cryostats and magnetic field control. A key player is Oxford Instruments (Abingdon).

6.5 Summary of mainstream UK quantum technologies

The main streams of nascent UK quantum technology development broadly follow the configuration of the hubs, plus several significant efforts outside (e.g. Lancaster, materials; and Imperial, atomic sensors). There is also a significant and expanding infrastructure with an increasing emphasis on manufacture (eg. e2v vacuum components and systems engineering, M^2 lasers for specialist lasers and allied technologies). We summarise the principle areas of activity as follows:

- Atomic physics using the wave-like nature of atoms. This is being used to realise inertial and gravitational sensors in several configurations, as well as magnetic sensors. Variations sense acceleration, gravity field gradients and rotation;
- Characteristics of atoms and single ions for ultra-precise clocks, and manipulation of quantum information for computing and possibly for the storage of quantum information;
- Manipulation of single photons ("light particles") for quantum key distribution and several associated communications functions; photons for quantum computing;
- The use of timing and quantum effects to develop new and powerful imaging techniques;
- The manipulation of atoms, ions and their interfaces, together with sophisticated control technology to perform quantum computing;
- Technology at the nanoscale to produce thermoelectrics,[94] thermovoltaics and materials with novel or improved properties.

There are many capabilities emerging to support quantum technologies, and these are becoming industries in their own right. For example:

- Micro- and nano- fabrication facilities to make component parts (such as chips and specialised laser diodes), crystals, resonators etc.;
- Specialised laser systems;
- Vacuum systems and infrastructure (e.g. magnets or electromagnetic shields);
- Specialised electronics, at the chip, FPGA[95] or system level;
- Theory groups and simulation facilities.

6.6 The World stage

6.6.1 Introduction

The extent of investigation into pure quantum physics, its frontiers and cross disciplinary activities, both experimental and theoretical, is immense. A full discourse would be much larger than this document and therefore out of scope. However, we are mainly concerned with the transition of the science toward value adding technologies and such activity is relatively sparse. Emerging technology or its precursors will be our focus.

There are few concerted, relatively mature efforts to develop the new, emerging quantum technologies in the rest of the world. The UK (arguably) displays the greatest "momentum" in this space. Many countries have aspirations to develop such technologies, although most of the existing effort is at TRL 2, 3 and comparatively few at TRL 4 or higher.

6.6.2 China

The People's Republic of China (PRC) is good at making technology plans and following their declared strategy as demonstrated by their historical track record:

- “863 plan” to stimulate technological development to make PRC independent of foreign technology;

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94 Thermoelectrics use heat gradients to generate electrical power; photovoltaics use light to generate electrical power.

95 FPGA = Field Programmable Gate Array

- “211 plan” started in 1996, to raise research standards with a budget of US$2.2Bn in the first 5 years;
- “985 plan” to make Chinese universities best in world (in 3 tiers) in 39 universities.

China is expending an immense effort in quantum S&T. The 15-year plan for the development of science and technology was initiated in 2006. The most recent details are difficult to assess, however, there does seem to be a significant concentration in the areas of quantum communications, quantum optics and quantum computing. The growth of quantum technology R&D in China has been spectacular. Total research has been doubling over periods shorter than 4 years although publication output lags significantly, only doubling every ~8 years. This might possibly be because of immense investment in staff development and ambitious infrastructure projects.

Quantum communications development is well advanced, with an experimental satellite system planned for launch in June 2016. There is a large "push" in the area of quantum computing and 2020 will see a decision point where the effort is evaluated and a decision made on the level of effort to be applied subsequently.

It is not easy to identify all quantum sensor activity in PRC but there is a great deal of ongoing work relating to QIP and quantum communications including development of extremely accurate atomic clocks (expected to be deployed in 2020) for the BeiDou Navigation Satellite System. Related activities include chip scale clocks, frequency combs, atom interferometers and atomic spin gyros. Other activities include:

- Thick film “quantum sensors” being developed for robotics (Dr. Feng Shuang group, Robot Sensor Lab, “Institue of Intelegence Machines” (sic), Chinese Academy of Sciences);
- Coherent ghost imaging (Key Laboratory for Quantum Optics and Centre for Cold Atom Physics of CAS[96], Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences);
- Navigation technologies (Beijing, Harbin and Nanjing Universities and the National University of Defence Technology).

CAS institutions researching quantum sensors include:

- National lab for superconductivity;
- State Key Laboratory of Magnetism;
- Key laboratory of optical physics;
- Nanoscale physics and devices laboratory;
- Solid state quantum information and quantum computation;
- MOE Key Laboratory of Fundamental Physical Quantities Measurement with gravity, clock and cold atom gyroscope projects;
- Laboratory of condensed matter theory and materials computation.

Recently, the information on Chinese progress in the quantum field has become limited.

96 CAS = Chinese Academy of Science

6.6.3 Singapore

The Centre for Quantum Technologies (CQT) comprises quantum physicists and computer scientists who are engaged in fundamental research into the quantum nature of reality and quantum technology development. The CQT was established in 2007, with a budget of Singapore$158 million over 10 years, as Singapore's first Research Centre of Excellence. It now has over 150 scientists and students addressing theory and experiment. CQT stakeholders include Singapore's National Research Foundation and the Ministry of Education and the Centre is hosted by the National University of Singapore, but with significant autonomy in research direction and governance.

CQT conducts interdisciplinary theoretical and experimental research in quantum theory and its application to information technologies with a focus on the technologies for the coherent control of photons and atoms for applications in quantum information.

Enabling technologies (cold atoms and molecules, atom and ion trapping, atom-photon interactions, optics and many body and macroscopic systems) and applications (information theory, cryptography, complexity, randomness and algorithms) are being actively developed.

6.6.4 Japan

Japan has traditionally invested heavily into quantum technologies but mainly in the civil research sector. The Japanese government has invested about £115 million in quantum research projects over a decade with major programmes including the Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST) which addressed quantum computing.

FIRST, administered by the Japanese Cabinet Office, ended in 2014. Topics were chosen by national strategic importance and targeted at the 30 top researchers in Japan. The Ministry of Internal Affairs and Communications (MIC) and its research institute, the National Institute for Information Communication Technology (NICT), continue investing into quantum research, there is an expectation that industry, including NEC, Toshiba and Hitachi, will commercialise the work. NICT is now developing in Tokyo what it plans to be one of the world's most advanced metropolitan secure quantum communications systems in time for the 2020 Olympics. NICT also plans to launch a satellite to experiment on space based quantum communications and quantum key distribution (QKD).

The successor to FIRST is ImPACT (Impulsing Paradigm Change through Disruptive Technologies) which is a high risk, high impact program being delivered through the Council for Science, Technology and Innovation, which is the Japanese government's centre for innovation policy. ImPACT's objective is to encourage high-risk, high-impact R&D, and aim to realize a sustainable and expandable innovation system. ImPACT's themes are to revitalise industry to create economic growth, and to realise an ecologically sound society. This would utilise networked information to link people with society more closely, provide the world's most comfortable living environment (despite a declining birth rate and aging population), and control and minimise damage from hazards and natural disasters. The project duration is 5 years (from 2013) with a ¥55 billion budget ($500 million at April 2016).

ImPACT is an applications pull programme rather than a focused technology push effort and spans multiple disruptive technologies. Quantum technology is included in the "Quantum artificial brain" project which aims to use QKD methods to securely network quantum simulators by optical fibre to solve combinatorial optimisation problems. Cold atoms, superconducting quantum circuits, and semiconductor device based quantum simulators will be developed and down selected.

6.6.5 Korea

The government funded Korean Institute for Advanced Study was founded in 1996 and is located in Seoul. It comprises a small (~10) group of researchers pursuing various aspects of Quantum Information Theory. These are:

- Quantum Algorithms, especially for searching quantum databases, and solving quantum many-body problems;
- Quantum Entanglement, which is being studied to understand the efficiency of quantum algorithms and quantum communication applications via experiments using quantum optics;
- Quantum Computing based on linear and nonlinear quantum optics and atom-molecule experiments;
- Quantum Cryptography;
- Quantum Teleportation;
- Quantum Error Correction, seeking optimal ways to implement error correction for quantum algorithms;
- Quantum Imaging including quantum holography and quantum ellipsometry[97].

6.6.6 The US

The US has a vast research effort in this area with some aspirations to develop quantum technology, particularly at the behest of DARPA, NASA and IARPA.[98] The institutions in the US tend to have a somewhat fragmented approach, although there are many examples of international collaboration.

The Joint Quantum Institute was established with the joint financing by the National Institute of Standards and Technology (NIST) and the University of Maryland (College Park).

DARPA is addressing, for example, the problem of GNSS denial.

These aim to achieve GPS-level timing and positioning performance without GPS by:

- Eliminating GPS as single point of failure;
- Providing redundant capabilities and adaptable architectures;
- Providing optimal PNT solutions based on all available data sources.

In addition, there are aspirations to outperform GPS systems to realise disruptive capabilities in:

- Ultra-stable clocks (short and long term) for electronic warfare, ISR, and communications;
- persistent PNT in environments where GPS was never designed for use: undersea, underground, indoors;

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97 Ellipsometry is an optical technique for investigating the dielectric properties (complex refractive index or dielectric function) of thin films. The technique measures the change of polarization upon reflection or transmission.

98 DARPA = Defence Advanced Projects Agency, NASA = National Aeronautics and Space Administration and IARPA = Intelligence Advanced Projects Agency.

- High precision PNT for cooperative effects (distributed electronic warfare, distributed ISR, autonomous formation flying, time transfer to disadvantaged users).

The DARPA Microsystems Technology Office/PNT is targeting:

- Unaided navigation and timing error of 20 m and 1 µs at 1 hour (= 87.6 km and 4.4 ms at 6 months);
- SWAPC constraints;
- The current demonstrator clock is at TRL4 having cost $1 million, with precursor R&D costs unknown; the project goal is 10 mm^3, 2 g, 1W.

Stanford, Sandia labs and AOSense have significant programmes in cold atom sensors. Sandia and AOSense have technology development work in addition to fundamental science interests.

Sandia has interests in atomic clocks, quantum enabled inertial and magnetic sensing using cold atoms. They are also developing ion traps and entangled atom devices for quantum communications and quantum information processing.

AOSense, a spin-out company from Stanford founded in 2004, is a developer and manufacturer of atom optic devices for the full range of precision navigation devices and systems, gravity measurement, and timekeeping. It carries out inertial sensor development for NSF, NASA, DoE (Lawrence Livermore National Laboratory), DARPA and other parts of the US DoD, DTRA and the intelligence community.

6.6.7 Australia

In 2011, two Australian Centres of Excellence (CoE) in Quantum Science transformation each received AUS$ 24.5 million of funding for 7 years to exploit international effort to develop quantum science into technology. Funding was derived from the Australian Research Council, the Australian Army, the Semiconductor Research Corporation and other sources. The objective was to establish world class technology institutes partnering with similar institutes across the world and the Australian Defence Science and Technology Organisation (DSTO) partnering in niche areas such as sensing.

The CoE for Quantum Computation & Communication Technology (CQC^2T) comprises the University of New South Wales (Sydney and Canberra plus the DSTO Defence Signal Directorate), the Australian National University, University of Melbourne, Griffith University and the University of Queensland. The focus is on systems for computing and communications and components that can be used as quantum sensors.

The CoE for Engineered Quantum Systems (EQuS) comprises the Universities of Queensland, Sydney, Macquarie and Western Australia together with the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The focus is on quantum metrology, sensors, synthetic quantum systems and quantum simulation. Activities include quantum sensing, where they are using the ability to probe or image single electron and nuclear spins, or measure single quanta in mechanical systems. These activities could lead to breakthroughs, including probing of bio and quantum mechanical phenomena in liquids and solids, and the non-invasive imaging of proteins and drugs in-vivo.

In late 2015, the Australian Government announced plans to invest $26 million in the development of quantum computing technology as part of the National Innovation and Science Agenda (NISA) with the objective of creating a modern, dynamic 21st century economy. Quantum computing is expected to produce jobs and economic growth with these quantum technologies playing a significant role in future defence and security (through secure communications, decryption and sensors).

6.6.8 Canada

Following a competitive selection process, in July 2015 the Minister of State (Science and Technology) announced CAN$33.5 million federal investment for the “From Quantum Science to Quantum Technology” project as part of the government’s Canada First Research Excellence Fund, which supports world-leading research at Canada’s universities and colleges. The project draws on the strengths of Canada’s top computer technology and advanced manufacturing research institutions and industry including the Canadian Institute for Advanced Research (CIFAR), IBM, the Microsoft Corporation, the Lockheed Martin Corporation and Google. This investment's objective is to effect lasting and tangible benefits in health, information technology, manufacturing and energy, for instance using quantum materials to develop magnetic resonance scanners the size of a small laptop and ultra-efficient electricity grids.

The Institute for Quantum Computing (IQC) in Waterloo, Canada, was founded in 2002 largely by Mike Lazaridis, creator of the Blackberry (with start-up funding of around CAD$ 300 million). It is currently the largest centre for quantum information worldwide. The IQC seeks to harness quantum mechanics to develop transformational technologies to benefit society and drive economic development by the international development of quantum information science and technology.

Research at IQC focuses on three main applications of quantum information science and technology using the physical sciences, mathematics and engineering from both theoretical and experimental perspectives. The three applications are quantum computing, which encompasses the manipulation and storage of quantum information; quantum communication, which is related to the transmission of quantum information; and quantum sensing, which is used to detect signals or stimuli that are present in the nano-scale world.

Research focuses on

- Quantum information theory;
- Quantum algorithms;
- Quantum complexity;
- Quantum error correction and fault tolerance;
- Optical, nano-electronics and spin-based quantum information processing;
- Quantum cryptography.

The Institute for Quantum Science and Technology (IQST) at the University of Calgary comprises a multidisciplinary group from Computer Science, Mathematics, Chemistry, and Physics. IQST's goals are to conduct leading research in key theoretical and experimental topics of quantum S&T, to provide excellent education and training in quantum S&T, and to create and nurture linkages between the Institute and other quantum science and technology institutes and with industrial partners. Research includes quantum information and computing, quantum optics, nanotechnology and molecular modelling.

The National Research Council is working with clients and government, academic and industrial partners to develop photonics-based, quantum-enhanced cyber security solutions which address increased demands for high-performance security for communications, data storage and data processing. The aim is to position Canada as a global leader in the new field of quantum cyber security.

Canada is also the home of D-Wave, a privately funded initiative to develop a quantum computer. See section 6.5.4.5 for more detail.

6.6.9 France

The Paris Centre for Quantum Computing (PCQC) comprises about 20 computer scientists, theoretical & experimental physicists and mathematicians working in and around Paris. PCQC's goal is to develop novel quantum information and communication technologies. The multi-disciplinary team of researchers is drawn from different organisations including CNRS (National Centre for Scientific Research), the information technology institute Télécom ParisTech, a number of universities (Paris Diderot, Pierre at Marie Curie and Paris Sud), INRIA (the French National Institute for computer science and applied mathematics), the CEA (Commissariat a l'Energie Atomique et Aux Energies Alternatives) and the Institut d'Optique. Principal research areas are:

- Computing: Quantum Algorithms and Complexity, Error Correction and Fault Tolerance, Distributed Quantum Computing and Quantum Metrology and Memories;
- Communications: Quantum Games, Quantum Communication Complexity, Hybrid Quantum Networks and Entangled Photon Sources and Delegation of Computation and Multipartite Resources;
- Security: Theoretical Quantum Cryptography, Device-Independence and Security in Realistic Conditions, Quantum Key Distribution and Cryptography beyond QKD;
- Foundations of Quantum Information: Entanglement Theory and Quantum Correlations, Non-locality, Quantum Axiomatics and Philosophy of Quantum Mechanics.

SYRTE (Sytèmes de Référence Temps Espace) is a division of the Observatoire de Paris and has an extensive research programme including optical frequency metrology, atom interferometry and inertial sensors. Optical frequency metrology includes optical lattice clocks, frequency combs, ultra-stable lasers, coherent optical links, application related clock development, including for space. Atom interferometry research addresses atoms in free fall and atoms trapped in single mode structures with the aim of producing compact interferometers. Expected applications include inertial navigation, geophysics, fundamental tests of relativity in space and gravitational wave detectors.

The science based Laser Physics Laboratory (LPL), part of Paris University, has research on ultra-cold chromium and strontium atoms, Bose-Einstein rubidium condensates, the Fermi sea, dipolar interactions, quantum magnetism and strongly correlated quantum states, confined quantum gases and superfluidity.

MuQuans is a technology spin out company exploiting quantum technology research at the Institut d'Optique and SYRTE/Observatoire de Paris. Muquans is developing a product line of ultra-high performance measurement instruments based on laser cooled, trapped atoms. The aim is for "turn key" instruments requiring little or no maintenance. Currently MuQuans offer an absolute quantum gravimeter and an atomic clock and a range of laser systems and associated electro-optic technologies. The vibration tolerant gravimeter is capable of measuring gravity over long periods with a cycle time of a few Hertz to a relative accuracy of 10^{-9}. The sensor head has a volume of ~ 80 litres, weighs 100 kg and requires a 300 W power source. The instrument is intended for geophysics applications. The atomic clock, which provides a time reference signal with a stability of 2.2 x 10^{-13} after 1 second averaging, has a volume of 25 litres and weighs 75 kg.

6.6.10 Germany

The principal German research institutes for quantum technology are:

- the Munich Quantum Centre and the Institute for Theoretical Physics at Erlangen for quantum optics and quantum information;
- the Centre for Integrated Quantum Science and Technology, IQST at Ulm and Stuttgart (Quantum electrical and optical engineering, Light-matter interfaces, Complex quantum systems, Tailored quantum states of matter and Foundations of quantum science);
- the Dahlem Centre for Complex Quantum Systems in Berlin, the Institute for Experimental Quantum Metrology at Braunschweig, the Centre of Applied Space Technology and Microgravity (covering experimental gravity and quantum optics research) at Bremen, the Centre for Optical Quantum Technologies at Hamburg and the Centre for Quantum Engineering and Space-Time Research at Hanover and Leibniz collectively focus on quantum sensor technology and metrology;
- the Max Planck Institute for Quantum optics in Garching has premier theoretical and experimental groups;
- the Institute for Quantum Information at Aachen and the Institute for Advanced Simulation at Jülich for quantum computing.

6.6.11 The Netherlands

QuTech is a world-class institute building devices for Quantum Computers and Quantum Internet in Delft and comprises parts of the Applied Physics, Electrical Engineering, Mathematics and Computer Sciences Departments within Delft University of Technology (TU Delft) and TNO (an independent, non-governmental organisation situated in The Hague whose role is to develop and apply knowledge widely across high tech industries and the health, energy, infrastructure and defence and security markets).

QuTech's focus is fault-tolerant and topological quantum computing and a quantum internet. In June 2015, the Dutch government, TU Delft, TNO, the Netherlands Organisation for Scientific Research (NWO) and Holland High Tech (TKI HTSM, which coordinates high-tech companies, research institutions and government R&D to commercially nurture and exploit technology development) signed a declaration of intent to financially support the QuTech initiative for a 10-year period with a budget of €135 million.

Roadmaps in the 3 technology areas summarise planned development of:

- quantum computing (using superconducting qubits, electron spin qubits in quantum dots, and spin qubits in diamond) with a current emphasis on achieving double-digit qubit devices and with an ultimate goal to demonstrate and exploit high fidelity qubit architectures compatible with surface-code (topological quantum error correcting code defined on a two-dimensional spin lattice);

- In collaboration with Microsoft topological qubits[99], implemented as pairs of semiconductor nanowires in contact with a superconductor (Majorana fermions), are being developed for naturally fault free quantum computing;
- QuTech's quantum internet will be an optically-connected network of (small) quantum processors with applications in secure communications and networked quantum computing.

6.6.12 Poland

The National Laboratory for Quantum Technologies (NLQT) is a nationwide network of laboratories working in the field of quantum technology funded by the National Centre for Research and Development. NLQT is a Polish national platform for cooperative research in quantum technologies created in 2008. Foci include quantum optics (QO), quantum information processing (QIP), quantum engineering (QE) and quantum networks (QN). The total equipment budget initially was $28 million but investment has been continuously increased. NLQT comprises departments within:

- University of Warsaw - QO, QIP, QE;
- Wroclaw University of Technology - QO, QIP, QE;
- Institute of Physics - QO, QIP, QE;
- Nicolaus Copernicus University in Toruń - QO, QIP, QE;
- Faculty of Physics, Astronomy and Informatics;
- Jagiellonian University - QO, QIP, QE;
- University of Gdańsk - QN;
- University of Łódź - QN;
- Centre for Theoretical Physics of the Polish Academy of Sciences - QN.

6.6.13 European Union (EU)

Since 2000 the European Commission has supported research and innovation in quantum technologies in a number of ways and about €250 million have been invested in projects in the field by Future and Emerging Technologies (FET). The European Union has recently increased R&D investment for Quantum Technologies in the Horizon 2020 Work Programme for 2016-2017, more than doubling the amount available for research on this topic from €10 million to over €20 million.

UK access to EU science funding is now in doubt, at least in the medium and long term, as a result of the UK proposed exit. This makes it imperative to ensure that UK research and technological development remains sufficiently funded, well-structured and well led.

In March 2016 the EU Commissioner for the Digital Economy and Society called for action to ensure that Europe remains a world leader in Quantum Technology. This recognises that competition in the field is becoming more intense globally (e.g. US and Asian competitors are actively investing) and there is an urgent need for investment so that Europe's innovators can successfully translate scientific excellence into marketable applications and thus facilitate global expansion of European industry.

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99 See here for Microsoft's work on quantum computing, including topological qubits.

In April 2016 the European Commission released its "Quantum manifesto[100]" and announced its intention to launch a "flagship-type initiative" in 2018 to stimulate the development of Quantum Technology. This is well behind the UK programme but will be a major initiative within the European H2020 research and innovation framework. It is expected to position Europe at the front of the emerging second quantum revolution, bringing transformative advances to science, industry and society. It will create new opportunities addressing global challenges, provide strategic capabilities for defence and security as well as stimulate as yet unknown future capabilities while creating a knowledge based stimulus to the European economy. It is not yet known how this will sit *vis-a-vis* the UK initiative.

The key goals are:

- Provide impulse to initiate a competitive and world leading European quantum industry;
- Sustain European scientific leadership and excellence in quantum research;
- Make Europe a dynamic and attractive region for innovative business;
- Provide European solutions contributing to grand challenges in fields such as energy, health, and security.

The programme will:

- Support growth in underpinning quantum science;
- Create a favourable ecosystem of innovation and business creation for quantum technologies;
- Facilitate a new level of coordination between academia and industry to facilitate industrialisation of quantum technologies;
- Create a new generation of quantum technology professionals in Europe through multi-disciplinary education;
- Raise public awareness of key ideas and capabilities;
- Coordinate public investments and strategies at European level.

The supporting parties of the Manifesto called for Member States and the European Commission to implement the proposed actions progressively and offer their support to help establish the European Initiative.

100 https://connect.innovateuk.org/c/document_library/get_file?groupId=11487824&folderId=0&title=Quantum Manifesto.pdf

7 Overview of quantum technologies

7.1 Introduction to quantum physics

7.1.1 Background

In this section we will provide an introduction to the science of quantum mechanics, most of which will be suitable for the non-expert.

Quantum physics is often perceived as an extremely difficult and complicated technical subject. Although the mathematics describing some of the phenomena can be sophisticated, the basic concepts are actually quite simple, just alien to our normal way of thinking. They are hard to imagine in terms of our everyday experiences.

Quantum physics may be succinctly described as physics that can't be described by classical laws such as Thermodynamics, Maxwell's equations of electromagnetism and Newton's laws of motion. Most of it derives from the fact that light, matter and energy are quantised, i.e. there is a smallest unit of each, known as a "quantum". For example, the unit (i.e. quantum) of light is a photon, and its energy depends on its wavelength[101]. Objects also exhibit wave-like behaviour, e.g. atoms and molecules can diffract and exhibit interference patterns. We are familiar with the concept of an atom being the smallest unit of everyday matter, however, both atoms and ensembles of atoms can exist as a continuous "matter wave" at ultra-low temperatures (less than one thousandth of a Kelvin). Often, these phenomena are referred to as "wave-particle duality".

The fundamentals of quantum mechanics, i.e. wave (or, equivalently, matrix) mechanics, were developed during the 1920s and led to a deep understanding of such areas as nuclear physics, atomic, molecular and solid state physics, and the detailed interactions between light and matter. The central 60 years or so of the 20th century gave rise to the area of quantum science that resulted in many of the advances that became familiar to us and which we now take for granted. Just as classical physics underpinned the industrial revolution, so quantum physics was harnessed to achieve many of the advances in the 20th century. It made possible the "information age" that began in the 1990s. The insights gained have resulted in many of the technologies that are familiar to us today. Some of these are:

- Nuclear energy;
- Solid state electronics (and hence integrated circuits, computers, telecoms etc.);
- Lasers;
- Digital cameras and other imaging devices such as thermal imagers.

It has gradually become apparent over the last 20 years or so that much of classical physics is an emergent property of quantum physics[102] and that the notion of information may be somewhat more sophisticated and its role more extensive than generally appreciated[103]. For a long time it had

[101] The shorter the wavelength, the higher the frequency and the more energy per particle (and vice versa).
[102] Sophisticated experiments are beginning to probe the "emergence" of classical physics from quantum
[103] See for example an information powered refrigerator arXiv version

been assumed that there was some kind of "boundary" between the classical (everyday) worlds and quantum, often attributed to scale. However, the extents of quantum phenomena are continuously being tested and experiments have recently been done to control the emergence of classical behaviour from quantum systems[104]. It has been said that the scale at which quantum effects can be observed depends on one's budget[105]. Certainly, we expect to see quantum effects exhibited by "large" objects such as bacteria soon.

The emerging field of quantum machines and quantum engines[106] is usually portrayed as an extension of classical thermodynamics. This area is likely to provide more insight into the fundamentals over the next few years, although we are still heavily attached to the classical paradigms that have pervaded our early education and upbringing. Perhaps new generations of physicists will find it easier to understand and think about quantum in its own terms.

From the outset it was apparent that there were paradoxes and counter-intuitive effects arising from quantum physics and over the last few decades in particular the list has been growing. Initially, such counter-intuitive and paradoxical behaviour caused immense consternation, but as our understanding has increased we are beginning to realise how such phenomena might be harnessed for our benefit.

7.1.2 Counter intuitive phenomena

As previously stated, the classical world which we see, hear and feel around us is an emergent property of quantum mechanics. Just how is not yet fully understood. The "quantum world" is mostly observed at the smallest scales and the "classical world" that we observe takes place at length scales (sizes) with which we are more familiar. Precisely how the transition between the two takes place has been a subject for debate for many years. There may not be any such "boundary", and it may simply represent a lacuna in our understanding, i.e. structure of our paradigms. Somehow the classical world is "cooked up" by interference patterns between quantum mechanical waves and their embedded symmetries[107]. Our natural starting point is to attempt to describe quantum phenomena in terms of our everyday, classical world[108]. When we do that, what we think of as common sense or inviolable logic often appears to break down and is supplanted by counter intuitive phenomena - described accurately by quantum mechanical theory. Such phenomena often offer fruitful sources of new technologies, sometimes decades after their discovery. Examples of such phenomena are:

- **Probability waves**: It is well known that classical waves e.g. waves in the sea can be a range of heights. The height is known as the *amplitude* and the square of the height represents the *energy* possessed by the wave. So a 2 metre high wave will carry four times the energy of a 1

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104 This technical paper explains how the emergence of quantum behaviour in ultra-cold gases may be controlled by a laser field

105 A quote from Sir Peter Knight, 2013

106 IOP article Quantum machines

107 It can be shown mathematically that conservation laws (i.e. "cosmic book keeping") can be derived from symmetries, for example the conservation of momentum is equivalent to the translational symmetry of "empty" space. A technical description of this extremely important result may be found here.

108 We tend to see most physical phenomena as existing against a "canvas", i.e. background, of space and time. Einstein showed that both interact, yet we don't understand the full implications, especially in the context of extremes such as black holes or the so called Big Bang.

metre high wave. However, the square of a *quantum* wave (function) represents the *probability* of finding the quantum in a given location, state etc.. This is a fundamental difference that has wide ranging consequences

- **Superfluidity and superconductivity:** These are essentially quantum phenomena that can occur on a large scale. We are used to friction and other dissipated processes, so when they become absent it seems very surprising to us. If liquid helium is cooled below about 2.1 K it begins to flow without friction[109] and quantised vortices (rotons) can be produced in the liquid rather like smoke rings. Only a fraction of the liquid is superfluid at this temperature, although the fraction increases as the temperature is further reduced. Liquid helium 3 will become a superfluid (A or B phases) due to complicated internal interactions, but this will only happen at temperatures below 0.0025 K.

  Superconductivity[110] is where electrons (usually) in a solid can pair up to become quasi particles[111] know as Cooper pairs. The electrical resistance drops to zero below a certain critical temperature. Superconductivity at room temperature has long been a "holy grail" of solid state physics but not yet been achieved.

  It is postulated that stars contain some extremely exotic states of matter. For example, neutron stars[112] are thought to be extreme objects that can be simultaneously superfluid and superconducting.

- **Bose-Einstein condensates (BEC[113]s):** This is a state of matter where atoms are moving so slowly that their wave-like behaviour extends past the point where it overlaps with nearby atoms. The whole ensemble of atoms then behaves like a single entity where they all exist in the same state. It is interesting to note that quasiparticles (see below) can form a condensate in the same manner. Only "particles" that possess integer values of (quantised) spin can form BECs. Particles that do not (i.e. have n-½ spin values) cannot coexist in the same state and so can't form BECs - except in circumstances where they form bound pairs which then have a total spin of an integer quantum value.

- **Quantum superposition.** In general, in the quantum regime, an object can appear to take on two related characteristics at once. For example, a particle can be spinning in one direction or another simultaneously. It may be travelling on two or more paths simultaneously.[114] Or, it can be in an excited state[115] or not simultaneously. The key point is that at the instant a

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109 See https://en.wikipedia.org/wiki/Superfluidity

110 See https://en.wikipedia.org/wiki/Superconductivity for a good introduction. Simple superconductors can be categorised into type 1 and type 2, which broadly governs their ability to remain superconducting in a given magnetic field. The critical field B_c at which the properties break down implies a current density limit beyond which the material loses its superconducting properties. A deeper discussion is beyond the scope of this report.

111 See section on quasiparticles, below

112 For a good introduction see https://en.wikipedia.org/wiki/Neutron_star

113 A Popular story of the Nobel prize winning work: Bose-Einstein Condensate also see A more technical story.

114 Ultimately, a trajectory may be calculated by a "sum of histories" (popular) i.e. "path integral" (technical) (Feynman)

115 An example is an atom which may or may not have absorbed a photon, which would boost one of its electrons into a higher orbit. The higher orbit represents an excited state of the atom.

test is made to determine which state it is in, it appears to "choose" one or another with a certain probability. This test is generically called a "measurement" even if performed by the general environment and the outcome depends on the object's wave function. A typical application is an atomic interferometer for measuring acceleration or rotation, where the wave like behaviour of atoms form interference patterns with themselves (almost as if they have an "alter ego") Matter wave interferometry relies on superposition.

- **Matter wave interferometry**: When atomic gases[116] are cooled to below a few tens of micro kelvin (typically < 20 µK) they may be split between two configuration or energy states with a certain probability (most often 50%). Their subsequent trajectories can then become ambiguous, i.e. they can take two paths at once; they are in a "superposition of states". If those paths are then brought together, the wave functions can interfere with *themselves*. if the relative path lengths between the two possibilities change, it will result in "fringes" in the distribution of the atoms after the waves are recombined. The atoms are said to be "split". This will only work if a "which path" measurement is *not* made during their time of flight. The behaviour is similar to an interferometer using light, or photons.

  It is much more difficult to use atoms. However, the interferometers can be used to make exquisitely fine measurement of gravity or inertial forces. The phenomena are being harnessed in the latest gravity gradiometers, gyros etc. to make instruments that are orders of magnitude more sensitive than the optical, or MEMS, counterparts.

- **Quantum tunnelling[117].** In our everyday lives, it makes sense that an object cannot pass through another. An analogy is that a tennis ball bouncing around a room cannot suddenly pass through a wall. However, at very tiny scales, this becomes possible due to the phenomenon of quantum tunnelling. Using our tennis ball analogy, the "tennis ball" *does* have a finite chance of passing through a "wall". The probability of tunnelling increases when the "wall" is thinner, or when it is less dense (e.g. plasterboard rather than brick). In the smallest examples of micro-electronics tunnelling can be a nuisance, leading to leakage of electric currents. The designers need to adapt accordingly where possible. The effect may also be harnessed e.g. in tunnel diodes, which are components with interesting and useful electrical characteristics.

- **Quantum information.** Classical information (usually[118]) consists of bits, each one being a 1 or a zero and containing a maximum of 1 bit of information. See section 4.6 on quantum computing for an explanation of quantum information which, effectively, has a *probability* of being either a "1" or a "0" when measured. That probability is represented by a qubit and can be carried through calculations and interact with others.

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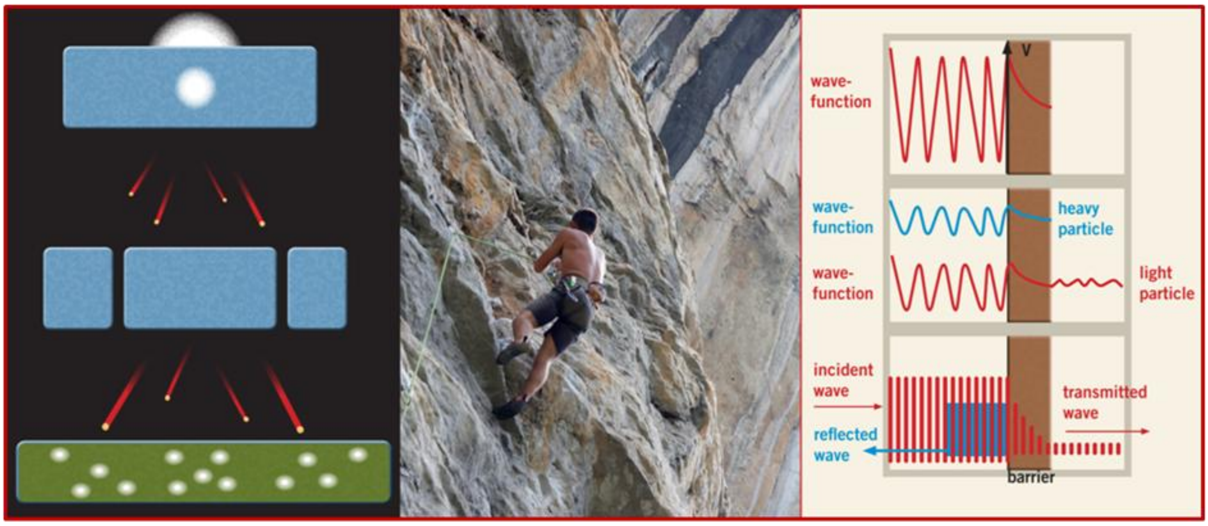
116 The range of materials that have been cooled and encouraged to display quantum properties has recently been expanding rapidly.

117 For a good basic level of understanding see https://en.wikipedia.org/wiki/Quantum_tunnelling

118 Classical information can be expressed as a probability, e.g. a fraction of a bit.



Wave like behaviour implies that particles are "fuzzed out"

Normally, one needs enough energy to climb a barrier to reach the other side

Not so our fuzzed out waves: they can "tunnel" through barriers

Figure 24: Quantum tunnelling

- **Quantum entanglement.** Objects and systems can be entangled in the sense that the information that they jointly hold exceeds the sum of that which they hold individually. This is unlike the classical notion of mutual information where two objects share information that the other has. In that case the total information is less than, or at most the same, as the sum of the information that each holds. So, entanglement might be considered as negative mutual information.

  For example, two different published dictionaries will usually have a lot of information in common - so by having both you won't possess as much information than their sum might suggest. However, two particles that are entangled in the parameter of spin (for example) will have opposite spins but it can be proved experimentally that they do not possess labels[119] that encode which is which. A measurement made on one will have a random outcome but will always be the opposite of a measurement made on the other, at any time.

  Therefore, both particles together hold *more* information than their sum. The total (e.g. spin") is conserved, the additional information is a *symmetry* i.e. a conserved quantity (angular momentum in this case). Despite the vagaries of quantum mechanics, the universe "keeps the books straight" in terms of conserved quantities, irrespective of time or spatial difference.

  When a measurement is made on either, the entanglement "disappears"[120]. Theoretically, there is no limit to their separation[121] while maintaining entanglement and, curiously, one particle can be entangled with another that has ceased to exist[122]. Even more curiously,

119 Known as "hidden variables"
120 In fact, it gets diluted into the environment and it is not feasible to recover it subsequently.
121 Thus entanglement is known as a "non local" phenomenon.
122 A flavour may be obtained from this popular article.

entanglement can be viewed as a resource that may be "distilled", and to a limited extent[123] can exist as a probabilistic network between an ensemble of particles or other entities. Examples of uses for entanglement include quantum computing and secure communications.

Entanglement usually concerns one parameter, such as spin. If two parameters are involved (e.g. spin and orbital angular momentum (see later)), this is known as "hyper entanglement"

- **The quantum Zeno effect**. This is, in effect, a real life version of "a watched pot never boils". If an evolving quantum state (see figure 25) is measured frequently, it will be repeatedly projected or "reset" into its initial state with high probability each time a measurement is made rather than making a transition. The more frequently it is measured, the more likely it is to remain in its original state. Examples of practical use are in certain types of quantum repeater or in a quantum analogy of a dynamic random access memory[124]. In some circumstances the probability of transition may be enhanced; this is known as the "quantum anti-Zeno effect". These are consequences of the *probability* of a measurement outcome being the *square of the amplitude* of a quantum mechanical wave[125]. An example is shown in Appendix 8.8.

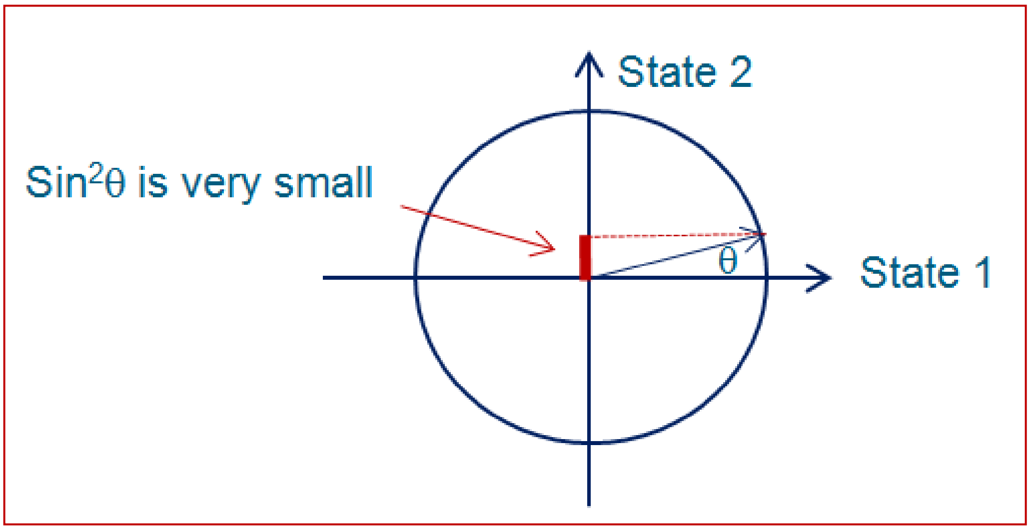


Figure 25: An evolving quantum state may be represented by a vector of radius 1 rotating from state 1 to state 2 at a rate governed by its half-life. Since the probability of finding the system in state 2 is $\sin^2\theta$, (the square of the angle) it will be very highly likely to remain in the same state if θ is very small.

123 Quantum monogamy dictates that no more than two particles may be fully jointly entangled in a single parameter. Partial entanglement may be viewed as a *probability* of being fully entangled. (conversation with Dr. Jacob Dunningham Sussex) thus complicated networks can be defined by a density matrix.

124 Fast computer memory is most likely to be a dynamic RAM. For the sake of capacity, size and speed the 0s and 1s are held on tiny capacitors (charge storage elements) which leak. That means they need refreshing regularly, row by row, by the chip. A quantum memory can put off decoherence, or "leakage" of quantum information, by swapping the qubit (quantum bit) from one state to another. Improvements of two orders of magnitude or more in decoherence time can be achieved.

125 Recap: in classical waves, e.g. those found on the surface of a pond, the square of the amplitude (height) is proportional to the *power* that can be delivered by the wave. That is what we are used to in everyday life.

- The vacuum, at extremely small scales, is not empty. Quantum theory portrays it as a roiling sea of activity, consisting of all possible fields and their associated particles. These "exist" below the fundamental uncertainty limit (or "blurriness") of the universe at its smallest scales. Although the (so called zero point) *energy* content of the vacuum appears to be immense it cannot be extracted in any meaningful amount at no cost; a classical analogy being the impossibility of a perpetual motion machine. Classical manifestations include the Casimir effect[126], where parallel plates experience an attractive force. This becomes significant for micro- and nano- engineering on a sub-micrometre scale. The exact nature and properties of the vacuum remain enigmatic, for example the phase of a photon given off during "spontaneous emission" is (arguably) an imprint of the vacuum zero point fields. This may give rise to the notion of "uncomputable" as opposed to randomness. It is a philosophical point.

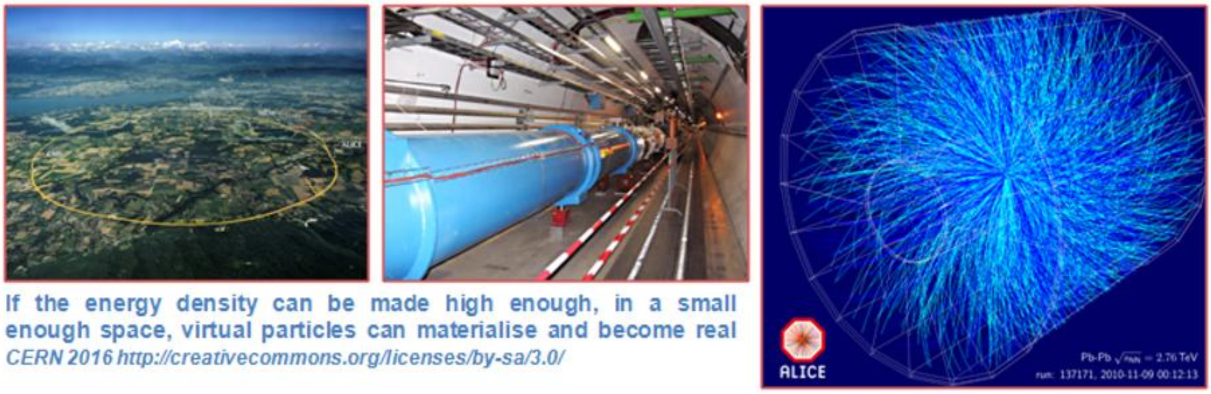


Figure 26: Using a big machine to conjure particles out of the vacuum

The residual "noise" in the quantum vacuum is strongly related to the uncertainty principle and it can be shown that a violation of the uncertainty principle (calibrated by Planck's constant[127]) would permit a violation of the second law of thermodynamics, i.e. unfettered extraction of energy from the vacuum. Quantum vacuum effects can become very significant for nanotechnology.

Recently, experiments have been done to shape the quantum vacuum by manipulating the zero point fields. Squeezing is a technique often used to improve the signal to noise ratio beyond the quantum limit at the expense of letting it increase in another dimension. Atomic lifetimes may be extended by engineering the vacuum near a "mirror" to generate a null in part of the spectrum at the point where an atom may be placed[128] and a wavelength that would cause it to decay. Eventually, such techniques might be used to extend or manipulate the half-life of certain unstable atomic species.

- **Quantum teleportation:** this is an unfortunate term which gives rise to the misconception that objects may be instantly teleported from one place to another. That is completely

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126 See Wikipedia entry

127 Planck's constant is a very small number, 6.62607004 × 10^{-34} m^2 kg s^{-1}. If it were zero, our universe would be completely classical, i.e. not quantised. That would introduce infinities leading to a number of mathematical and logical paradoxes.

128 An interesting article is http://arxiv.org/pdf/1410.8840v1.pdf with a popular description HERE.

incorrect and the limit of the speed of light still applies. It is the transmission of a *quantum state* from one place to another. Although no classical information (or matter, or energy) is transported during "teleportation", a message via a classical channel is required first. This will instruct the receiver in which measurement needs to be made to an object at the receiver, which has to be already entangled with the transmitter. See section 6.3.6 for further discussion.

7.1.3 Frontiers of quantum physics

The underlying mechanism of quantum mechanics gives rise to many rich, expanding avenues of research. Some of these topics are relatively new[129], some are old yet deserving of further investigation and interpretation, and some are interesting analogies of classical ideas. It is a fertile area for creative innovation with the potential to create entirely new technologies. It is far from being fully explored. As implied earlier, human intuition finds it difficult to keep up, and a (classical!) computer program has even been developed to design novel quantum experiments[130]. Here, we briefly summarise just a few of the more interesting and possibly significant concepts.

- **Quantum ground state:** A system cannot lose all of its mechanical energy. The coldest state of an object still retains some fundamental fluctuations, or vibrations; these represent a fundamental uncertainty and the state is known as the "quantum ground state" or zero-point energy of the system. Recently, nano- and micro- mechanical oscillators have been cooled by laser using an optomechanical system, where the oscillator (or resonator) is coupled into the laser beam via a cavity. It is a "requirement" that the overall disorder (entropy) of the system increases; as with laser cooling of free atoms the added disorder is carried away by the scattered light.

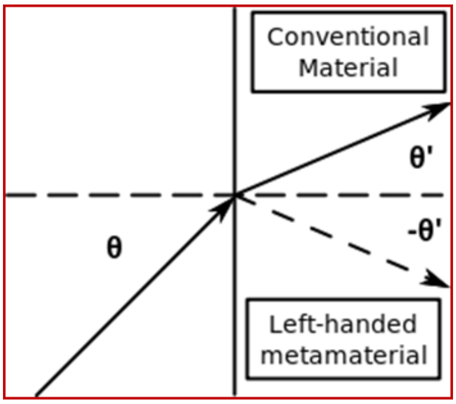

Figure 27: Illustrating the difference between normal refraction (conventional material) and negative refraction

Practical uses for a mechanical quantum ground state still need to be explored, but are most likely to find uses in the field of nanotechnology. Molecular laser cooling[131] is a developing subject that offers a wide variety of opportunities to explore novel physics. The field overlaps with many disciplines, including particle physics, quantum chemistry, quantum information etc.;

- **Negative refractive index for matter waves:** An analogy to a negative refractive index medium has been experimentally demonstrated for matter waves[132]. This may eventually find application for super-resolution in metrology, or a probe of many-body effects in optical lattices. However, manipulation of the analogue of refractive index is a very young field of research[133], while investigation of photonic negative refractive index effects are also at a relatively early stage. An explanation of this phenomenon known as "Versagio lensing" is here[134]. Even more curious is a

129 A good source of interesting up-to-date articles on this subject may be found at: http://phys.org/tags/quantum+correlations/

130 See this article for a popular description; the detail appears in http://arxiv.org/pdf/1509.02749v2.pdf

131 See for a technical example Valentina Zhelyazkova's thesis (working with Professor Ed Hinds at Imperial College)

132 NB this does not imply that matter (or information) can travel faster than the speed of light. See http://arxiv.org/ftp/arxiv/papers/1402/1402.3132.pdf for a technical article on the subject

133 See http://arxiv.org/ftp/arxiv/papers/1402/1402.3132.pdf for a technical article on the subject

134 See for example http://arxiv.org/pdf/1411.3594v8.pdf

viewpoint that describes gravitational fields in terms of refractive indices[135]. This is more mathematically challenging than surprising (we've all heard of "gravitational lensing" although the nature and density function of the "lens" is different);

- **Characterising the quantum vacuum:** We suggested (above) that the exact nature of the quantum vacuum is enigmatic. New research could eventually lead to new insights in physics as well as novel technological applications. A complete exposition is beyond the scope of this report;

- **The Vector Potential** The vector potential (or "magnetic vector potential", usually designated as A) is an aspect of the electromagnetic field that is parallel to the direction of electric currents such that its "curl" (a mathematical measure of inside curvature) is associated with a magnetic field. For example, in a solenoid, the magnetic field is essentially contained within the coil but the vector potential exists outside parallel to the windings. It is real, and the effect can be measured by its effects on electron wave functions outside (e.g. in the Aharonov-Bohm effect[136]). Technically, it is intriguing as A often extends outside our normal conception of the system envelope, i.e. beyond containers and barriers etc. It might offer the possibility of a new mode of detection. However, it is very difficult to visualise a physical configuration that would work since the absolute value of the phase of the electron wave function cannot be defined at any particular point.

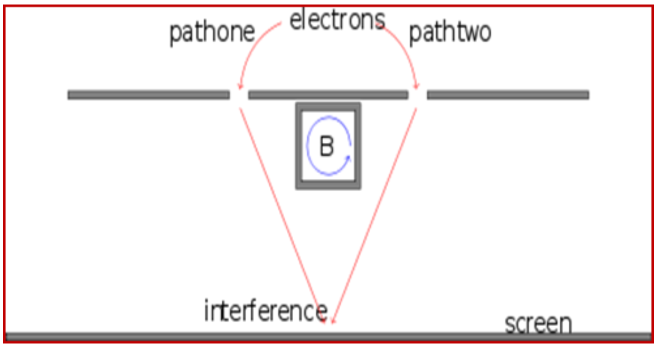

Figure 28: The Aharonov Bohm effect. The electrons' interference pattern is shifted due to a magnetic field inside the solenoid despite negligible interaction between the two. The vector potential circulates outside the solenoid, creating opposite phase shifts of the electron wave function on each side.
Credit Sebastian Schmittner
http://creativecommons.org/licenses/by-sa/3.0/

The magnetic vector potential also has a deeper meaning[137], and a deeper mathematical understanding of quantum mechanics, electrodynamics and the Standard Model[138] is required to appreciate it properly. It is the change in phase per unit charge by a charged particle as it moves along the "lines" of A. So, as it moves along in space, the vector potential causes the phase of its quantum-mechanical wave function to change by

$$\Delta\varphi = q\hbar\int A\cdot dx.$$

This can be directly observed in the Aharonov--Bohm experiment, figure 28. A magnetic monopole implies a mathematical singularity ("source or sink") in the vector potential; monopoles have never been observed in practice although pairs are "allowed" and have been observed in certain crystals[139].

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135 See http://www2.ups.edu/faculty/jcevans/Matter%20waves%20gravity.pdf

136 See https://en.wikipedia.org/wiki/Aharonov%E2%80%93Bohm_effect for a reasonably simple explanation.

137 *From the standard model, a photon is represented by a four-component vector potential Aµ (x) with a Lorentz index µ = 0, 1, 2, 3. In a certain sense A can be considered to be the "stuff" from which photons are made.*

138 The standard model is our best unified theory of how the universe "works", although it doesn't include gravity.

139 See https://www.sciencedaily.com/releases/2015/11/151112055717.htm and https://www.sciencedaily.com/releases/2015/11/151112055717.htm, or for those interested in the history and theory see https://en.wikipedia.org/wiki/Magnetic_monopole

Note that the electric scalar potential is the change in phase per unit charge that a charged particle picks up as it moves through time. The electric scalar potential times charge is potential energy, and the Schrödinger equation tells us that energy of the particle is the rate at which its phase evolves with time, times a factor of ħ.[140] *So the magnetic vector potential bears the same relationship to space as the electric scalar potential bears to time;*

- **Extension of laser cooling:** Currently, laser cooling to near zero degrees is limited to a few atomic species with a favourable atomic (excitation) structure[141]. Experiments at Southampton University (Himsworth, Freegarde *et. al.*) have demonstrated species independent cooling using matter wave interferometry.[142] This is likely to generate a rich field of exploration and possibly new physics. Also see "quantum ground state" (above);

- **Quantum discord[143]:** This is the set of non-classical correlations that are present in quantum systems. Quantum entanglement is a *subset* of these. The concept is very subtle, but discord without entanglement has been shown to have applications (albeit esoteric), most likely in quantum information processing;

- **Quantum information engines** Quantum information engines (as a variety of "Maxwell's demon" (figure 29) is an entity that can separate high and low speed molecules in a gas. Supposedly, it achieves this by opening a trap door in a membrane to let approaching

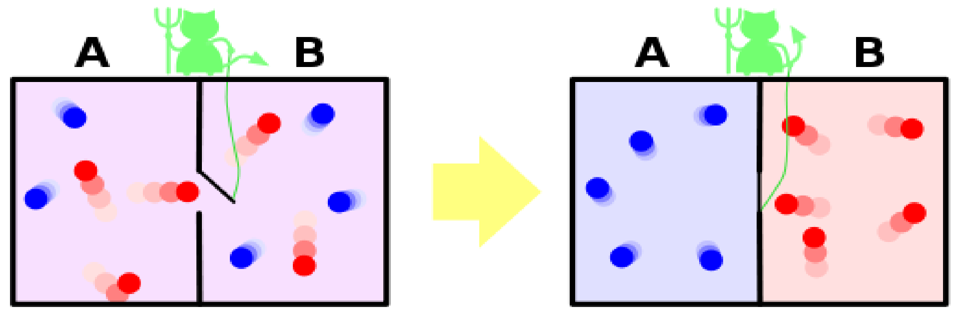

Figure 29: Maxwell's thought experiment envisaged using a trap door to sort fast and slow particles. It eventually emerged that the demon's lack of information concerning the approaching particles prevented the scheme from working, as there was a "cost" involved.

molecules pass or bounce depending on their speed. This separation would lead to the possibility of virtually limitless free energy, i.e. the process would break the second law of thermodynamics which is generally considered to be impossible. The resolution of this paradox is that information is gained during this process and information processing has a thermodynamic energy cost equivalent to that gained by the separation. The (entropic) penalty paid to erase the information destroys any overall gain in free energy that the demon made. Experiments have shown that the demon can be realised classically[144] and

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140 ħ is the symbol for Planck's constant which represents, approximately the noise floor of the universe. It is a very small number: i.e. $6.62607004 \times 10^{-34}$ m^2 kg s^{-1} (the 10^{-34} means 34 zeros to the right of the decimal point before the first 6)

141 "Conventional" experiments to achieve molecular cooling are being carried out e.g. by Prof. Ed Hinds at Imperial College

142 See for example Science Daily article or for a technical description http://arxiv.org/pdf/1408.6877v2.pdf

143 See https://en.wikipedia.org/wiki/Quantum_discord for a technical article on the subject

144 See Nature paper or Physorg popular version.

more recently it has been found that quantum mechanical information can also be used to generate work (i.e. useful "free" energy)[145] in this manner.

- **Bell's inequality and Leggett-Garg (L-G) inequalities:** These lead to the notion of non-locality in quantum mechanics; Bell's in space and L-G in time (assuming a non-relativistic scenario, which would complicate the context). A very loose analogy quoted from Einstein: " is the moon not there when I am not looking at it?" The violation of Bell's inequality is used as a test in the engineering of quantum systems. It is classically counter-intuitive and proves that entangled particles do not possess labels[146] encoding their states. A violation of Leggett-Garg inequalities implies either the impossibility of measuring a system without disturbing it or the absence of a "realistic" description of it *between events*. Both apply in quantum mechanics. The applications to quantum technology appear at a deep level; full implications remain to be understood in the context of our classical world - if that is possible. Bell's inequality finds use in quantum sensors, communications and computing, while L-G may eventually find uses in quantum biology, quantum transport and nanosystems[147]

- **Quasiparticles** These are entities that exist, usually but not uniquely, in solids, see figure 30. They can be seen as an interesting generalisation of the principles of quantum mechanics. A simpler and more commonly known example is an exciton. This is a bound state of an electron and an electron hole (i.e. an absence of an electron) which are attracted to each other by the electrostatic Coulomb force in a semiconductor. It is an electrically neutral quasiparticle that exists in insulators, semiconductors and in some liquids. Another example is that sound waves in solids are quantised, where the quanta are referred to as phonons.

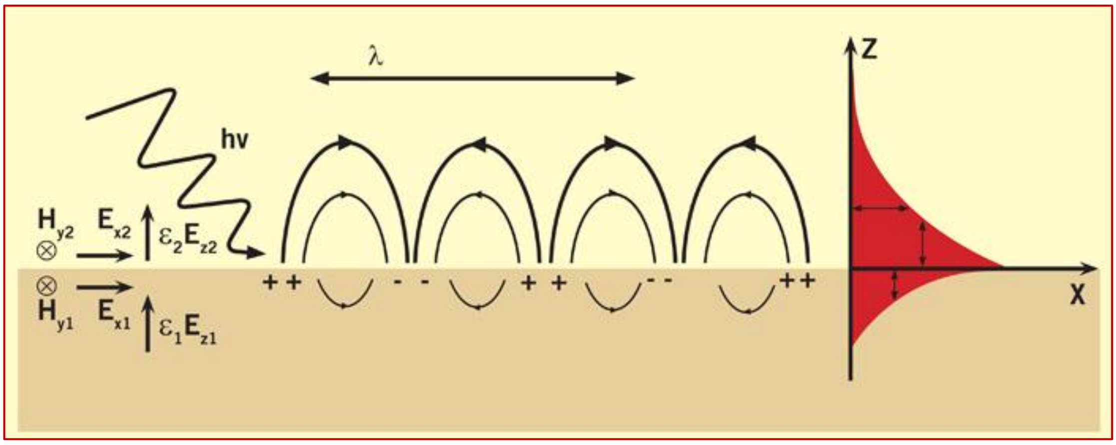

Figure 30: Surface plasmon polaritons are hybridised oscillations (like coupled pendula) that are mixtures of electromagnetic waves and surface electron plasma oscillations. These are quantised and behave as particles as entities in their own right.

There are also exotic manifestations that might find applications in future technologies, such as Weyl fermions and Dirac hoses.[148] Particles can be considered as a "bundle" of bound parameters (effectively conserved quantities, i.e. symmetries) that are "comfortable" as a

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145 See http://phys.org/news/2013-12-maxwell-demon-quantum.html for a "popular" account or http://arxiv.org/pdf/1302.3011v2.pdf for a more technical description. The technique is a practical application of quantum discord (see above).

146 i.e. hidden variables)

147 For the preprint article (technical) please see here

148 Dirac hoses are long tubes containing magnetic fields. The distance between poles makes each act as if it were a monopole. Similar effects can arise in crystals, where the apparent existence of a magnetic monopole must be balanced by the appearance of an opposite pole elsewhere.

single entity, e.g. electrons in some materials can split into its three key parameters e.g. its spin, its orbit and its charge. Even more interesting, the parameters (such as charge) may exist in fractional form compared to the quantisation found in free particles. Examples of that phenomenon include the fractional quantum Hall effect[149] (implying quasiparticles with fractional elementary charge) and, arguably, quarks, which cannot be isolated and which carry a charge of + 2/3 or -1/3 depending on the species. A full exposition would be very technical and beyond the scope of this report, however, there are many technology applications for quasiparticles known and most likely many unknown. Potential applications include topological quantum computers, Weyl fermions (for fast electronics) and spin waves (magnons) leading to "magnonics[150]", for novel forms of electronic devices. The field of quasiparticles represent a vast subject area where generalised "quantum thinking" can be applied to many parameters in many situations to uncover new and interesting facets of physics.

There are many more avenues of exploration that will yield important results in the future, most likely together with the opportunity to create more novel quantum technologies.

7.1.4 Black swans

"Black swans" are unexpected technologies with significant applications or implications that may come into play rapidly, as defined in the Blackett report[151].

Figure 31: unexpected black swans *https://creativecommons.org/licenses/by-sa/3.0/deed.en no author*

It is quite possible that novel quantum technologies that are not contained within our headings can emerge with potential for disruptive effects, possibly in most or all parts of our lives. Their emergence could be extremely rapid. One obvious example is a room temperature superconductor with high current carrying capacity and benign mechanical properties. That would have potential for ubiquitous use, and would change almost all aspects of our lives.

7.1.5 The far future: Limits and exotic physics

Physics is governed by limits that are not always appreciated by the general population and, ultimately, such limits in turn place fundamental limits on what we might achieve. For example, the phenomenon of special relativity runs counter to our "Newtonian" perception of time and space as being an unchanging four-dimensional grid. Due to the malleability of space-time and its dependence on the observer, we are for all practical purposes trapped inside our solar system.

In principle, using an extreme amount of energy, a space ship could be accelerated to within a very small fraction of the speed of light (not beyond) and, given enough time, decelerate and eventually

149 See the easily understood Nobel lecture by Horst Stormer December 1998 on fractional quantum numbers and the fractional Hall effect.

150 See for example quantum magnonics at Oxford

151 I.e. high impact low probability risks see http://www.bris.ac.uk/eng-systems-centre/allpdf/blackett-review.pdf. A Blackett report specifically concerning quantum technology is currently being composed and is due for publication in the late autumn of 2016.

return home. However, time at home would have advanced maybe thousands or even millions of years compared to ship's time during a return journey to and from another galaxy. Worse, a collision with a grain of sand part way through the journey would probably destroy the ship. The Star Trek scenario is just not a true reflection of reality.

There may be a limit to what we can practically control. It is unlikely that we will ever be able to move stars around. At the very smallest scale, elementary particle physics is complicated and quite beguiling. Although its characteristics are beautifully captured by 20th century mathematics, it appears to have a description as incomplete as mathematics itself. The long chain of inference supported by carefully conducted experiments (usually collisions) has yielded as many mysteries as it has solved. The particles themselves may be some sort of "personification" of our classical ideas, and the notion of causality itself an emergent property of the quantum world.

All phenomena are subject to the rules of quantum mechanics, and all laws (including quantum mechanics) are trumped by the second law of thermodynamics[152].

Perhaps we might eventually be able to harness some of the more abstruse aspects of the physics that we understand. For example, some of the smallest (inseparable) units of matter appear to be the quarks. These interact via the *strong* force, a force mediated by gluons (the analogue of photons in electromagnetism - but massive). They appear to possess three types of charge, labelled as "colour charge", for convenience known as red, green and blue together with their opposites cyan, magenta and yellow respectively. Each triad has its own field lines mediated by its own set of gluons. Will we ever be able to manipulate and use this system for our own purpose? Nobody knows, although 500 years ago electrostatics, lightning and magnetism were equally mysterious. In our example the chains of inference just appear much longer with the fundamentals more complicated.

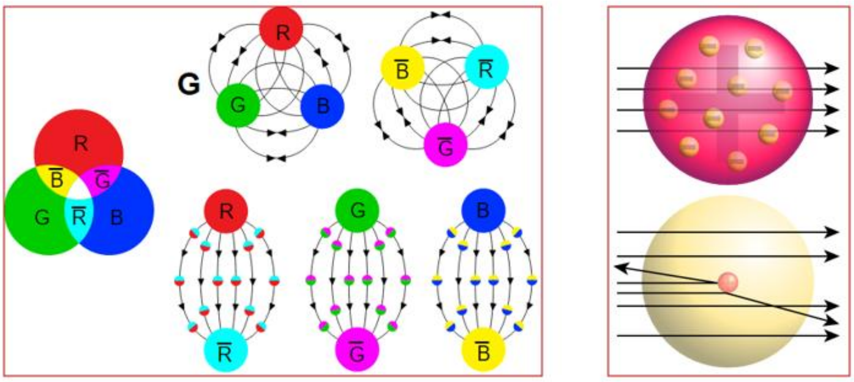

Figure 32: The diagram on the left shows the field lines and force carriers associated with quarks. The diagram on the right shows the expected versus actual results of Rutherford's experiment to test scattering by atoms. What will we be seeing in the year 2109? *CCo 1.0 public domain declaration*

[152] Fundamentally, this states that a closed system inevitably becomes more disordered with the passage of time, with the most elegant exact description becoming more complicated. The effect is irreversible.

8 Introduction to emerging quantum technologies

8.1 Overview

Quantum technology is, indirectly, familiar to most people. There are very many 20th century applications and their ramifications extend throughout our daily lives.

As in the previous edition of this document, the technologies are arranged in approximate order of degree of maturity, and we have added an additional section on quantum materials and nanotechnology. The sections are as follows:

- Quantum timing and clocks
- Quantum communications
- Quantum sensing
- Quantum imaging
- Quantum computing
- Quantum materials and nanotechnology

Most sections overlap to a certain extent, and most share some common aspects of quantum behaviour to achieve their functionality.

8.2 Quantum timing and clocks

8.2.1 Introduction

The operating principles of atomic clocks lie in atomic physics and (nearly all[153]) make use of the electromagnetic radiation that electrons in atoms emit or absorb when they change energy levels[154]. Early atomic clocks used quantum effects but the most recent developments are either making use of more subtle phenomena, or harnessing energy levels in more subtle ways. However, we would like to consider significant advances in all species of atomic clocks. Early (microwave) atomic clocks made use of electronic transitions corresponding to frequencies in the microwave region of the electromagnetic spectrum. More recent optical atomic clocks use transitions associated with the optical (visible) part of the spectrum or even the UV (Ultra-Violet).

The central importance of precision timing has been increasingly acknowledged in recent years. The Royal Academy of Engineering (RAE) has warned[155] that many sectors of today's industrialised society are now "dangerously over-reliant" on navigation and timing signals from satellites. The vulnerabilities could not only arise from active jamming devices or natural phenomena such as solar

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153 There have been some experiments using other principles, such as Compton clocks, but these have not, to date, been sufficiently successful.

154 A good introduction to atomic clocks http://resource.npl.co.uk/docs/networks/time/meeting10/curtis.pdf

155 [4] "Global Navigation Space Systems: reliance and vulnerabilities", Royal Academy of Engineering, March 2011. ://www.raeng.org.uk/news/publications/list/reports/RAoE_Global_Navigation_Systems_Report.pdf

storms,[156] but also from faulty software uploads or human error. Any of these could result in a full or partial malfunction.

Global navigation satellite systems (GNSS) are used in many sectors of the civilian economy; examples include emergency services, shipping and air transport, railways, agriculture, data networks and financial systems. The 2011 RAE report estimated that around 7% of the UK economy was dependent on GNSS (particularly the US system known as the Global Positioning System GPS). Furthermore, the report anticipated that this proportion will grow rapidly in subsequent years and this has indeed happened. In the report on the potential effect of solar storms, the RAE recommended that "all critical infrastructure and safety-critical systems that require accurate GNSS derived time and or timing should be specified to operate with holdover technology for up to three days.[157]" The Financial Times highlighted the publication of both RAE reports, illustrating the relevance to the UK business community.[158] The availability of precise timing to the military is also of immense importance.

Atomic clocks are widely regarded to be precise, stable and accurate. Precision relates to the rate of "ticking" of the clock which is provided by the natural frequency of the electronic transitions in the atoms used. Higher frequencies allow time to be divided (internally) into smaller units, thus optical clocks (see later) are more precise ("tick" more frequently) than microwave clocks. The accuracy of an atomic clock is related to the extent to which the clock can reproduce the unperturbed frequency of the atomic transition by minimising or correcting for systematic frequency shifts or biases. These shifts include factors due to atomic collisions, the Zeeman effect of magnetic fields, interaction with black body radiation, the Doppler effect and the second order Doppler effect[159]. All of these change the energy read-out of atomic states in small but quantifiable ways, the biggest effects usually being caused by magnetic fields, temperature or black body radiation.

No atomic clock is just the physics package (i.e. the "working atom(s)"). The output needs to be manipulated somehow to make it usable or to inject it into the system it is supporting. Often this is by phase-locking (or other locking) another oscillator to the atom(s), or by multiplying/dividing using another subsystem. The issue is that expertise in this field is relatively sparse in the UK and the practical performance of a clock can be jeopardised by the performance of the locked oscillator or conversion system. This could be via vibration induced phase noise, acceleration sensitivity, radiation induced shot noise, etc. These factors are particularly important for portable military systems.

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[156] "Extreme space weather: impacts on engineered systems and infrastructure", Royal Academy of Engineering, February 2013. http://www.raeng.org.uk/news/publications/list/reports/space_weather_full_report_final.pdf

[157] I.e. a stability of very approximately 1 in 10^{14}.

[158] http://www.ft.com/cms/s/2/68d0eb1c-48ee-11e0-af8c-00144feab49a.html#axzz2kXDonY63; http://www.ft.com/cms/s/0/f30d9e54-7067-11e2-ab31-00144feab49a.html?siteedition=uk#axzz2kXDonY63

[159] This is a systematic "slowing" due to relativistic time dilation and occurs independently of the atoms' direction.

Finally, General Relativity causes a difference in the flow of time due to gravitational potential[160] (a height reduction of 1 metre at "sea level"[161] is approximately equivalent to a 10^{-16} change in frequency) which must be accounted for at such levels of accuracy. The stability of a clock, its capability to deliver a frequency reference unchanging over a specified time interval, is a measure of the tendency of a clock's rate to vary, perhaps because of a changing environment. The expression of accuracy as "5 x 10^{-9}" - equivalent to "2 in 10^{10}" - is a very loose measure which we will use (in either format)

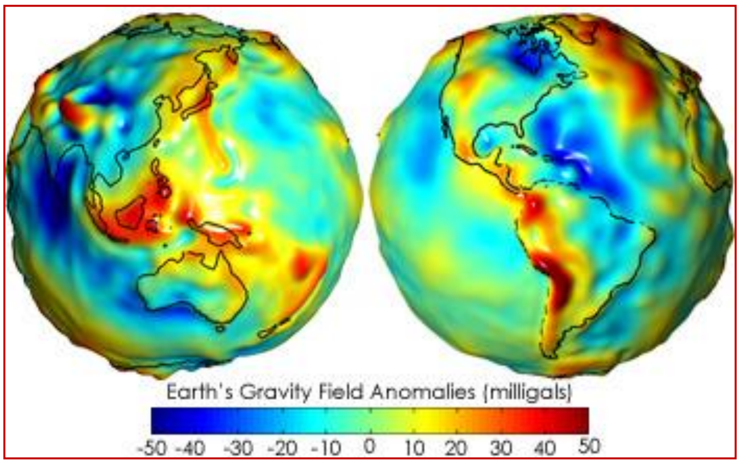

Figure 33 3-D visualisation of the difference between the geoid and the reference ellipsoid that approximates the Earth's surface
Courtesy NASA/JPL-Caltech

for the purpose of this report. In practice, there are many factors to be considered, such as jitter, long term accuracy and other measures of stability. Time measured by a precise clock depends on its altitude at a fixed point (see figure 33) or geographic position at a fixed altitude. In the generation of international timescales using current national frequency standards this must be taken into account.

8.2.2 Technology development and accuracy of atomic clocks

The idea of using atomic transitions (in sodium and hydrogen) atoms to measure time was suggested by William Thompson, later Lord Kelvin (from an idea first proposed by Lord Maxwell), and Peter Guthrie in 1879 before the Bohr model of the atom had been proposed[162]. The basic concepts were later developed during the 1930s and 40s by Rabi resulting in the suggestion of a practical method in 1945. His concept was to use hyperfine[163] atomic transitions in the ^{133}Cs atom at the microwave frequency of 9.1914 GHz. However, the first atomic clock demonstrated was an ammonia maser device built by Lyons and co-workers in 1949 at the U.S. National Bureau of Standards (NBS, now NIST, National Institute of Standards and Technology). It was less accurate than the then existing quartz clocks, but served to demonstrate the concept.

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160 I.e. the depth at which the clock sits in a gravitational field. This is in contrast to the field *strength*, which is the rate at which the potential varies with (usually) vertical distance.

161 Sea level is a very poor description of the gravitational field strength used to allow an intuitive understanding here. The difference in clock rates depends on the difference in gravitational potential.

162 Note (from a 2011 article by Lombard): The Scottish physicist James Clerk Maxwell was perhaps the first person to recognize that atoms could be used to keep time. In an era where the Earth's rotation was the timekeeping standard, Maxwell remarkably suggested to William Thomson (Lord Kelvin) that the "period of vibration of a piece of quartz crystal" would be a better absolute standard of time than the mean solar second, but would still depend "essentially on one particular piece of matter, and is therefore liable to accidents." Atoms would work

163 Hyperfine (very narrow) energy level splitting is caused by the interaction of electrons in atoms and their nuclei.

The first Cs atomic clock with greater accuracy than a quartz device was built by Louis Essen in 1955 at the National Physical Laboratory (NPL) in the UK. NPL has remained world leading ever since.

Figure 34 illustrates the evolving accuracy of atomic clocks since Essen and Parry's laboratory demonstration of the first caesium microwave atomic clock.

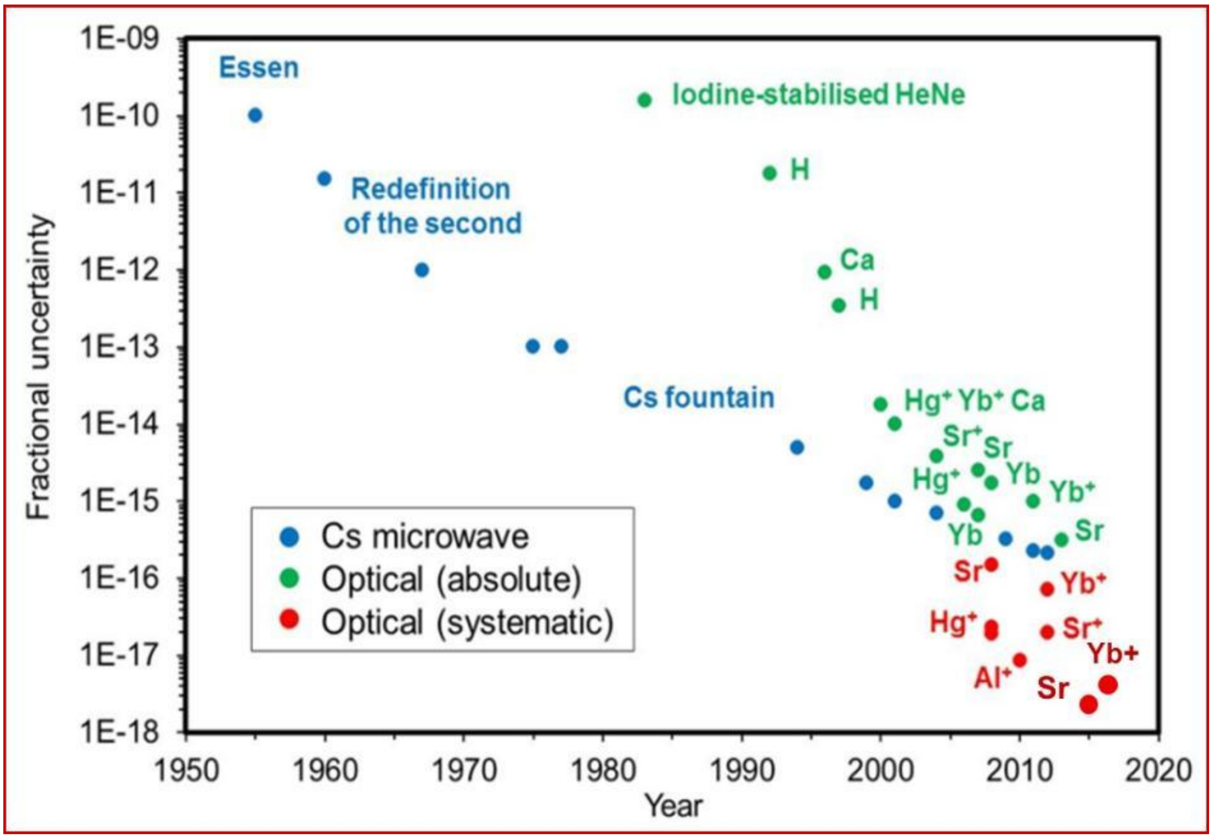

Figure 34: Increase in accuracy of atomic clocks by year.
Reproduced by kind permission of Professor Patrick Gill of the UK National Physical Laboratory

The first commercial caesium standard clock became available in 1956 but it was the compact Hewlett-Packard model 5060, the forerunner of the HP 5071; which became widely adopted and developed into the current Microsemi 5071A clock. Typically, this has an accuracy of 2.5 x 10^{-11} although the actual number depends on specific options. Improvements in the accuracy of the caesium standard were subsequently pursued by NBS/NIST in the form of the US NIST F1. SYRTE[164] *were the group who led the way with fountains and had the first operational Cs fountain. NPL's CsF2 was the lowest uncertainty clock for a period, but not by more than a factor of 2 over NIST F1, and only slightly better than SYRTE. Then came NIST-F2 cryogenic fountain with uncertainty of 1 - 2 in 10^{-16} but there are disagreements between Jefferts (NIST) and Gibble (Pennsylvania State University) over some of the uncertainty contributions. Increasing the Ramsey cavity length, improved vacuum, better state selection of atoms (ultimately by lasers rather than permanent magnets) and lower atomic temperatures contributed to these improvements.*

[164] SYRTE (SYstèmes de Référence Temps Espace - Time Space Reference Systems) is a department of the Paris Observatory

The atomic clocks currently used as primary standards to realise the SI second are atomic fountain clocks.[165] The accuracy of the US NIST-F2 is not far from the fundamental limit for such devices, while SYRTE, NPL and USNO have developed Rb fountains operating with larger clouds and thus capable of slightly better stability.[166] An increase in performance to better than about 1 in 10^{17} demands rapidly increasing sophistication as ever more fundamental limitations are encountered, each requiring a work-around. It is unlikely that this level will be exceeded with fountains. Cryogenic operation reduces the limitation of blackbody shift to about 7 x 10^{-17} in a number of atom and ion atomic clocks.[167] Reduction in size of atomic clocks incurs a performance penalty, illustrated semi-quantitatively in figure 35, however, size, weight and power (SWAP) can be critical factors, especially for some military and aerospace applications. Accordingly, there have been a number of programmes to develop low SWAP devices with as high performance as possible.

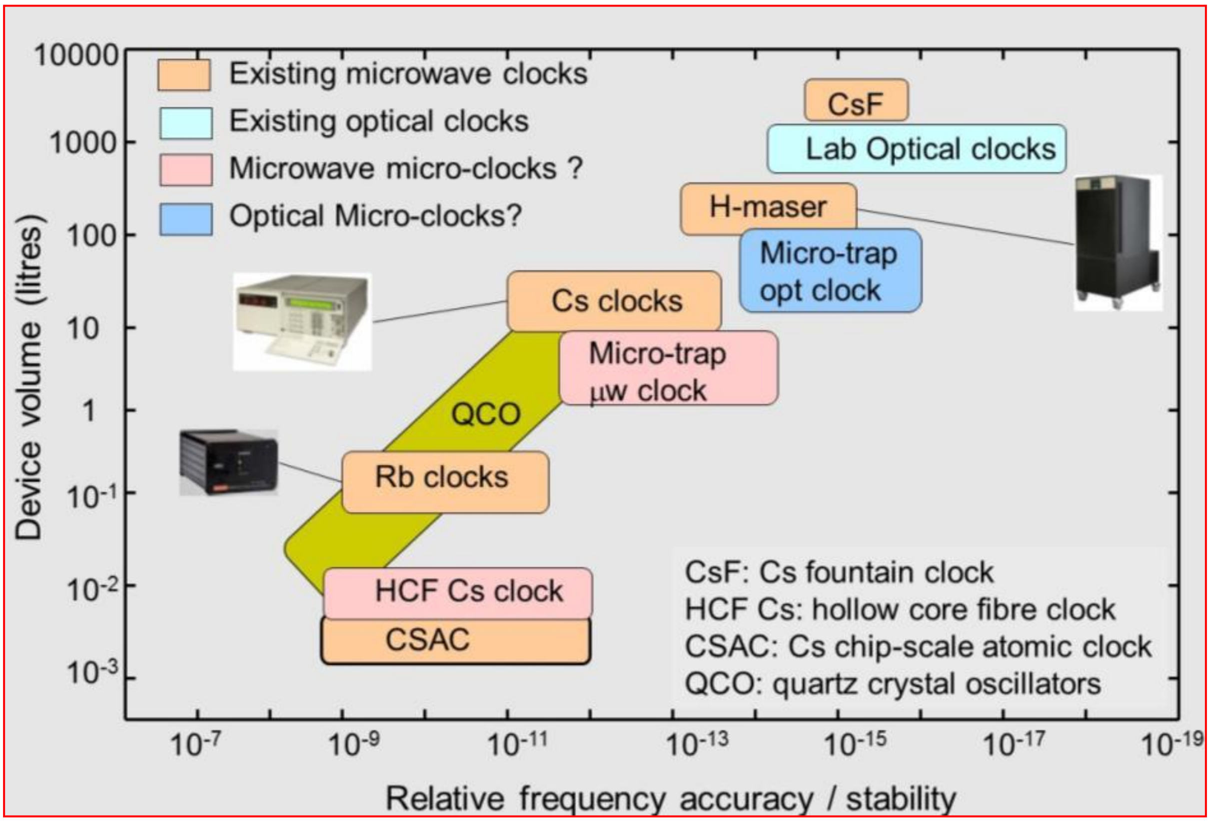

Figure 35 Clock performance as a function of device volume (2016). NB: Performance of optical clocks increases over microwave systems, but so does clock complexity and hence development time and cost. ***Reproduced by kind permission of Professor Patrick Gill of the UK National Physical Laboratory*****.**

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[165] For a simple explanation of their operation see http://www.npl.co.uk/science-technology/time-frequency/research/microwave-frequency-standards/operation-of-atomic-fountain

[166] See http://tf.boulder.nist.gov/general/pdf/2500.pdf and http://www.npl.co.uk/science-technology/time-frequency/research/microwave-frequency-standards/rb-fountain

[167] http://www.physics.udel.edu/~msafrono/Papers/IEEE2011-paper.pdf

8.2.3 Coherent population trapping (CPT) and other compact clocks

Microwave clocks using passive, vapour-cell frequency references based on coherent population trapping have enabled significant miniaturisation of clocks[168]. Without CPT the minimum size of the clock "physics package" is largely determined by the cavity in which microwave atomic excitation takes place resulting in high power consumption and significant bulk.

In CPT clocks, a diode laser is modulated and the light passed through the atomic vapour, which acts as an extremely sharp notch filter. A change in the transmission of the light through the cell is used to lock the modulation frequency to the atomic resonance.

A chip scale version of the CPT clock was originally demonstrated at NIST (possibly with early DARPA funding), and a subsequent DARPA funding programme led to the commercially available CSAC[169] in the US (see figure 36). This has been commercialised through a number of stages that resulted in the commercially available Chip Scale Atomic Clock (CSAC) manufactured by Symmetricom Inc. (now Microsemi).

Work at Strathclyde[170] has developed micro-fabricated 4 beam pyramid mirror (P) and grating (G) MOTs (known as PMOTs and GMOTs respectively,) both of which split and steer a single incident vertical laser beam into three upwards trapping beams. Using frequency modulated lasers and a Λ system[171] such as ^{85}Rb coherent population trapping spectroscopy in these MOTs has been investigated for clock or field sensing. (The GMOT is completely flat and therefore ideal for atom chip devices capable of measuring the 3D gradients of local magnetic fields or gravitational acceleration.)

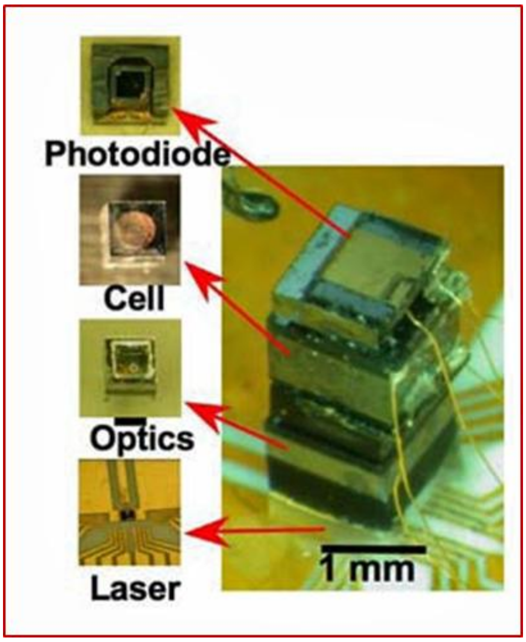

Figure 36 The original CSAC as commissioned by DARPA ***Credit DARPA***

The caesium based SA 45s CSAC device uses a custom microwave modulated VCSEL[172] *operating at a different wavelength to those commonly used in the telecoms industry to pump the upper level of the hyperfine transition ($6^2s_{1/2}$ (F=3) ↔ $6^2s_{1/2}$ (F=4) at 9,192,631,770 Hz). The modulated VCSEL at 852 nm or 894 nm drives between the upper and lower hyperfine levels via the resonance or near resonance with the upper level of the optical transition via a lambda (Λ) arrangement. It is specified to have an accuracy of ~ 2 x 10^{-12} at shipment, weighs 35g, has a volume of 16 cm^3, and a power consumption < 120 mW. The device has a warm up time of ~ 2 - 3 minutes and an advertised lifetime > 100,000 hours.* With

168 For an explanation of CPT see http://tf.nist.gov/timefreq/ofm/smallclock/CPT_clocks.html
169 DARPA = Defence Advanced Projects Agency
170 'Atom trapping in non-trivial geometries for micro-fabrication applications' M Vangeleyn, PhD Thesis (2011)
171 The lambda system refers to the energy transitions (in this case in Rb) that are used for timing. There are two closely spaced (hyperfine) lower levels and a third higher level. The transition diagram represents the Greek letter lambda Λ.
172 VCSEL = Vertical Cavity Surface Emitting Laser

careful characterisation and environmental control, the accuracy achieved can be improved,[173] although tests commissioned by Dstl on several devices have indicated considerable inconsistency between devices and a tendency toward early failure.

More recently, NPL in the UK has started work on an alternative miniaturised physics package using an alternative energy transition swapping caesium D1 with D2 ($6^2S_{1/2}$ (F=3) ↔ $6^2S_{1/2}$ (F=4) clock transitions but with different Λ schemes i.e. D1 with $^6p_{1/2}$ state at 894 nm rather than the D2 with $^6P_{3/2}$ state at 852nm relative to the 6 $^2S_{1/2}$ (F=3) ground state). If successful, this could offer a better signal to noise ratio, narrower linewidth and improved stability.

The "physics package" for a compact strontium neutral atom optical clock[174] has been developed by AO Sense, Inc. (Sunnyvale CA). Full details have not been released but it is known that it comprises a 6 litre package which contains all lasers, a spectrometer and a vacuum system consisting of pumps, strontium oven source, Zeeman slower[175] and magneto-optical trap. The device is probably not a lattice clock, but based on a repeatedly interrogated freely-expanding cold atom cloud following Zeeman slowing and Magneto Optic Trap (MOT) containment. It will therefore most likely have some issues of longer averaging times, as did NIST's original cold calcium clock based on a similar arrangement. Alternatively, it might just be a 3D MOT arrangement, which will give good stability but limited accuracy on account of the large ac Stark shifts[176] (the alternative of trapping the atoms using "magic" laser frequencies[177] via the lattice arrangement avoids this).

8.2.4 Optical clocks and their technical drivers

The next two sections indicate why and how using a higher (than microwave) frequency as a read-out for the clock can significantly improve the performance. They are more technical than many of the descriptions in this paper and may be safely skipped by the non-technical reader.

The accuracy of an atomic clock is determined by how well the measured frequency matches that of the atoms' unperturbed natural frequency. It depends on the type of atoms used and how well they can be isolated from environmental effects during the spectroscopy that is used to provide the clock read-out. The precision of the clock represents the repeatability of the measured clock frequency over a given averaging time. Mathematically, it can be expressed as the Allan[178] deviation which, in fractional frequency units, is

[173] NIST have suggested the limit of frequency uncertainty in such clocks may be ~ ν/ν = 4 × 10^{-14} per 100 kHz of laser frequency uncertainty.

[174] This is not for a CPT clock

[175] This is a device that is used to slow atoms in a vacuum by applying a magnetic field as a "brake". The Zeeman slower is usually used as a preliminary step to cool the atoms in order to trap them in a magneto-optical trap.

[176] A Stark shift is a shift in atomic energy levels due to an ambient electric field, as opposed to a Zeeman shift which is caused by a magnetic field.

[177] These are frequencies where undesirable frequencies cancel, see later.

[178] The Allan deviation (or Allan variance) is a spirited attempt to reduce the measure of clock performance to a single number. Allan Variance is a useful guide to the performance of time references, although other factors like aging, temperature stability and several other factors ultimately determine what makes one clock better than another.

$$\sigma(\tau) = \frac{\delta v(\tau)_{rms}}{v} = \frac{\chi}{2\pi Q S_N}\sqrt{\frac{t_c}{\tau}}$$.

is the quality factor (sharpness) of the clock transition for line width[179] Δv, S_N is the signal to noise ratio obtained in the measurement cycle time t_c and χ is a constant which depends on the line shape of the clock transition. Conventionally, the averaging time τ is taken to be 100 seconds. Thus the most precise clock will have large Q and S_N values. The Cs clock satisfies these criteria as the 9.2 GHz transition can be resolved with a transition width of about 0.5 Hz giving a Q > 10^{10}, and since large numbers of atoms can be used good signal to noise is possible. Some of-the best Cs clocks achieve stabilities ~10^{-14} $\tau^{-0.5}$. In principle larger Qs are possible but in current fountain clock designs atomic interaction times are limited to ~ 1 second resulting in linewidths ~ 0.5 Hz. (A line width narrower by a factor of 10 would require a fountain 10 metres tall). Thus any further increase in the clock stability requires large signal to noise values which for Cs fountain clocks means the number of interacting atoms must be increased since the projection noise limit is already achieved in current clock experiments.

For quantum projection noise[180] limited measurements, S_N ~ $\sqrt{N_a}$ where N_a is the number of atoms used in the measurements. This square root dependence of the signal to noise ratio on the number of atoms practically limits the improvements in stability possible from increasing N_a since as N_a is increased the number of atomic collisions increase and this degrades clock performance.

An alternative option to improve clock stability is therefore to increase the frequency of the clock transition used and this has been the driver to using optical clock transitions. Microwave transitions occur in the 1 - 10 GHz[181] range while optical transitions (in the visible and UV) operate at frequencies ~ 10^{15} Hz offering, in principle, a 10^5 improvement in stability.

Neutral atom optical clocks are a natural extension of the Cs primary standard, as the basic physics of the measurement is the same but the precision is increased. Alkaline earth atoms are promising candidates for optical clocks as the electronic energy levels are suited to laser cooling of the atom ensembles as well as providing narrow clock transitions which are insensitive to frequency shifts caused by external electric or magnetic fields. The most studied early neutral atom optical clock was currently based on freely expanding clouds of laser-cooled Ca atoms. (The reference frequency is the $^1s_0 \leftrightarrow 3p_1$ transition which has a narrow linewidth of ~ 300 Hz). A stability of 4 × 10^{-15} after 1 second integration has been demonstrated and the clock instability has been reduced to 6.6×10^{-15} in a number of laboratories. The analogous transition has also been explored in Mg.

Neutral atom clock accuracies are limited by the Doppler effect resulting from atomic motion in the atom cloud. Single cooled and trapped ions, however, provide a reference free of the Doppler shift problems that hinder free space measurements of neutral atoms. In these

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179 The linewidth is the sharpness of the resonance at the frequency ν

180 Very loosely, projection noise is an error that occurs when a quantum state is measured to yield a classical value (typically caused by population fluctuations in two level systems) e.g. see this

181 Hz stands for Hertz, a measure of frequency i.e. cycles per second.

systems the ions are tightly trapped in the Lamb-Dicke regime[182] where the ion motion is much smaller than the wavelength of the spectroscopy laser. In this regime, the atomic motion has a negligible effect on the transition width, and long interrogation times can be used such that large Qs in the region of 10^{14} - 10^{15} have been achieved. The trapped Hg^{+} clock demonstrated at NIST in 2006 out-performed Cs clocks and achieved a stability of 4×10^{-15} $\tau^{-0.5}$ even with the reduced signal to noise ratio available from only one atom. The elimination of Doppler effects allows clock instabilities significantly below those achievable for fountain clocks and although the fundamental stabilities of single ion clocks are inferior to those of neutral atom clocks due to the ion number (N=1). Intrinsically smaller SWAP[183] requirements will ensure that ion clocks remain attractive technology options for realising accurate and stable miniature atomic clocks.

8.2.5 Frequency combs for optical clocks

Although optical clocks offer better stability than microwave clocks, there are technical difficulties associated with readout of such clocks, i.e. the "tick" of the clock. Microwave clocks, such as Cs, operate at frequencies compatible with fast electronic detectors and frequency counters, making measurement and utilisation of the clock signal straight forward. Optical frequencies, however, are difficult to measure accurately because of their much higher values (about one million times greater than microwave frequencies). Traditionally, optical frequencies were determined by using frequency chains[184] which multiplied up microwave frequencies in a series of steps to reach the optical frequency. This was a complex, resource intensive process impractical for all but the most sophisticated laboratories and doesn't work well for this particular application. However, the past decade and a half[185] has seen the development of devices called optical frequency combs which allow the opposite process of frequency down conversion[186] in an efficient manner. This work led to one half of the Nobel Prize in Physics being shared by John L. Hall and Theodor W. Hänsch in 2005.

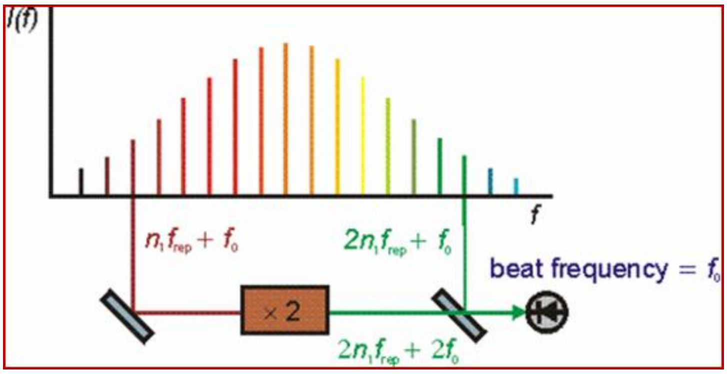

Figure 37: An optical frequency comb *courtesy of NPL*

In the frequency domain, the output of a femtosecond pulsed laser consists of a large number of modes - the comb, see figure 37 - evenly spaced by the frequency at which pulses are emitted, the repetition rate f_{rep}. Because of dispersion effects[187], the mode frequencies are not exact harmonics of the repetition frequency and the comb is offset from zero[188] in frequency by

182 Technical article Lamb Dicke regime
183 SWAP = Size, Weight And Power
184 See: https://en.wikipedia.org/wiki/Frequency_divider
185 See "Femtosecond Optical Frequency Comb: Principle, Operation, and Applications" edited by J. Ye and S. T. Cundiff (Springer, New York, (2004)) for a review. The full text may be found HERE.
186 Microwave frequencies are relatively easy to handle electronically
187 "Outside" a vacuum, different frequencies usually travel at different rates. This is known as dispersion.
188 Meaning that if the if the comb did extend down to zero (DC) there would not be a mode at that value.

a small amount, f_0, whose value is typically counted in microwave frequencies. If f_{rep} and f_0 are known, then the frequency of the n^{th} comb mode is $\nu_n = nf_{rep} + f_0$. This relationship expresses the optical frequency ν_n in terms of two microwave frequencies and an integer n. Thus an optical clock frequency can be measured via heterodyne beating with the nearest comb mode, $\nu_{clock}=\nu_n+\nu_{beat}$ The optical frequency is completely determined by microwave frequencies plus an integer. The femtosecond laser effectively provides a coherent link between the optical and microwave regions of the electromagnetic spectrum, allowing a simplified system for measuring optical frequencies with traditional microwave technology. For practical purposes, combs need to have a spectral coverage matched to the optical clock wavelengths of interest and span at least an octave (i.e. may be used in "self-referencing" mode; this makes subsequent processing a much simpler task).

Current frequency combs are large items of laboratory equipment but NPL, NIST and other laboratories are developing miniaturised versions based on a range of micro-resonators fabricated from several experimental materials including SiO_2, various fluorides and Si_3N_4.[189] Apart from addressing SWAP issues of optical clocks, miniature frequency combs have many applications, for instance as handheld sources of "exotic" frequencies for spectroscopic identification of chemicals. They are an important enabling technology.

8.2.6 Quantum logic and single ion clocks

An alternative approach to achieving greater accuracy has been the development of quantum logic clocks using spectroscopy and "quantum logic" ions. The term "quantum logic clock" is used as it exploits the same operation as atoms storing data in certain quantum information processing devices. The accuracy obtained is competitive with atomic standards or better.

The first such clock was developed by NIST in the US and used closely positioned beryllium (logic), and aluminium (clock) ions (resonating in the ultra-violet region[190]) in a linear ion trap to achieve an uncertainty of 9 x 10^{-18} (cf. the best caesium fountain clocks typically have uncertainties ~ 2 in 10^{16}). The "tick" of the clock is in effect measured by heterodyning the clock laser frequency stabilised to the optical clock transition with the nearest comb mode[191]. This is sufficient to demonstrate gravitational time dilation for differences in height in the Earth's field of about 30 cm (depending on integration time). Also under development is a portable aluminium optical clock. The aim is to accommodate the vacuum and optical assembly on two optical breadboards, and the stabilised lasers (including ultra-stable cavities) and instrumentation mounted in a 19-inch rack mount.

Sandia National Laboratories (Albuquerque NM) is developing a low-power, miniature $^{171}Yb^+$ ion clock[192] under the DARPA Integrated Micro Primary Atomic Clock Technology (IMPACT) project. This aims to deliver a clock of 5 cm^3 volume and 50 mW power consumption, with a stability of 2 x 10^{-14} per month. This is based on the 12.6 GHz microwave clock transition. The current reported status of the project comprises a custom built 3 cm^3 vacuum package

189 The first demonstration was P del'Haye *et. al*., Nature 450, 1214 (2007); del'Haye is now at NPL.

190 See http://www.nist.gov/pml/div688/logicclock_020410.cfm

191 See above for a technical explanation. of the frequency comb. See http://www.nist.gov/public_affairs/releases/frequency_combs.cfm

192 a ytterbium (Yb) ion is a charged atom of the element ytterbium. You will notice that various elements are used as the timing mechanisms for atomic clocks. Each have uses dependent on their excitation spectra that are optimum for different apparatus configurations and stabilities / accuracies.

containing the ion trap integrated with a photo multiplier tube, miniaturized laser sources at 369 nm and 935nm, a local oscillator and control electronics. The physics package was initially assembled on a 10 cm x 15 cm breadboard and the long-term fractional frequency instability measured to be 6×10^{-14} at 25 days of integration. Subsequently the device was further miniaturised, and the frequency instability was measured to be $2 \times 10^{-11} \tau^{-0.5}$ with integration times up to 10,000 s for a stability of 2×10^{-13})

There is a good opportunity for NPL to develop a very competitive microwave micro-size atomic clock capability in the short to medium term, given their extensive experience with the cold Yb^{+} ion clocks[193] and using their ion chip trap technology, illustrated in figure 38. Prototypes can be tested quickly using the microwave arrangement in the linear blade trap[194], and subsequently transferring to the chip traps as they come on line. This chip trap design appears to be currently the best option for scaling traps and very precise intensity and pointing controls, needed to reduce signal noise, have been developed.

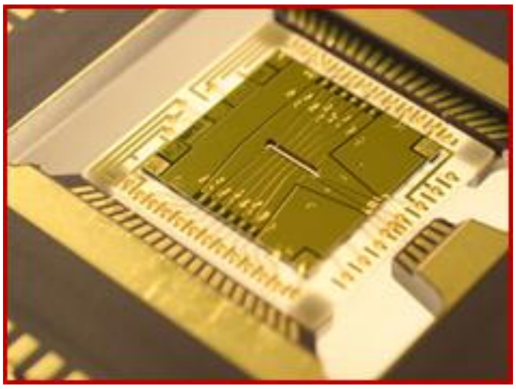

Figure 38: Typical atom chip wafer containing a blade trap (for ion clock) ***courtesy of NPL***

On February 1st 2016 DARPA publicised the Atomic Clocks with Enhanced Stability (ACES) program. The $50 million programme aims to develop palm-sized, battery-powered atomic clocks that perform up to 1,000 times better than the current Chip-Scale Atomic Clock (CSAC) and consume no more than 250 mW of power. DARPA expect "success will require record-breaking advances that counter accuracy-eroding processes in current atomic clocks, among them variations in atomic frequencies that result from temperature fluctuations and subtle frequency differences that can occur if the power shuts down and then starts up again. It will take a collaboration of teams with skill sets from diverse fields, including atomic physics, optics, photonics, micro fabrication and vacuum technology to achieve the unprecedented clock stability.” The clock components - including lasers, thermal controllers, shutters, modulators and other optical elements plus the atom chamber -must not exceed 30 cm^3 and the total device size including drive electronics must occupy a volume no more than 50 cm^3 and be suitable to fly in small unmanned aerial vehicles.

Sussex (Hensinger) is working on methods to use microwaves instead of lasers for entanglement generation and combining this technology with ion chips. Such integrated microwave ion chip technology may allow the development of portable entanglement based chip clocks.

More broadly, the UK are involved in development of similar types of cavity-stabilised lasers and optical clocks for space within ESA contracts (NPL and Sussex using both ions and atoms, Birmingham and Strathclyde using atoms). Volumetric footprint reduction and auto-control functionalities that allow the clock systems to run unaided are key objectives of the work.

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[193] S. A. King, R. M. Godun, S. A. Webster, H. S. Margolis, L. A. M. Johnson, K. Szymaniec, P. E. G. Baird and P. Gill, "Absolute frequency measurement of the $^2S_{1/2} - {}^2F_{7/2}$ electric octupole transition in a single ion of $^{171}Yb^{+}$ with 10^{-15} fractional uncertainty" New Journal of Physics 14, 013045 (2012). See HERE for the full article.

[194] Blade traps are described in http://heart-c704.uibk.ac.at/publications/dissertation/brandstaetter_diss.pdf

Qubits and quantum logic gates based on single $^{40}Ca^+$ and $^{43}Ca^+$ ions have been demonstrated at NIST in the US, which remain the only group to have fully demonstrated quantum logic operations in their clocks. Meanwhile, Oxford (where they are exploring the performance of fundamental quantum logic operations) have achieved state of art performance in the detection fidelity of the quantum state i.e. the read-out of the state. These functions are directly applicable to the quantum logic spectroscopy used in the most precise optical clocks.

The Al^+ quantum logic clock recently held the record for fractional frequency uncertainty. However, it is no longer the most precise optical clock. Both the Sr lattice clock and the Yb+ ion clock have reported fractional frequency uncertainties in the low x 10^{-18} s.

The UK has also developed world-leading component technologies which are highly relevant to these atom- or ion- based devices. Specific examples of micro fabricated components for atomic systems include an ion microchip,[195] an atom chip[196] and an array of integrated atom-photon junctions.[197]

8.2.7 Summary of current atomic clock performance

Table 1 lists the frequency stability performance of microwave and optical atomic clock systems for 100-second averaging times, for primary clocks operated in national standards labs[198], commercial fixed or portable clocks, and micro-clocks. Also included (in red) is information for quantum systems not yet realised as fully-operational clocks, with projected performance figures. Note that stability over 100 seconds, rather than accuracy, is used to ease the comparison between systems.

In December 2015,[199] researchers from the Physikalisch-Technische Bundesanstalt (PTB) published results from an analysis of the noise processes in their neutral strontium atom based optical lattice clock, see figure 39. A newly developed, highly stable, laser system allows high-precision measurements in a short time. The resonator has a length of 48 cm with good thermal and mechanical isolation from the clock's environment; it has allowed demonstration of a fractional

[195] G. Wilpers, P. See, P. Gill and A. G. Sinclair, “A monolithic array of three-dimensional ion traps fabricated with conventional semiconductor technology”, Nature Nanotechnology, 7, 572 (2012.) http://dx.doi.org/10.1038/nnano.2012.126

[196] C. C. Nshii, M. Vangeleyn, J. P. Cotter, P. F. Griffin, E. A. Hinds, C. N. Ironside, P. See, A. G. Sinclair, E. Riis and A. S. Arnold, “A surface-patterned chip as a strong source of ultra cold atoms for quantum technologies”, Nature Nanotechnology 8, 321 (2013).http://dx.doi.org/10.1038/nnano.2013.47

[197] M. Kohnen, M. Succo, P. G. Petrov, R. A. Nyman, M. Trupke & E. A. Hinds, “An array of integrated atom–photon junctions”, Nature Photonics 5, 35 (2011).http://dx.doi.org/10.1038/nphoton.2010.255

[198] There are other clocks that are not operated in a national standards lab but which have the potential to occupy a place e.g. work of Erling Riis (Strathclyde)

[199] Ali Al-Masoudi, Sören Dörscher, Sebastian Häfner, Uwe Sterr, and Christian Lisdat Phys. Rev. A 92, 063814 (2015)

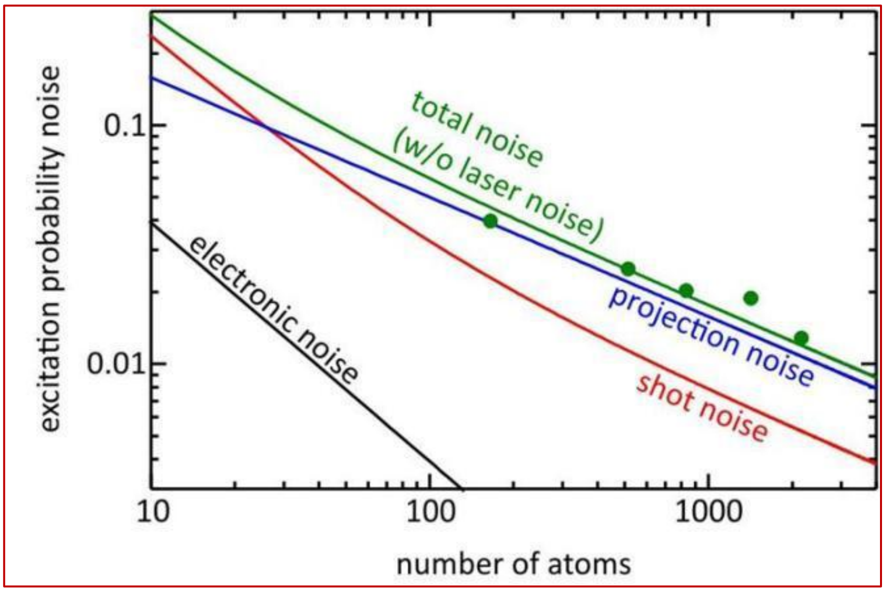

Figure 39: Noise contributions of the PTB strontium lattice clock as a function of the number of atoms. The predicted total noise at suppressed frequency noise of the interrogation laser (green line) is confirmed by experimental data (green circles). *Courtesy NPL*

frequency instability, at the quantum projection noise limit, of 1.6 x 10^{-16} $\tau^{-0.5}$ with just 130 atoms. (However, we note that, upon more detailed inspection of the publication, this value is an inferred value, not a measured value. Their measured value is 4.7 x $10^{-16}\tau^{-0.5}$. These figures can be compared against other workers' values of 3.2 x 10^{-16}…., 2.2 x 10^{-16} …… and 1.8 x $10^{-16}\tau^{-0.5}$, which are measurements made by NIST, JILA, and RIKEN[200] although they are not precisely the same measurement.) The analysis in the paper required understanding of the laser frequency noise, and from this a future reduction of the total measurement uncertainty down to a few parts in 10^{18} is believed to be achievable. The results that have demonstrated lowest stability ie. at longest averaging times are Sr at JILA and Katori both ~ 2 x 10^{-18}, and Yb at NIST (similar). Those with lowest reported systematic uncertainty are JILA and Katori giving the same number, and Yb^{+} ion at PTB giving lowest systematic uncertainty at 3x10^{-18}. Note instability is different to uncertainty.

8.2.8 Atom chip and lattice clocks

The first low temperature (micro Kelvin) atom traps were reported in 1987 when ~ 10^{7} sodium atoms were optically trapped for ~ 2 minutes at densities exceeding 10^{11} cm^{-3} and a temperature of 0.4 K, although the set up was large, complex and required significant power.

200 Rikagaku Kenkyūsho, a Japanese natural sciences research institute including the Quantum Metrology Laboratory

	Microwave clock stability			Optical clock stability			
	Thermal atoms	Cold atoms	Cold ions	Single cold ion clocks	Multiple cold ion clock	Cold atom opt. lattice clock	Entangle-ment based clock
Primary clocks	H-maser 1.4 GHz	Cs fountain 9.2 GHz	Hg^{+} 40 GHz 7-ion string	Yb^{+} 642 THz Sr^{+} 445 THz single ion	Al^{+} [Be+] 1121 THz dual ion QLC	Sr 429 THz Yb 518THz lattice	
Stability @ 100s	10^{-14}	2.10^{-15}	3.10^{-14}	3.10^{-16}	3.10^{-16}	3.10^{-17} N ~ 2000	
Fixed / portable clock	Cs & Rb commercial clocks	Rb 6.8 GHz atoms on magchip trap	Yb^{+} 12.6 GHz ion cloud Hg^{+} 40 GHz Buffer-gas cooled	Ca^{+} single ion	Al^{+} [Ca+] or In^{+} [Yb+] dual ion QLC	Cold Sr 2D MOT 6-litre	
Stability @ 100s	10^{-12}	6.10^{-14}	10^{-14}		3.10^{-16}	10^{-16}	
Micro-clocks	Cs CSAC Cs HCF	Rb 6.8 GHz atoms in opt trap	Yb^{+} 12.6 GHz Microtrap string	Micro-trap single ion / dual ion QLC	Micro-trap array (N ~ 100 ions)		Micro-trap 10 ions entangled
Stability @ 100s	3.10^{-11} 10^{-11} projection		3.10^{-13} projection	3.10^{-16} projection	3.10^{-17} projection		3.10^{-17} projection

Table 1 Comparison of current microwave and optical clock performance parameters. (CSAC, chip-scale atomic clock; HCF, hollow core fibre clock; QLC, quantum logic clock; 2D MOT, 2-dimensional magneto-optical trap; N, number of atoms or ions. The 100-second stability data is chosen to facilitate ease of comparison between systems, and to indicate performance in the short term (minutes to hours) window relevant to micro-clock operation. Note these are stability data, not accuracies.) Reproduced by kind permission of Professor Gill of the UK National Physical Laboratory

During the last decade, the technology has advanced quickly through step changes in cooling, trapping and fabrication techniques. Systems can now be realised as miniature devices requiring little power and much reduced infrastructure, since the vapour cells and cooling lasers could be integrated into a chip. The main obstacles to miniaturisation have been the development of effective, integrated, magneto-optical traps (MOTs) and loading atoms into the traps.

"Atom chip" clocks are being investigated by some workers[201] where current carrying wires on the chip are used to create the magnetic fields that trap a cloud of ultra-cold atoms above the surface.

Optical lattice clocks use the transitions of ultra-cold (~ 1μK) atoms held in a lattice formed by intersecting laser beams. The best of these are already achieving uncertainties of 2 in 10^{18}, sufficient to measure gravity potential to the centimetre level at the Earth's surface. An optical lattice clock using trapped ytterbium atoms was reported in May 2013[202] with a stability of 1 in 1.6 X 10^{18}.

201 E.g. SYRTE, see http://syrte.obspm.fr/tfc/h_puce_en.php

202 See http://arxiv.org/pdf/1305.5869v1.pdf and Hinkley, N. *et. al*. Science 341, 1215–1218 (2013). A Sr clock at JILA has achieved similar stability (Nature, vol. 506, 71 (2014) and Nature Communications, vol. 6, pp. 6896/1-8, 2015). Recent review papers describing the development of clocks are i) “Optical atomic clocks”, Reviews of Modern Physics, vol. 87, no. 2, pp. 637 - 701, 2015 and ii) “Progress on the optical lattice clock”, Comptes Rendus Physique, vol. 16, no. 5, pp. 499 - 505, 2015.

8.2.9 Quantum clock synchronisation

Synchronisation of two separated clocks is important for many practical applications, such as the global positioning system (GPS) and very long baseline interferometry (VLBI) and is a major focus for practical applications of precise clocks.

Clock synchronisation is an increasingly critical part of computing where financial trading has been the major driver, but it is also important in gaming, electric power systems, telecommunication networks, big data and distributed databases. The motivation for synchronisation is to allow multiple independent agents to coordinate without discussion. Thus in financial trading multiple computers must be able to share the trading load and simultaneously produce a record of when, and between whom, trades were initiated and confirmations received. Time synchronisation allows different parts of a communications grid to connect or disconnect without disrupting supplies, it allows "internet of things" networks to impose order on data streams from dispersed sensors and in databases synchronised clocks make possible high frequency data processing in parallel with timestamps to resolve conflicts.

The complexity in modern clock synchronization comes from the required precision (in many applications this is at least tenths of microseconds), the length of time for which synchronisation must be maintained and the delays and reliability of the networks used to carry the reference time. As clocks become more stable and accurate, compensation will become more important for relativistic effects. These are effects due to gravity (the US GPS systems already needs to take account of this), high speed manoeuvre over an extended period (aircraft) and the speed of light. The speed of light causes a delay of very approximately one nanosecond (0.000,000,001 second or 10^{-9} seconds) per 30 cm.

Conventionally, the synchronisation is performed by transmitting timing signals between the clocks. If compensation for special and general relativistic effects and differing delays are implemented properly, and corrections for atmospheric disturbance made, then the accuracy of the synchronisation process is limited by the uncertainty in the timing signal. Ultimately, the best result achievable is limited by the signal to noise ratio (SNR). Given adequate resources, sources of systematic noise can be eliminated so that the fundamental constraint is the shot noise limit (SNL) imposed by the charge on single electrons. In principle, specially prepared quantum states can reduce the effective noise below the SNL but the difficulties of preparing such states are significant.

Depending on the size of a network, numbers of clocks to be synchronised may vary from a few to many hundreds. Protocols define how time information is coded and what is exchanged between time sources and time clients. There are two standard protocols for synchronising and re-synchronising over a standard packet network: the older Network Time Protocol (NTP) and the newer IEEE 1588 Precision Time Protocol (PTP). Both protocols can be used to produce similar levels of accuracy.

GNSS signals are frequently used in networks to provide time references but this is now widely recognised to introduce (manmade and natural) network vulnerabilities. After two decades of increasing reliance, alternatives are now urgently being sought. One alternative is e-Loran (enhanced Loran) which is based on the World War II loran (LONg RAnge Navigation) technology[203]. It operates

[203] https://en.wikipedia.org/wiki/LORAN

at a carrier frequency of 100 kHz in a band, from 90 to 110 kHz. Inexpensive e-Loran precision timing receivers have been demonstrated, intended both as a backup for GPS receivers and as precision frequency stabilized sources to reduce the effect of the intentional dither in civil broadcast GPS signals. All European sites have now been closed except for Anthorn which transmits the MSF signal[204]. With only one transmitter active it is very difficult to enable navigation with e-Loran (using only timing, which needs access to a timing signal eg UTC or an appropriately set up local clock).

The most resilient solution for robust networks of course is to embed atomic clocks of appropriate stability throughout the network and this is an important driver for miniature atomic clock programmes such as DARPA's ACES.

8.2.10 Accurate frequency distribution

An issue related to clock synchronisation is the accurate distribution of frequency from one place to another. This will be required for some applications of quantum clocks, e.g. for measuring gravity potential, because it is only the apparent frequency of the clock compared to an observer in a different gravity potential that changes. So some method is required to compare the frequency of two clocks at different locations. Between certain locations this can be done extremely well using phase-noise-cancelled optical fibre links. This requires optical-electronic interfaces in the link and suitable networks over which frequency can be distributed are limited in some areas. If these networks were extended to key locations for quantum clock development, then they could be used both to aid in the development process (by providing ready access to national standards) and for technology demonstrator experiments (e.g. measurement of gravity potential differences using the clocks).

8.2.11 Issues and challenges

The key challenge is to realise a progressive development in accuracy, combined with a reduction of size, weight, power and cost. Ideally, there will be a number of "disruptive" advances set against a background of continuous improvement. Concurrently, a number of challenging technical issues will become increasingly important to address. These include susceptibility to stray magnetic or electric fields, vibration, shock and temperature. It is not only the ultimate precision that counts as improvement, but also the length of time taken to make a measurement.

Also important is the issue of validation of the performance of different clock technologies. This requires comparison of miniature clocks against a standard with known, better, performance. For the most stable and accurate miniature clocks this means either bringing the clock to a national lab or comparing it with a national standard remotely.

An important consideration is where there might be a need for clocks more precise than currently available. Space navigation, imaging and communications are likely commercial drivers. Ultimately, clocks with stability ≥1 in 10^{22} could be used for detecting and characterising gravitational waves[205].

In the short term, the strongest driver for clocks of extreme accuracy, due to their bulk and fragility, almost certainly will be in demand for increased precision in scientific measurements. Apart from

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[204] http://www.npl.co.uk/science-technology/time-frequency/products-and-services/time/msf-radio-time-signal

[205] Holberg *et. al.* Philosophical Transactions A to be published.

metrology, this will benefit high energy particle physics, astrophysics and extreme tests of relativity, fundamental constants and the behaviour of fields and forces.

Current GPS satellites carry two Cs, and a number of Rb, microwave atomic clocks, theoretically providing GPS time accurate to ~ 15 ns, but more practically accurate to ~ 100 ns. Current GLONASS, BeiDou and Galileo satellites have similar capabilities. Microwave atomic clocks will be replaced by optical lattice clocks offering significantly more precise time and positioning services but the development of high performance, transportable and space qualified optical clocks will provide a significant challenge.[206] Other drivers include fundamental physics experiments. For example, ESA, with EU FP7 funding, has proposed STE-QUEST (Space-Time Explorer and Quantum Equivalence Principle Space Test) to put an optical lattice clock on the International Space Station by 2020. This will investigate precise measurements of the effect of gravity on time and matter using an atomic clock and an atom interferometer. It will allow Einstein's Equivalence Principle to be tested to a high degree of precision[207] or detect gravity waves with improved sensitivity.[208] ^{87}Sr and ^{171}Yb are currently considered as the most promising species to use in space optical clocks.

The ultimate aim will not just be clocks with unprecedented accuracy. It will be the ability to use atom chip or other micro scale trap technology to produce miniature devices which are cheap and simple to use, integrated into current systems, thereby producing step changes in sensing, data processing and communication capabilities.

One problem is timing synchronisation when a mobile communications link needs to be re-established with a network. It's related to signal coding, but if one considers the problem of achieving lock with a Gold code[209] (like GPS but also CDMA[210] for mobile phones) it requires the new node to have a fair idea of the ‘right time’ to join, or you must wait while an extensive search is undertaken. The problem of a mobile communications device joining or re-joining networks can become acute if timing information is lost; we have come to rely on GPS to provide that timing for all kinds of purposes, without realising the dependence.

There are safety issues. We have already mentioned "dangerous" over-reliance of global navigation satellite systems (GNSS). Misleading or missing signals could result in vehicle or shipping accidents, goods stolen from consignments that can no longer be tracked, or misrepresented financial transactions. Small, cheap and highly accurate clocks would mitigate against many of the problems by enabling rapid re-acquisition of signals and the ability to keep time to an accuracy of a microsecond or less for days, weeks or more.

Foreign technology is becoming export controlled. An indigenous capability is essential; UK has world leading strengths in crucial relevant areas i.e. atomic fountains, trapped ions and neutral

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206 https://arxiv.org/ftp/arxiv/papers/1206/1206.3765.pdf

207 'Optical Atomic Clocks for Space', P Gill et. al., http://www.npl.co.uk/upload/pdf/atomic_clocks_space.pdf

208 http://physicsworld.com/cws/article/news/2016/jun/20/atomic-clocks-in-space-could-detect-gravitational-waves

209 Gold codes are sequences of binary bits that have very limited cross correlation, i.e. are very dissimilar to each other.

210 CDMA = Code Division Multiple Access, a way of containing many signals in one channel, or a single signal spread over a band to improve energy efficiency or minimise unwanted exploitation.

atoms. Meanwhile Dstl, with NPL, is supporting investigation of a CSAC alternative, and with Birmingham University is exploring the technology required to build a miniature, low power lattice clock with an accuracy comparable with much larger frequency standards.

With indigenous, miniature atomic clock capability, significant advances can be made with radar and sonar, especially in the context of multi-static architectures[211]. Defence exports are a significant contributor to UK wealth (the top two are defence and aerospace, with the third being pharma).

8.2.12 Synopsis

The field of quantum clocks (i.e. atomic clocks) is becoming wider, and is advancing rapidly as they are becoming progressively smaller, cheaper, more robust and more power efficient. This is gradually raising the performance and utility of practical devices that can be incorporated into systems. Due to the extensive expertise present in the UK we can expect significant capability and economic benefits given a sufficient level of investment and support.

New generations of clocks are becoming so accurate that they will allow relativistic effects to be measured in a lab environment instead of sending them into space. Sensitive lab-based tests of special and general relativity will become possible.

In the short term the UK is well positioned to develop and commercialize a low-power, low-cost, miniature precise timing device to provide GPS holdover for ~10 days. This would be a leading international solution, and not subject to US export controls. A miniature size, weight and power (SWAP) solution might be based on a hollow-core fibre or capillary clock if initial tests are encouraging (in ~1-year timescale and a possible 12 - 18 months' development phase for the technology to reach TRL8). The necessary (subsystem and component) technology capabilities developed as part of such a programme would be relevant across most of the range of quantum technologies and benefit the wider UK community.

In the longer term, precision timing technologies will enable other applications based on quantum technology such as quantum sensing and quantum information processing. National investment in NPL's Quantum Metrology Institute (QMI), accessible to industry and academia, will serve as a useful way to accelerate progress, build translational capability and help to equip the UK with skills it needs to lead internationally in the new, emerging quantum technologies.

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[211] Multi-static architectures include one or more receivers and one or more transmitters, some or all of which may be separate to each other.

8.3 Quantum communications

8.3.1 Introduction

There are two aspects of quantum communications. The first is the use of quantum technologies to provide secure transmission of classical information ("1"s and "0"s).[212] This is generally seen as one of the means to facilitate cryptographic keys robust to attack by a quantum computer which was able to solve discrete logarithms[213] and factoring large integers[214]. For this, the maintenance of quantum coherence at the transmitter and receiver is not necessary.

The second is to transmit quantum information (qubits), typically as part of a distributed quantum information processing system, or as a relay that has to maintain quantum coherence of the traffic passing through. From a systems point of view the two concepts overlap. In the latter case, quantum coherence and entanglement between the generator and the end processor must be maintained.

The transmission of quantum information can take place using physical qubits (such as photons[215] or atoms), or it can be transmitted using the phenomenon of quantum teleportation. Quantum repeaters would be required for many real-world applications since the signals degrade over distance and the probability of losing qubits rises to an unacceptable level. A chain of repeaters for long-distance signals would use the quantum Zeno effect to keep resetting the probability of decay or "decoherence" of the qubit to zero. Developing practical quantum repeaters is the subject of current research.

8.3.2 Quantum communications technologies

One of the early practical applications of quantum communications is to quantum key distribution (QKD), a method to establish cryptographic keys used to encrypt classical data ("1"s and "0"s) between two users who wish to communicate securely. There is existing IP on many potential applications in systems, such as passwords, entry keys and passports.

QKD should really be viewed as a component of a larger secure communications system, since it only solves part of the security challenge. To make the system as a whole work properly requires many other supporting security mechanisms such as access control (passwords, biometrics or entry keys), data integrity checks and authentication mechanisms (digital signatures). It is hoped that future generations of quantum communications currently under research, such as quantum digital signatures (QDS), will address some of these other requirements for the secure transmission of classical information. Indeed, the class of quantum communications is much broader than mere secure classical data transfer; it is planned that QKD will be just the first generation of this class.

8.3.3 Early quantum key distribution (QKD)technologies

The first Quantum Key Distribution (QKD) scheme was described by Bennett and Brassard in 1984 and is known as the BB84 protocol. It was originally described, and later implemented, using a

[212] Technically, the technology provides photonic links at the physical layer to provide additional cryptographic keying material for use within host applications' cryptographic protocols.
[213] The basis of the Diffie-Hellman and DSA digital signature protocols and most elliptic curve-based cryptography
[214] The basis of the RSA key establishment and digital signature protocols
[215] When photons are used as qubits they are often referred to as "flying qubits"

physical channel, usually fibre or free space, to transmit photon polarisation states. Measurement data from this physical channel may be passed to a host application for conversion into cryptographic keying material. Separate (classical) data channels are used to provide management information and classical authentication for this QKD process, and to provide the actual payload channel within which the keys will then be used.

Improvements and refinements, such as phase comparison and time binning, were developed over the late 1990s and early 2000s, and now BB84 systems may be bought as commercial products.[216] The principal challenges have been range, bit rate and (in free space) washout from photons in the environment, although performance has steadily been improving. Recently, ranges of hundreds of kilometres have been achieved including key exchange with aircraft. UK expertise is well represented by the hubs in the context of experiment, theory and technology implementation.[217]

8.3.4 Second generation QKD

The E91 protocol was described by Artur Ekert in 1991. This scheme uses entangled pairs of photons. Tests known as "Bell tests" may be performed to be sure that the quantum mechanism of the link is not compromised. E91 technology is not as well established as the BB84 protocol[218].

However, there are senses in which E91 can be made stronger in the far future. These are known as "device independent QKD"[219] and "measurement device independent QKD"[220] which are claimed to be more robust than the earlier QKD. Device-independent QKD claims that significant parts of the quantum channel could in principle be placed outside the security boundary, so that e.g. photon detection or photon generation could be outsourced to an untrusted service provider.

One of the weaknesses of real world commercial QKD systems is in what is known as "side channel attacks". These exploit the physical limitations of real engineering, principally at the detectors, although such attacks are usually detectable and so counter measures could, in principle, be deployed. The important requirement is that the assumptions made in the theoretical security analyses correctly interpreted and instantiated in the real-world QKD devices. This emphasises the importance of the definition and use of commercial standards.

8.3.5 QKD networks

Several quantum key distribution networks have been trialled in the US (DARPA[221]), Vienna, Tokyo, China, Singapore, Vienna and Geneva. The challenge for this technology is switching or channelling the light through nodes and switches in the system. This must be achieved in such a way that the carriers (photons) on the route are not compromised because the nodes need to be made secure, and the carriers (photons) on the route are not compromised by information exchange between them and the nodes due to environmental decoherence.

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216 For example, from, ID Quantique, MagiQ Technologies, Quintessence Labs and SeQureNet

217 See http://www.quantumcommshub.net/

218 This is an abbreviated description. A survey of QKD protocols and applications can be found at: http://www.ma.rhul.ac.uk/static/techrep/2011/RHUL-MA-2011-05.pdf

219 See for example http://arxiv.org/pdf/1210.1810v2.pdf

220 See for example http://arxiv.org/pdf/1109.1473v2.pdf

221 DARPA = Defense Advanced Research Projects Agency

This technology is gradually becoming mature and the challenge is being addressed by the Cambridge partner in the York quantum hub and Bristol, which has a large research programme in partnership with the High Performance Networking (HPN) group.

Currently, the simple switch nodes still have to be physically secured by the service provider to be "trusted" and there is no "amplification."[222] In this situation, the switching ability allows the network to be more complex but does not extend the range of any point - to point link that passes through the switch.

If such a trusted node model is acceptable then a QKD network can be extended over long distances without specialised repeaters. However, a quantum repeater would be absolutely necessary to extend the distance over which *quantum* information (i.e. qubits) may be transmitted, or for the network to be extended where the nodes cannot be trusted. It is much more of a challenge as the photon needs to be absorbed and then re-emitted in the repeater without its state being measured, or "read". Such a technology would need to allow for errors as well as simply losses.[223]

There are potential applications of such systems across the quantum programme, not least in distributed quantum computing, and we expect that many more remain to be discovered.

8.3.6 Quantum information transmission and teleportation

The field of quantum networks is developing rapidly with many innovations being produced. For example, as mentioned in Section 4.6, quantum computers might be realised by connecting many small groups of qubits together using a reliable network. This could help mitigate the problem of scalability, or enable other functions such as secure remote or "cloud" computing. The Oxford hub NQIT[224] is doing a lot of relevant work in this area.

There are systems level developments as well, at varying levels of maturity. For example, precise timing could allow quantum and classical communications to coexist on the same carrier. BT, ADVA, NPL and others have already demonstrated this by using QKD down one channel of a multichannel fibre to implement AES[225] (rather than a onetime pad).[226] Eventually, quantum relays using solid state systems will be possible.

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222 In this context, "amplification" means a sharp reduction in the probability of photon decoherence.

223 *Technically speaking, repeaters would need to use "entanglement swapping" to stretch out the entanglement over longer distances followed by "entanglement purification" to increase its quality (at the expense of bit rate). These requirements demand some non-trivial quantum processing somewhere to effect a practical repeater. What's needed is heralded entangled pairs that can then be routed into a teleportation protocol (see next section) with payload quanta. It is important that there be no decoherence between the heralding and the measurement of the teleportation protocol. Quantum memory would be very useful, since it is otherwise a nightmare to manage the routing problem. These ideas are very advanced, but even without memory, one can get a lot done with quantum error-correction codes.*

224 NQIT = Networked Quantum Information Technologies

225 AES = Enhanced Encryption Standard; for example see AES certification etc.

226 Also see I. Choi, Yu R. Zhou, J. F. Dynes, Z. Yuan, A. Klar, A. Sharpe, A. Plews, M. Lucamarini, C. Radig, J. Neubert, H. Griesser, M. Eiselt, C. Chunnilall, G. Lepert, A. Sinclair, J.-P. Elbers, A. Lord and A. J. Shields, Optics Express Vol. 22, Issue 19, pp. 23121-23128 (2014) and Toshiba and BT network security paper

Quantum teleportation is a method of transporting a quantum state from one location to another without it being transmitted through the intervening space (or being copied). However, it does need a precursor in the form of remote entanglement and a classical message to instruct the receiver on the measurement(s) to make. It is an example of the peculiar "non-locality" property exhibited by quantum mechanics. To achieve teleportation, one member of an entangled pair plus two classical bits (i.e. standard "1"s or "0"s) need to be transmitted between the two locations. "Entanglement" can be swapped between pairs in an approximately similar manner, potentially to enable quantum relays (see previous section). See figure 40 for a conceptual view of this phenomenon[227] (gradients of lines not to scale!).

Teleportation is intuitively a surprising phenomenon, although it is not the same as the teleportation described in science fiction. Quantum teleportation does *not* apply to the transfer of matter, energy or classical information; only *quantum* information is actually teleported. To implement quantum teleportation, the transmission of classical bits via a conventional communications channel, constrained by the speed of light, is still required to make the process work.

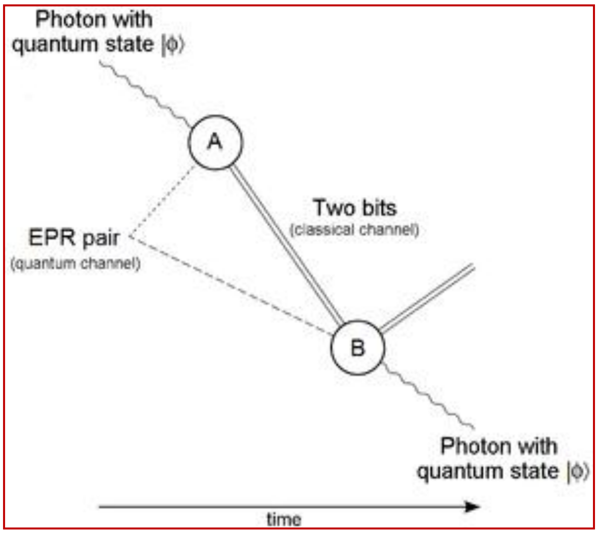

Figure 40 Quantum teleportation flow diagram
GNU free documentation licence

It is possible to entangle two separate objects remotely. This could have applications in computing, communications or sensing.[228]

A complete understanding of how teleportation may be used in a technological sense has not yet been achieved, although it has been proposed as a basis for teleportation based networking and computing[229]. It can usefully be thought of as a "primitive" from which other distributed quantum tasks can be built.

8.3.7 Quantum random number generators (RNGs)

Truly random and completely unpredictable bit streams (ideally) need to possess maximum algorithmic entropy,[230] that means that they need to pass *all* tests for randomness.[231] Quantum

[227] An EPR pair is an entangled pair of quanta (photons in this case), named after the Einstein–Podolsky–Rosen paradox that originally gave rise to the concept of Bell states. We now understand this as "entanglement".

[228] See http://phys.org/news/2011-05-matter-matter-entanglement-distance.html for example; this has more recently been demonstrated between nitrogen vacancy centres in diamond.

[229] See for example http://www.ncbi.nlm.nih.gov/pubmed/15697787

[230] Algorithmic entropy, or Kolmogorov complexity, is measured by the minimum computer program length required to generate a binary string. When the length of the program has to be as long as the string the algorithmic complexity is at a maximum. Although most possible long strings are maximally random, most of *those* can't be generated classically by conventional computers. It has been proved impossible to write a general program that measures algorithmic entropy. There are similarities with the challenge of testing for an "elegant", i.e. minimal length, computer programme.

[231] Technical note: Pragmatically speaking, if you only require them to be able to pass all tests that can be physically implemented without knowledge of a cryptographic secret, then a keyed cryptographic hash can

mechanics allows the generation of truly random numbers using techniques such as (for example) the measurement of entangled particles, or broadband measurements of the vacuum field contained in the RF sidebands of a single-mode laser. The build quality of commercial quantum RNGs is considered to be poor although "hashing down" pseudo random numbers is often "good enough" to pass many of the statistical tests.

A QKD system will need to incorporate random number generation. In addition, there are many other commercial uses for "truly" random numbers, including:

- Communications;
- Data processing;
- Secure ID;
- Simulation (e.g. Monte Carlo);
- Stochastic data processing;
- Gambling.

8.3.8 Issues and challenges

The issue of whether quantum key distribution is perfectly secure in practice has been debated extensively. Crucially, it depends on whether the technology meets the assumptions made in the theoretical security proofs. Any gap will be the cause of practical limitations and perfect security may not be possible. It is important to note that security proofs that apply only to infinite length keys will not be applicable to the finite length keys that are used in practice (such as AES keys). However, many security proofs that now address finite key lengths will provide an upper bound on information leakage.

Note that a major security concern is the denial-of-service attack. Having a single inflexible point-to-point link that contains expensive detectors is a conspicuous vulnerability.

Quantum key distribution is a 30+ year old technology and there are many reasons why it has not become commonplace. The principal ones are summarised below together with some steps that are being taken to try to mitigate the problems:

- There are practical limitations. To date, the transmission range (although having vastly improved) is still limited to ~ 150km. BB84 is fundamentally a point-to-point system, and does not integrate well with the internet and its underlying packet based protocols. New research is beginning to address this challenge by understanding how switching and more complex networks may be implemented;
- It is a physical technology and to date has needed expensive, special purpose hardware. This makes it unsuitable for cheap commodity mobile and embedded (RFID) devices. Bristol University as a partner to the York quantum hub are developing integrated transmitters

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extend entropy arbitrarily. (256 bits of key material is more than enough to inhibit all tests that usually terminate within 13 billion years.)

(Alice) that could be cheaply added to mobile phones, with the costlier (Bob[232]) units integrated into base stations e.g. ATMs or entry portals. A later step planned is to demonstrate both the Bob and the Alice subsystems in a commercial scenario;[233]

- QKD on its own only addresses part of the security problem space. For example, authentication and integrity are not easily covered. Note that *public* authentication requires public key cryptography. It can be proved that this cannot be achieved in any information-theoretic context, including quantum physics;
- A major security concern is the denial-of-service (DOS) attack. Having a single inflexible point-to-point link that contains expensive detectors is a conspicuous vulnerability;
- Current cryptography solutions are currently sufficient for short term use (legacy data is a serious concern) but will become useless in most scenarios as soon as a large scale quantum computer becomes available. New algorithms based upon cryptographic primitives that are not efficiently breakable using quantum computers are being developed and these may provide a more cost effective solution. Unfortunately, it remains to be proven that such algorithms[234] are robust against all current *and* future quantum computer algorithms;
- The development of standards is relatively immature. These will be essential, not only for interoperability and standardisation, but also to ensure that the guarantee of security is maintained. Standards are essential for all approaches, not just quantum;

The UK has delivered world class research addressing some of these practical problems. Toshiba has worked on moving implementation on dedicated dark fibre to commercial leased systems. Bristol has been working on miniaturising QKD for handheld devices. The work of Toshiba, BT, NPL and ADVA is important together with the chip scale work being undertaken by Glasgow.

Principal challenges for QKD networks:

- Faster, smaller, cheaper:
    - Better components and hardware;
- Improved understanding of vulnerability to side-channel attack;
- Implementation of security and standards;
- Integration into standard telecom networks;
- Ground to satellite, satellite to satellite and satellite to ground links to achieve worldwide coverage. This is not a mainstream agenda for the York hub but is on their agenda to explore via extensive collaboration. The Chinese had planned to launch a test system in June 2016;[235]
- New quantum protocol development;
- Applications engineering:
    - Fibre networks;
    - Mobile phone;

[232] It is a convention that the transmitter (A) is known as Alice, and the receiver (B) is known as Bob. In a similar vein, an eavesdropper on the transmission is known as Eve.
[233] Recently, Bristol have demonstrated the world's first chip to chip system
[234] Known as "post quantum cryptography".
[235] See http://www.nature.com/news/china-s-quantum-space-pioneer-we-need-to-explore-the-unknown-1.19166

  - Other mobile devices;
- Need to identify more early adopters in UK and then implement a pilot scheme to trigger early adoption. Bristol is setting up a company nominally known as KETS, which won Bristol's new enterprise competition this year.

Key challenges for quantum internet (based on distributed entanglement):

- Sources of pure single photons and entangled pairs on demand;
- Efficient quantum detectors. If superconducting detectors can be implemented through cheap, compact cryogenics and they prove to be the most efficient, they may become practical for quantum trusted or repeater nodes;
- Quantum memory (sufficiently long term);
- Network architectures;
- Protocols and applications.

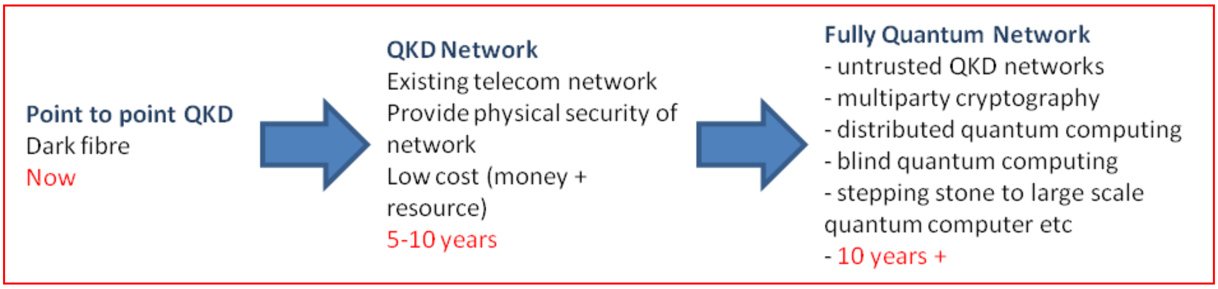

Figure 41: Evolution of quantum communications ***Courtesy Professor Tim Spiller***

As a *relatively* mature technology there is an issue of interoperability and standardisation. Well written standards are essential to ensure minimum acceptable levels for functionality and build quality, and they would stimulate the market and encourage competition.

The establishment of a ubiquitous network for quantum information is a significant challenge. It seems much more likely that such systems might be adopted for bespoke applications for research customers in the medium term, rather than for any high volume public access networks, see figure 41. In the longer term, distributed quantum computing using such systems may become commonplace although it is as yet too early to tell.

8.3.9 Summary of potential applications (York)

The following list of potential applications has been generated by the quantum communications hub at York. Activities include application development and industry engagement in many sectors, pilot projects and system integration. This includes security analysis and assurance for the crypto system.

Near term (→ 5 years)

- Off-site backup;
- Disaster recovery;
- Random number generation.

Midterm (→ 15 years)

- Secure fibre and free space networks;
    - Finance;
    - Health;
    - Defence;
    - Government;
    - Utility grids;
    - Critical infrastructure.
- Secure data storage networks;
    - Cloud storage.
- Other delivery platforms;
    - Between ships;
    - Satellites (global communications and re-keying);
    - Submarines (?);
    - Between buildings;
    - Autonomous vehicles.
- Mobile devices;
    - Free space.

Long term (20 years +)

- Distributed client-server quantum computation;
- Quantum internet;
- Quantum sensing networks.

8.3.10 Synopsis

Secure point to point transfer of coherent quanta, for the purpose of deriving cryptographic keying material (QKD), is now a commercial commodity, although improvements need to be made to enable communications via satellites or complex networks. There are many competitors, both industrial and research, that are working to make the necessary improvements.

However, special purpose hardware is required and the quantum systems only address one aspect of the security issue. The technology may, conceptually, be overtaken by so called post-quantum cryptography[236] which would consist of cryptographic primitives that are not efficiently breakable

[236] The first scheme later to become referred to as "post quantum cryptography" was proposed in 1978, see https://en.wikipedia.org/wiki/McEliece_cryptosystem

using quantum computers.[237] To understand better the comparative advantage of quantum technology will require research focussed upon the system issues.

The York hub's goal is for the UK to contribute to this market, possibly at the component level (e.g. trusted or untrusted repeaters) or the systems level (insertion of quantum channels into existing carriers) or as miniature integrated photonic devices. The York hub will have user engagement points at Bristol, Cambridge and BT Adastral Park to communicate with users (Government, military, SMEs and larger enterprises). Through such engagement, new ideas for applications and services can be developed. It is unlikely that the scientists will discover the full breadth of all truly disruptive applications by themselves.

Note that the transmission of *quantum* information will probably form an essential ingredient of later quantum technologies.

[237] Unfortunately, their immunity is very hard to prove and this has not yet been rigorously achieved.

8.4 Quantum Inertial, magnetic and electric field sensors

8.4.1 Introduction

In this section our emphasis is on sensors that are enabled by comparatively recent quantum developments, together with some comparisons with classical and more traditional quantum devices.

Sensors are of crucial importance for an immense number of applications in the civil, military and security world. Sensors also represent an important economic activity. By several measures,[238] the UK punches above its weight and has 6 - 7% of the world market in sensor components and sensor systems. In 2009 the global sensors market was estimated to be growing at 7.5%[239] per annum but more recent estimates produced by BCC Research show actual and projected growth of the global market value for sensors exceeds this, see Table 2. Growth in the sensors market appears to have been unaffected by the worldwide recession, doubling in about seven years and outstripping the projected growth.

	Actual ($ bn)	**2011 proj ($bn)** @7.8%	**2013 proj ($bn)** @7.9%	**2014 proj ($bn)** @10.1%	**2016 proj ($bn)** @11.0%
2010	56.3	(56.3)			
2011		62.8			
2012	68.2		(68.2)		
2013	79.5			(79.5)	
2014			79.5		
2015	101.9			95.3	(101.9)
2016		91.5			113.2
2017					
2018					
2019			116.1		
2020				154.4	
2021					190.6

Table 2: actual and projected global market value for sensor components and systems

238 See eg. Research carried out by the old Sensors and Instrumentation KTN in 2009 and based on a variety of sources, including the UK Statistics Authority and the German / Continental Association for Sensors Technology (AMA)

239 Frost & Sullivan: World Sensors and Instruments Report, February 2009

Sensor Type	Best classical	Quantum demonstrated	Quantum potential	Comments
Gravity	0.2 nGal/Hz$^{1/2}$ GOCE [a]	4.2 μGal/Hz ^{½} [2] <100 nGal/Hz$^{1/2}$ (10m fountain, inferred) [3]	< 1fGal/Hz$^{1/2}$	GOCE sensor unlikely to achieve this precision on Earth. Other noise sources may limit quantum sensors.[240]
Force/mass	< 1 zN/Hz$^{1/2}$ [b] 1.41 ± 0.02 ykg [c]		~ 1 zN/Hz$^{1/2}$ [d]	
Rotation	12.0 prad/s/ Hz$^{1/2}$ [e] [5]	600 prad/s/Hz$^{1/2}$ [6]	5 prad/s /Hz$^{1/2}$ [7]	Best classical being an impractical, large area (4m x 4m) ring laser gyro
Magnetic Field		200 aT/Hz$^{1/2}$ [8] 160 aT/Hz$^{1/2}$ [9]	< 10 aT/Hz$^{1/2}$	Size is important
Microwave magnetic field		77 pT/Hz$^{1/2}$ in 20 μm^3 [10]		Size matters Non-invasive
Microwave electric field sensors	1 m V/cm/Hz$^{1/2}$ [11]	30 μV/cm/Hz$^{1/2}$ [11]	100 nV/cm [11] (timescale unclear)	
Phonons	>10^{-12} W/Hz$^{1/2}$	10^{-15} W/Hz$^{1/2}$ [12]	10^{-20} W/Hz$^{1/2}$ [13]	
Short range gravitational acceleration		α~10^6 at 3.5 μm [15] ≡ 1 mGal/Hz$^{1/2}$	[15] Appendix α~10^{10} at 1 μm implies ~ 100 nGal/ Hz$^{1/2}$	Mostly fundamental research so far; size is important

Table 3 Comparison of the performance of quantum sensors with their classical counterparts (courtesy of Prof. Kai Bongs Birmingham)

The most important markets by sensors mode (irrespective of type, i.e. quantum or otherwise) are biosensors, flow sensors, pressure sensors, temperature sensors, imaging sensors, position and displacement sensors, level sensors, accelerometers, motion sensors, magnetic sensors and gas sensors.

For some types of sensing, quantum sensors can offer a step change in sensitivity or accuracy, sometimes of many orders of magnitude, or even alternative modalities not accessible to classical devices. Table 3 compares the demonstrated and potential performance of basic quantum sensors with their classical counterparts.

This is an updated table from that given in the previous version of this document[241] which contains references 1 - 15 in an Appendix. Additional references are given in the footnote below.[242]

240 https://arxiv.org/ftp/arxiv/papers/1404/1404.6722.pdf
241 Quantum Technology Landscape 2014
242 (a) http://www.esa.int/esapub/bulletin/bulletin133/bul133c_fehringer.pdf; (b) the value attributed to ref [5] appears to be a misprint. The reference (Karl Ulrich Schreiber and Jon-Paul R. Wells, " Large ring lasers for rotation sensing" Rev. Sci. Instrum. 84, 041101 (2013); http://dx.doi.org/10.1063/1.4798216) actually gives 12 prad/s. Hz-$^{-0.5}$;

When considering a sensor, it is important to assess whether any additional sensitivity or stability can be useful to its parent *system*. It is quite possible for such a device to be overwhelmed by environmental factors, for example a gravimeter (gravity field strength measuring device) can have its readings perturbed by distant waves on a sea shore, or even by imperceptible vibrations of the floor. Special measures need to be taken to deal with the interference, and may not always be possible. It is also important to take into account the *scale* of the sensor, for example some sensors are sensitive to magnetic fields on a very small length scale and some are not.

8.4.2 Matter wave interferometers

Matter waves (i.e. the behaviour of matter objects such as atoms at extremely small length scales) show interference behaviour just as do light waves or water waves. Atom interferometers coherently split and recombine atomic wave packets.[243] Because typical atom deBroglie wavelengths (~ 1/6 of an Angstrom i.e. 0.000000000016 metre) are about 30,000 times smaller than optical wavelengths, and because atoms have mass and internal structure, atom interferometers are exquisitely sensitive devices to measure inertial forces, electromagnetic fields and interactions with other atoms.

> *Solid beam splitters, such as for neutrons and photons, are not possible for atoms because of the large potential energy of atoms in solids which makes the tunnelling depth of a free atom at thermal energies much smaller than an atomic diameter. Consequently, other methods have been developed including (i) reflection from the atomic planes of a crystal surface, (ii) transmission through the periodic potential formed by a standing wave of near resonant light and (iii) transmission through a free-standing, nano- to micro-scale periodic structure. The atoms may also be guided around a track using suitable light beam geometries.*
>
> *A fourth approach is (iv) to use stimulated Raman transitions in which atoms are trapped in a superposition of two momentum states differing by two units of photon momentum. The spatial separation of the atoms is accomplished by the momentum recoil induced by the electromagnetic field used to drive the atoms from one internal state to another. This method is limited to atoms that have accessible laser transitions and frequently requires optical state preparation of the atoms.*
>
> *The two commonest methods in use today are (ii)[244] and (iv).[245]*

---

243 Here, a wave packet refers to an entity such as an atom. "Splitting" means it is "kicked" into a superposition of taking two paths at once, over to an area where its wave function interferes with itself. Differences between the two paths alters its behaviour where the two "possibilities" meet each other. Strange if we think about in everyday terms, but nevertheless true.

244 A Phys. Rev. Lett. 75 2633 (1995)

245 Kasevich M and Chu S Phys. Rev. Lett. 67 181 (1991)

[a] http://www.esa.int/esapub/bulletin/bulletin133/bul133c_fehringer.pdf

[b] G Ranjit, M Cunningham, K Casey and A Geraci, " Zeptonewton force sensing with nanospheres in an optical lattice" http://128.84.21.199/pdf/1603.02122.pdf

[c] M Kumar and H Bhaskaran, " Ultrasensitive Room Temperature Piezoresistive Transduction in Graphene Based Nanoelectromechanical Systems" Nano Lett., 15, 2562–2567 (2015)

[d] B Rodenburg, L P Neukirch, A N Vamivakas and M Bhattacharya, " Quantum model of cooling and force sensing with an optically trapped nanoparticle" Optica, 3, 318 - 323 (2016) preprint version: http://arxiv.org/pdf/1503.05233v3.pdf

The manipulating process includes several steps: preparation of atoms in initial states, splitting of atom clouds, evolution of atoms, combining of atomic wave packets, probe of internal state populations, and extraction of state information. Extraction is usually performed by illuminating the atom "cloud" using a suitable wavelength and measuring absorption or fluorescence, depending on the system setup. Strathclyde are investigating contrast interferometry whereby a complete interference pattern is obtained in one shot by scattering light off a matter wave grating. This approach could enormously improve sensor bandwidth.

8.4.3 Inertial and gravitational sensors

There are many varieties (and variations) proposed. Unlike their optical counterparts, many of these sensors are also directly sensitive to electric and magnetic fields. Such characteristics could be useful, or a nuisance, depending on the application. Since acceleration is fundamentally indistinguishable to gravity,[246] complications can often ensue when using this genre of sensor and the possibility of mixing or the effects of the local environment ("gravitational noise") needs to be taken into account.

Some of these sensors rely on "atom chip" technology, streams of ultra-low temperature atoms, or coherent condensates[247] (Bose Einstein Condensates (BEC) of such atoms) producing atoms which can be guided along paths on the surface of a "chip". The UK National Quantum Technology Hub in Sensors and Metrology is world leading in driving the technology of practical atom-based sensors for gravity (Birmingham), rotation (Nottingham, Southampton and Strathclyde), magnetic fields (Nottingham, Strathclyde, Sussex and UCL) and time (Birmingham, NPL, Strathclyde). They are moving the technologies towards commercial applications (e.g. collaborations with e2v and MSquared). World class research on interferometers using BECs is taking place at NPL, Nottingham, Strathclyde, Imperial and Oxford.

Gravity and gravity gradient sensors have a range of applications including:

- geophysics (hydrocarbon, water and mineral prospecting);
- seismology;
- engineering (vibration of structures and vehicles and process control systems), biology (animal behaviour studies), industry (the monitoring of machines to detect faults before failure) used in many industries such as car manufacturing, machining, power generation, paper production, food production, water processing, electric power plants and chemical and steel manufacturing), civil engineering;
- navigation and transport;
- Archaeology;
- Detection and location of sinkholes and tunnels;
- Detection of fissile materials.

[246] This is known as the "equivalence principle" proposed by Einstein, which led to his general theory of relativity.

[247] Loosely speaking, BECs are ensembles of atoms that are so cold that they have coalesced into a single quantum object. They are not essential for interferometry and can even be undesirable; streams of single atoms may be used provided that their wavelength is suitable.

For many applications gravity sensors, or more generally inertial sensors (accelerometers and gyros[248]), comprise simple silicon based MEMS devices which are cheap, compatible with CMOS processing, low SWAP (typically 10's mm^3 and requiring ~100 mW) and robust. These are excellent devices for many applications, although they have limited sensitivity and suffer from bias and drift.

A new generation of MEMS devices with optical readout have recently been demonstrated out of the Glasgow led Quantum Enhanced Imaging Hub, combining exquisite sensitivity with excellent long term stability and low drift (comparable to a Scintrex CG5 gravimeter). This MEMS has been used to perform a first measurement of the Earth Tides with a MEMS device.[249]

MEMS accelerometers consist of a mass-spring system encapsulated in a partial vacuum. Accelerating the device results in a displacement of the mass in the spring system which is usually, and conveniently, read using a change in the value of a capacitor. (Read out can also be done using piezo resistive, piezoelectric and thermal techniques.) MEMS accelerometers are available as 1D, 2D and 3D devices.

MEMS gyroscopes have a small vibrating mass mounted on a spring system that oscillates at 10's of kHz. Readout is via a capacitive system as it is in many accelerometers. When rotated, a perpendicular Coriolis force is exerted on the mass which becomes larger the further away is the mass from the centre of rotation. There is thus a different read-out when the mass is on opposite sides of the oscillation cycle and this is a measure of rotation rate. Such gyroscopes are typically subject to "g-sensitivity" caused by the gravitational deformation of the spring system.

Table 4 summarises the required gyro bias stability and accuracy for different device applications. Green/red shading indicates MEMS devices meet/do not meet the necessary specification.

Grade	Bias stability	Relative accuracy	Application
	Consumer and motor vehicles		
	(°/s)	(%)	
Consumer	10	3	Motion detection
Vehicle	1	0.3	Electronic stability programme
	High performance		
	(°/hr)	Ppm	
Industrial	10	10	Projectile guidance
Tactical	1	1	Platform stabilisation
Short duration navigation	0.1	0.1	Missile navigation
Navigation	0.01	0.01	Aeronautical navigation
Strategic	0.001	0.001	Submarine navigation

Table 4: grades of conventional inertial navigators

248 Accelerometers measure acceleration and gyros measure rotation. Different interferometer geometries measure either acceleration, rotation (or rate of rotation) or both and it is often very difficult to sense only one without contamination by the other. A typical source of "noise" compared with the Earth's surface for an extremely sensitive gyro is the Earth's rotation, which gives rise to the Coriolis force.

249 Measurement of the Earth tides with a MEMS gravimeter, R. P. Middlemiss *et. al.*, Nature, 531, 614–617, 2016, doi:10.1038/nature17397 also see BBC news article

Manufacturing is trending toward combined, monolithic, 6 degrees of freedom (DOF) devices to measure acceleration, rotation, magnetic field, pressure (altitude), ... to provide a complete inertial measurement unit (IMU) on a single chip. In reality, however, most IMUs are still multi-chip modules (including Application Specific Integrated Circuits, ASICs). This does relax some manufacturing problems (for instance, gyros require vacuum encapsulation whilst accelerometers require only enclosure in a partial atmosphere chamber) and technology insertion mid-cycle is easier.

> *Currently demonstrated cold atom inertial sensors can achieve accelerometer bias stabilities of ~ 0.1 ng or 0.0000000001g (but difficult to quantify exactly without an accurate gravity model), significantly superior to strategic grade MEMS accelerometers which have bias stabilities of 50 µg i.e. 0.000005g. Gyro bias stabilities for baseline cold atom devices are ~ 0.000015 °/hr, approximately 50 x better than MEMS devices.*

This superior performance of cold atom sensors includes:

- Low noise floors of ~ 1 ng $Hz^{-0.5}$ for acceleration and, for rotation, ~ 1 nrad s^{-1} $Hz^{-0.5}$;
- Lack of bias and drift;
- Rapid read out (seconds compared to minutes)

These should ensure that cold atom gravity sensors take a large share of the existing gravity surveying market and, because of their enhanced performance, create new applications in meteorology, earth sciences and surveying the built environment. Many areas of scientific research will also benefit, for example tests of Newton's Universal Law of Gravity and atom neutrality (through the Aharonov-Bohm effect). Table 5 summarises the gravitational noise expected in various application areas. Gravity gradiometry[250] will have greater utility than gravimetry for nearby sensing as it is relatively insensitive to such phenomena.

A challenge with quantum gravity sensors is that during the drop time[251] of a fraction of a second the system is sensitive to vibration or non-gravitational accelerations. As a result, a gradiometer configuration (consisting of a pair of linked gravimeters), or an isolation system, must be employed. MEMS systems, which can operate continuously, may not necessarily suffer from this problem. Thus the option of a hybrid sensing scheme, where quantum sensors are coupled to optical readout MEMS, is a potentially exciting area of further study.

Type	**Approximate magnitude**
Regional gravity variations	1000 ng
Atmospheric gravity density	300 ng/m
Simple tidal effects	100 ng
Atmospheric pressure	0.3 ng/mbar
Vehicles, people (range dependent)	1 ng
Buildings	10 ng
Tectonic plate movements	1 ng/year
Inner/outer Earth core movement	0.001 ng

Table 5: some contributions to "gravitational noise"

250 Measuring the *gradient* of the gravitational acceleration rather than its *strength* (gravimetry).

251 During a measurement, the atoms (which are in a superposition of states) are dropped and allowed to free fall in a vacuum chamber. The duration of the free fall is known as the “drop time”.

The reasons for the superiority of cold atom inertial sensors over conventional devices are due to a number of factors:

1. Cold atoms in high vacuum provide a nearly perfect inertial reference with no mechanically moving parts and, for specified isotopes, no materials inconsistencies between devices;
2. The sensor accuracy derives from the exceptional stability of the optical wavefronts of the controlling lasers and direct read-out of angular and linear displacements is straightforward;
3. Cold atom inertial sensors allow the creation of high environment suppression gradiometers; for surveying this is the only way to reduce the measurement time per point from minutes to seconds;
4. Cold atom gravimeters are absolute. This coupled with the zero-wear/no tolerances opens disruptive capabilities for long term observation applications (i.e. over years, or re-measuring years later) such as rail track monitoring, improved satellite laser ranging and monitoring of carbon sequestration.

Current sensitivity limits to measure the Earth's gravity field have been estimated by Kasevitch[252] *as* $\Delta\phi = mgzT/\hbar \sim 2 \times 10^{11}$ *radian for wavepackets separated by* $z = 10\ m$ *and a free fall time of 1 second. For a readout signal to noise,* SN*, of* 10^5 */ s, the resolution for changes in* g *is estimated as* $\delta g \ \sim \ 1/\Delta\phi * SN \ \sim 4 \times 10^{-17}$ *g. Thus for* 10^6 *seconds of data collection the resolution of changes in* g *is* $\delta g \ \sim \ 4 \times 10^{-20}$ *g.*

Noting that sensitivity scales with count rate, to approach these limits will require improved high-flux atomic sources. These require further work to develop better lasers and atom sources.

Some examples of future cold atom inertial sensors are illustrated below.

8.4.3.1 Enhanced Sagnac effect ring gyros

The Sagnac effect[253] is a rotational effect initially discovered in optics. It consists of accumulation of phase shift between two similar counter-propagating light waves around the same closed loop and this forms a rotational reference frame. It is not a relativistic effect. See figure 42.

An increase in precision of (potentially) orders of magnitude may be achieved by replacing the laser by a gas of atoms in the ring to be used as the gain medium. The refractive index of certain species may be controlled externally, and, if this index can be appropriately manipulated, significantly more wavelengths can be enclosed in the ring. This will lead to a greatly enhanced phase shift when the ring is rotated and in turn this will lead to greater sensitivity.

8.4.3.2 Sagnac matter wave interferometer

The Sagnac effect applies equally to matter waves. However, the relative sensitivity to phase of matter waves is of the order of 10^{10} greater than in optical systems. Strathclyde are studying matter wave interferometry on BECs in ring traps.[254]

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[252] See calyptus.caltech.edu/qis2009/documents/kasevichQIS0409.pdf

[253] See http://en.wikipedia.org/wiki/Sagnac_effect

[254] A Dinkelaker, PhD Thesis 2013. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.699.9130&rep=rep1&type=pdf

In principle, sensors with the sensitivities estimated by Kasevich could be realised that would be able to measure rotational effects down to the level of the effects of general relativity in the local environment, or tidal effects caused by the moon and even (potentially) the planets. A number of variations of the principals involved have been proposed, such as two component BECs and superpositions of rotation states. Durham, Cambridge, Sussex, Nottingham (the trapped ring gyro work, guided sensors within the Hub and the EU projects Matterwave and QTEA) and NPL are studying this phenomenon.

Guided matter wave sensors ideally use an atom laser that produces a coherent matter wave, akin to the continuous wave emitted by an optical laser (although a population inversion is not required). The principle difference is that the atoms cannot (easily) be created and destroyed; they need to be obtained from a cold atom reservoir. A continuous stream of atoms above the condensation temperature is useful to avoid intermittent operation. This might be achieved with a guided wave system and would provide a more realistic analogue of optical interferometers, although discrete packets of atoms may be used as an intermediate step.

A serious problem arises when an atom interferometer is configured to be in the vertical plane. If the atom packets (waves) are travelling too slowly they will not have sufficient momentum to reach the top of the device and will simply fall to a heap at the bottom. In that scenario, a gradient in potential facilitated by a light field may be applied counter this problem. The subject of "painted potentials[255]" is an exciting, newly emerging field.

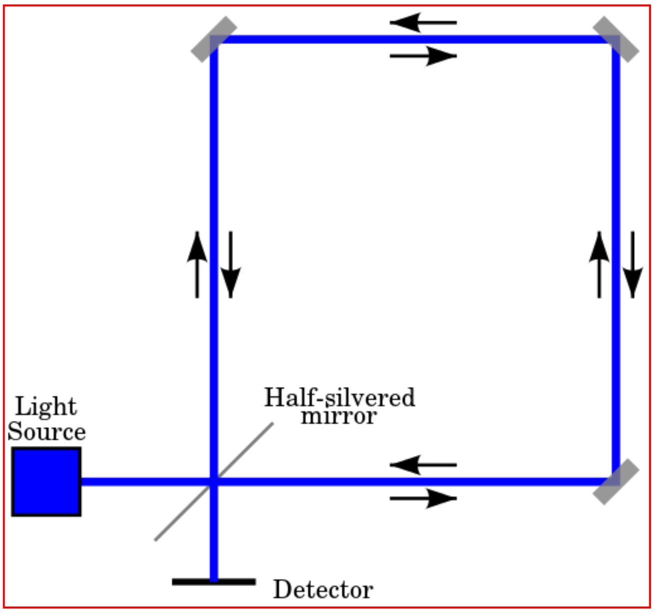

Figure 42: Schematic of a Sagnac interferometer. In the atomic version, the wavefunction is split into a superposition of states that travel around the apparatus in opposite directions.

[255] A "painted" potential. See M Boshier *et. al.*, " Waveguide BEC Interferometry with Painted Potentials" Bulletin of the American Physical Society (2016)

In the context of a gyro device, Dowling[256] discussed the quantum phase-noise limit to the sensitivity of a Mach-Zehnder interferometer in which the incident quantum particles enter via two input ports. He showed that if the incident particles are entangled and correlated properly, then the phase sensitivity asymptotically approaches the Heisenberg limit (1/N), for large N, where N is the number of atoms incident per unit time. In a one input port device, the sensitivity can be at best 1/√N. Although this is likely to be many years away, he proposed that an atom-laser could be used to obtain the required entanglements to achieve this Heisenberg limited sensitivity with atomic matter waves.

Guided interferometers still have to reach the same sensitivity as devices based on freely falling atoms, although they might have higher sensitivity in the future. Difficult technical challenges come into play when designing for “non-ideal”, i.e. realistic, environments such as vibrations, rapid rotation or changes in geometry due to temperature fluctuations.

A practical atom laser gain element needs to emit coherent matter waves into two directions of a wave guide formed into a micro-fabricated ring resonator. The first pulsed sodium atom laser was demonstrated at MIT by Ketterle *et. al.* in 1996. A pseudo-continuously operating atom laser, with a duty cycle of 1%, was demonstrated for the first time by Hänsch, Bloch and Esslinger at the Max Planck Institute for Quantum Optics in 1999.

A directional coupler[257] allows differential detection of the atoms in the two arms using quantum state manipulation via an analogy with a heterodyne detector.[258] Estimated sensitivity for this configuration is ~ 10^6 improvement over state of the art (this will be dependent on several parameters such as atomic flux from the atom laser). All of the *components* have been demonstrated in the lab, the requirement is now for the *system* to be realised. Groups at NPL, Strathclyde and Nottingham are working on guided wave ring interferometers.

> *The brightest atom lasers so far reported use time-dependent adiabatic potentials formed by applying a radio-frequency field to a magnetic Ioffe-Pritchard trap (see figure 43). By changing the frequency and amplitude of this RF field the trapping parameters including the trap depth can be varied. At large frequencies, i.e. high trap depths, it is possible to trap thermal clouds. As the frequency is lowered the atoms cool by forced evaporation and for sufficiently low trap depths a BEC is formed. The atom laser beam forms as the trap depth reaches the chemical potential of the condensate. The figure below shows recent results[259]. The same group has recently shown that for large RF detuning the atom flux scales as the 3/2 power of the detuning.[260]*

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256 "Correlated input-port, matter-wave interferometer: Quantum-noise limits to the atom-laser gyroscope" J P Dowling, Phys Rev A, 57, 4736 - 4746 (1998)

257 This is conceptually similar to the half silvered mirror used to split a light beam.

258 A description of such a device may be found in http://www.dtic.mil/dtic/tr/fulltext/u2/a424482.pdf

259 V. Bolpasi, N. K. Efremidis, M. J. Morrissey, P. Condylis, D. Sahagun, M. Baker, and W. von Klitzing, New Journal of Physics 16, 033036 (2014) An ultra-bright atom laser.

9. I. Lesanovsky and W. von Klitzing, Phys. Rev. Lett. 99, 083001

260 "Adiabatic potentials and atom lasers" V Bolpasi and W von Klitzing, Romanian Reports in Physics, Vol. 67, No. 1, P. 295–303 (2015)

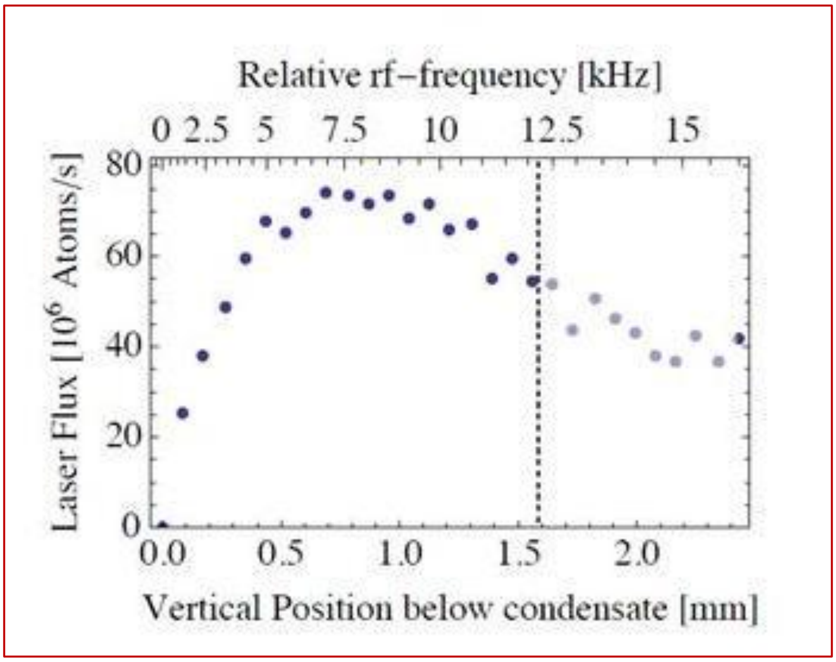

Figure 43. The flux of an atom laser reported by Bolparsi[261]

8.4.3.3 Mach-Zehnder and Michelson BEC interferometers

Matter wave analogies of optical counterparts to Mach-Zehnder[262] and Michelson [263] interferometers are beginning to be realised. The key component is the analogy of the half silvered mirror used in optics; this may be implemented as a semi-reflective potential barrier or an appropriately configured micro-grating. Strathclyde and NPL are performing some work on this technology.

The basic layout of a Mach-Zehnder interferometer is shown in figure 44 (below). Changes in the relative path lengths or unequal phase shifts due to inertial or other forces will result in changes in the ratio of outputs from the recombiner.

[261] V. Bolpasi, N. K. Efremidis, M. J. Morrissey, P. Condylis, D. Sahagun, M. Baker, and W. von Klitzing, New Journal of Physics 16, 033036 (2014) An ultra-bright atom laser
9. I. Lesanovsky and W. von Klitzing, Phys. Rev. Lett. 99, 083001

[262] See http://arxiv.org/pdf/1303.1030v3.pdf

[263] See for example: http://arxiv.org/ftp/cond-mat/papers/0407/0407689.pdf

These devices may be used to make a wide variety of precision measurements and have been demonstrated to surpass classical sensors in sensitivity to gravitational and inertial effects. Useful parameters to measure, depending on application, are rotation, gravitational field strength and gravitational field gradient. It is likely that in the ~ 5 - 10-year timescale a gravitational "imager" will be demonstrated, sensitive to small variations of the local field with the ability to compile a local "density map" of energy and matter.[264]

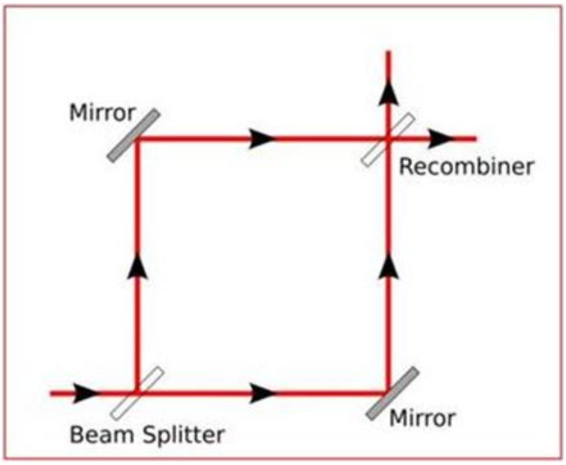

Figure 44: Layout of a Mach Zehnder interferometer. The wave packets are split between the two different routes.

The practical use of existing classical and quantum gravimeters is limited by ground vibrations and seismic noise with the baseline coming from wind and wave activity. The respective noise floor can be reduced by averaging, which is currently limited to a few minutes in spring-based sensors due to drifts. Quantum gravity sensors with freely falling atoms are absolute sensors and hence drift-free, allowing further averaging to reduce more fundamental sources of noise. However, this again increases the measurement time and assumes the target is static although this cannot be used for change detection. Atom interferometers with freely falling atoms allow construction of gravity gradient sensors with intrinsic suppression of ground vibration noise. This enables the ability to achieve a combination of a speed-up of measurement times and better precision, as an engineering trade off. In addition, they reduce alignment requirements by a factor of 100, allowing tolerances of a few degrees in practical applications. This promises a step-change in the applicability of gravity measurements in field operation, reducing survey times from days or even weeks to minutes or hours (depending on the survey area). Birmingham has a world-leading cross-disciplinary program investigating gravity gradient sensors and their applications.

These sensors and their applications in gravity imaging and navigation are under investigation in the UK National Quantum Technology Hub in Sensors in Metrology (gravity: Birmingham; rotation: Nottingham, Strathclyde and Southampton [using free atoms and sophisticated laser pulse shaping]).

It is also possible to use a quantum superposition of momentum eigenstates to measure projectile body acceleration – a time based rather than space based approach. This method is currently under study at Aberdeen University as part of an MoD funded Anglo-French PhD.

8.4.4 Atomic spin gyros

ASGs (Atomic spin gyroscopes) use ensembles of atomic spins (the nuclei of atoms in the gas phase) to sense rotation. These can be realised as compact, possibly chip scale, devices capability of sensing with high precision but many challenges need to be overcome to fabricate deployable devices, e.g. for inertial navigation systems.

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264 There are two main challenges in imaging gravity. The first is the detection of the gravitational field, preferably via its gradient for short ranges (for reasons *op. cit.*). The second is the formation of the image from the sensor outputs; this is a very difficult "inversion problem" where the mass configuration id ambiguous and special techniques need to be applied.

At their simplest ASGs comprise atoms of one or more atomic types with non-zero nuclear spins in a vapour cell with buffer gas. Initially in the 1960s and 1970s species such as ^{199}Hg and ^{201}Hg gas cells were used placed in a constant, uniform, reference magnetic field B_z. Because of the non-zero nuclear spin the nuclei will precess around the external magnetic field at the Larmor precession frequency, $\nu_L = (\gamma_n/2\pi)B_z$ where the gyromagnetic ratio is $\gamma_n = (e/2m_P)g_n = g_n\mu_N/\hbar$. ($n$ denotes the nuclear isotope and m_P, g_n and μ_N are, respectively, the proton mass, the isotope g-factor and the nuclear magneton.) A detection laser which is fixed in the gas cell coordinate system detects the precession frequency of the atoms plus that of the gas cell, ν_{cell}. Since ν_L can be calculated, given g_n and B_z, the gas cell rotation rate is obtained by subtracting ν_L from ν_{cell}.

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Although ASGs have advantages over conventional gyros (no moving parts, high precision and high impact resistance, they require very precise control of the magnetic field which needs superconducting magnets and shielding. This makes practical, high precision ASGs expensive and bulky. They also exhibit long start up times, and (to date) a disappointing sensitivity in comparison with their theoretical best.

A way to overcome problems due to an unstable reference magnetic field is by using two nucleon species in a so-called co-magnetometer ASG. These devices are based on a bias magnetic field tuned to the point at which the two spin species are strongly coupled forming a hybrid oscillator insensitive to transverse magnetic field and gradients. The co-magnetometer ASG detects the shift of the polarisation's orientation of the nuclear spins caused by the inertial rotation. The sensitivity is greatly enhanced by using a high density alkali metal vapour in a spin exchange relaxation free regime. Remaining challenges include the long start up time, and low dynamic range and bandwidth.

However, there are many groups around the world addressing these challenges. Using ^{129}Xe-Cs[265] co-magnetometers, sensitivities of 7×10^{-5} ° s^{-1} $Hz^{-0.5}$, a reduction from several hours to ten minutes start up time, an improvement of two orders of magnitude in the dynamic range and one order of magnitude improvement in bandwidth have been achieved.[266] Novel ASGs are in development in which two noble-gas isotopes and alkali-metal atoms are coupled together in a co-magnetometer ASG configuration; such devices will utilise the features of the two types of ASGs to form a 3-axis system.

8.4.5 Atomic single ion and optical lattice clocks

As clocks become more accurate, they become more useful for sensing gravity, with a possible long term goal of a comprehensive system forming a gravity "imager". Single ion and optical lattice clocks of sufficient accuracy, and with appropriate integration time, may be used to detect differences in gravity potential, i.e. the height above the Earth's geoid.

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[265] The electron spin of the Cs is coupled to the nuclear spin of Xe, hence the Cs isotope used is not critical

[266] Fang *et. al.*, " Atomic spin gyroscope based on ^{129}Xe-Cs comagnetometer" Chinese Science Bulletin, Applied Physics Letters, **58**, 1512 - 1515 (2013); Fang *et. al.*, " Advances in Atomic Gyroscopes: A View from Inertial Navigation Applications", Sensors, 12, 6331 - 6346 (2012) http://www.mdpi.com/1424-8220/12/5/6331/pdf

We need to understand that, fundamentally, gravity potential is itself not an observable and depends on what is known technically as a *gauge*. That means that we need two clocks to sense *differences* in potential, which we know as height. The notion that clocks "run more slowly in a gravitational field" (i.e. the red shift) is only true when compared with a clock that is outside, i.e. further away.

Absolute height comparison (potential difference) has value for Earth coordinate system definition, construction projects, ballistic flying objects, etc. As an ensemble, clocks can measure field strength, gradient and higher order derivatives. Some experiments have been performed, but the particular mix of sensors that should be used to achieve the best performance will be discovered by future R&D.

8.4.6 Optical lattice atomic sensors

An optical lattice is a lattice of trapped "cold atoms" which can be implemented in 1, 2 or 3 dimensional arrays and held in place by a set of interfering optical beams. There are immense technical challenges involved, not the least being the ideal of placing a single atom in every lattice position to achieve the ideal performance and characteristics. There are many sensing applications of this configuration. For example, a "Wannier-Stark ladder" may be configured to measure gravitational fields and the characteristics of short range effects such as Casimir or van der Waals forces. Potentially, these systems could also be used to measure gravitational and inertial parameters used for navigation and orientation, also with unprecedented sensitivity. Currently these systems are more than a factor of 100 less sensitive than free fall systems, but they carry the promise of ultimately reducing system size to sub-cm level.[267]

8.4.7 Magnetic field sensors

Magnetic field sensors can be categorized into four types depending on the magnitude of the measured field. If the targeted magnetic field is larger than the Earth's magnetic field (≤ 60 μT), the sensor does not need to be very sensitive. To measure fields larger than the geomagnetic noise (~ 0.1 nT),[268] better sensors are required. For magnetic anomaly detection, arrays of sensors are required to cancel the spatial-correlation and to measure fields less than the geomagnetic noise, much more sensitive magnetic field sensors are needed; such sensors are used in medical and biomedical applications, such as MRI and molecule tagging.

There are many magnetic sensor devices including:

- Hall effect sensors;
- Magneto-diodes;
- Magneto-transistors;
- Anisotropic Magnetoresistance Magnetometers (AMR);

[267] At this level, the gravity potential and its derivatives (gradients and gradients of gradients etc. will exhibit a fine grained "lumpiness" due to objects in the local environment.

[268] Note in this section that the prefix "n" and similar indicate order of magnitude e.g. n= nano (see appendix 8.5) and Tesla is the unit of magnetic field strength.

- Giant Magneto-Resistance (GMR) magnetometers;[269]
- Magnetic tunnel junction magnetometer;
- Magneto-optical sensor;
- MEMS sensors (which sense the mechanical motion of the MEMS structure due to the Lorentz force acting on the current-carrying conductor in the magnetic field);
- Electron Tunnelling based MEMS sensors;
- Nuclear precession magnetic field sensors;
- Optically pumped magnetic field sensors;
- Fluxgate magnetometers;
- Search coil magnetic field sensors.

The superconducting quantum interference device (SQUID) was the most sensitive available magnetic sensor for decades. It requires cryogenic temperatures to operate (usually a liquid helium system) and the devices can be difficult to set up. It uses the phenomenon of quantum interference in a superconducting circuit to measure extremely small vector magnetic fields. Their noise levels are as low as 3 fT $Hz^{-0.5}$ in commercial instruments and 0.4 fT $Hz^{-0.5}$ in experimental devices. Commercial SQUIDs can achieve a flat noise spectrum from less than 1 Hz up to tens of kilohertz. Competing spin exchange relaxation-free (SERF) atomic magnetometers so far demonstrated have sensitivities of about 200 $aT^{-0.5}$ and reach competitive noise floors but in only narrow frequency ranges.

There are many novel realisations of quantum magnetic sensors offering superior performance over a range of length scales; some examples are outlined below:

- Nitrogen Vacancy (NV) centres in diamond[270] (+ entangled centres). Nitrogen vacancy centres are very sensitive to magnetic fields at the smallest scale, i.e. sub-micrometre. These may be remotely entangled to provide greater sensitivity (a naive analogy is the Wheatstone Bridge). NV centres are not the only sensitive impurities that can be embedded in diamond as an impurity, however, they are the most widely studied. Others include silicon and germanium. There are several centres of activity in the UK including Oxford, Cambridge and Warwick universities*;*

  In 2016 Warwick developed a novel technique to sense all the components of a 3D magnetic field simultaneously[271] with enhanced precision. The method is being explored for experimental implementation by the NV centre group at Warwick. The main application would be room temperature MRI scanners. The same method can also be used for any 3D field sensing such as acceleration, velocity, rotation, gravitation.

  Recently an NV centre device was demonstrated with a projected photon-shot-noise-limited sensitivity of 0.2 V.cm^{-1} Hz$^{-0.5}$ and 0.1 nT Hz$^{-0.5}$ respectively probing electric and magnetic fields. Operation of a prototype diamond-Electromagnetically Induced Transparency (EIT) magnetometer measured a noise floor of < 1 nT Hz$^{-0.5}$ for

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269 GMR is a thin film quantum phenomenon that is used in today's hard disk drive to achieve multi-terabyte storage in small packages. The 2007 Nobel Prize in Physics was awarded to Albert Fert and Peter Grünberg for the discovery of GMR

270 An NV centre is a point defect in a diamond lattice which consists of a nearest neighbour pair of a nitrogen atom and a lattice vacancy which together substitute for a carbon atom.

271 Baumgratz and Datta, 'Quantum Enhanced Estimation of a Multidimensional Field' Phys. Rev. Lett., 116, 030801 (2016)

frequencies > 10 Hz and an Allan deviation of 1.3 ± 1.1 nT after 100 s integration demonstrating the potential of such devices for a range applications including quantum-optical memory, precision measurement and tests of fundamental physics;

- Bose-Einstein condensates offer the highest sensitivity at the micrometre scale and allow the simultaneous capture of one-dimensional field maps. Trapped Bose-Einstein condensates uniquely combine single micron resolution with pT $Hz^{-0.5}$ sensitivity while acquiring large field-of-view (100s of microns) single-shot images in less than a millisecond. This type of sensor is under study at the University of Nottingham;
- Magnetic field sensing beyond the standard quantum limit using NOON[272] States;
- Time resolved magnetic sensing with NV centres in diamond; magnetic resonance imaging using nanoscale magnetometers;
- Hall probes;
- Magnetic force microscopes;
- Atomic vapour cell magnetometers based on atomic ensembles and operating at room temperature sensors outperform SQUIDs, reaching the best sensitivities of all sensors in the aT $Hz^{-0.5}$ range and at above mm scale. These devices are studied at Nottingham, NPL, Strathclyde, Glasgow nanocentre and Southampton University;
- Atomic vapour cell magnetometers also reach sub-femtoTesla sensitivity for oscillating magnetic fields up to MHz frequencies, opening applications in healthcare (magnetic induction tomography) and in explosive detection. UCL (Renzoni) performs leading work in this area;
- Trapped ions can be used for the detection of the magnetic fields with nanometre resolution[273] with a measurement sensitivity of 15 pT $Hz^{-0.5}$;
- The NIST chip scale ^{87}Rb magnetometer operating in the spin-exchange relaxation-free regime allowing high magnetic field sensitivities is useful in applications requiring array-based magnetometers where RF magnetic fields can induce cross-talk among adjacent sensors. Changes in flux density of 2 pT $Hz^{-0.5}$ at 10 Hz[274] have been measured, limited principally by photon shot-noise and weak optical pumping.

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[272] A NOON state is a quantum-mechanical many-body entangled state in which N particles in mode *a* are in a superposition with zero particles in mode *b*, and vice versa. The particles must obey Bose-Einstein statistics and are usually photons. Such states in their conventional form are probably too difficult to set up and fragile to be of much practical use. The magnetic (spin) version of N00N states are called GHZ (Greenberger-Horne-Zeilinger) states. They are easier to produce than N00N states, though still quite fragile. Recent quantum control techniques can be of help to alleviate this.

[273] Reference: Nature 473, 61–65 (05 May 2011) http://arxiv.org/pdf/1101.4885v1.pdf

[274] "An optically modulated zero-field atomic magnetometer with suppressed spin-exchange broadening" R. Jiménez-Martínez, S. Knapp and J. Kitching, Rev. Sci. Instruments, 85, 045124 (2014); public version available HERE

In many experimental contexts, spatial resolution is as important as sensitivity. The literature is extensive and a full exposition of the sensors available is beyond the scope of this report. Figure 45 shows performance vs resolution for the most important families, and references used to construct the graph are contained in the appendix to the Quantum Technology Landscape 2014 document.

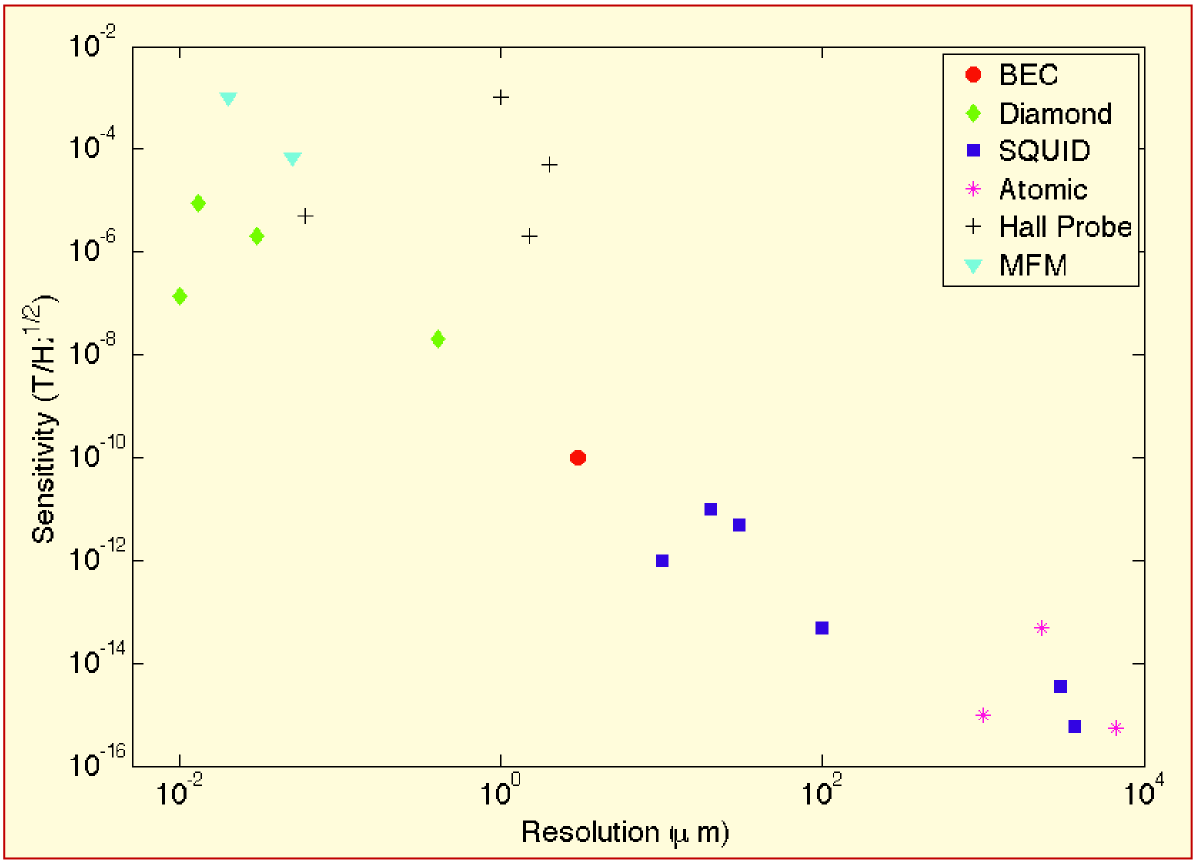

Figure 45: Chart of sensitivity versus resolution for magnetometers ***courtesy of Prof. Peter Krüger Nottingham University***

Meanwhile, magnetometers using atomic vapour cells continue to be refined.[275]

8.4.8 Quantum current standards

The basis of synchronous manipulation of individual electrons in solid-state devices has its origins in single electronic devices first produced in the 1990s. Cooled, ultra-small structures allow the addressing of electrons singly. Thus a fundamental-level check of voltages measured using the Josephson effect and resistances from the quantum Hall effect against current measured via Ohm's law becomes possible. A number of attempts to create a metrological current source that would comply with the criteria of extreme accuracy, high yield and implementation have been reported using a number of different technologies which can be called collectively single electron pumps (SEPs).[276]

Electron pumps are used to allow a single electron to pass through a gate each clock cycle. A reliable SEP pumps precisely one electron at a time to ensure accuracy, and pumps them quickly to generate

[275] http://physicsworld.com/cws/article/news/2013/apr/24/atomic-magnetometer-is-most-sensitive-yet

[276] See http://www.npl.co.uk/science-technology/quantum-detection/research/quantum-current-standards/

a sufficiently large current. These techniques can be used to generate very precise electrical currents, which might be used to compile the unit of current, the ampere. Single electron devices may also be a building block in future quantum circuitry and can be used to test the understanding of the laws of quantum mechanics.

8.4.8.1 Single electron pump (SEP) technologies[277]

Nanoscale SEPs have been realised in Australo-Finnish research using silicon-based quantum dot structures with tuneable tunnel barriers providing the source of quantized current.[278] The charge transfer accuracy of the pump can be enhanced by controlling the electrostatic confinement of the dot using engineered gate electrodes. Improvements in the operational robustness, as well as suppression of nonadiabatic transitions that reduce pumping accuracy, are achieved via small adjustments of the gate voltages. Output currents > 80 pA have been achieved with relative uncertainty below 50 parts per million.

The world's first graphene SEP was announced by NPL in November 2015 and demonstrated the ability to detect the presence or absence of individual electrons with unprecedented accuracy.[279] The technique, developed jointly by NPL's Quantum Detection Group and the University of Cambridge, is capable of counting the number of electrons trapped in an electron pump with an accuracy of one part per million. NPL and Cambridge used a quantum point contact to measure the number of electrons inside the pump confined in an area ~ 250 nm in diameter. Key to the measurement was cancelling intrinsic electronic noise. The experiment yielded new insights into one electron processes such as back-tunnelling but there were instances when the pump loaded two electrons. In one million attempts to load two electrons into a tuned device, a single electron was loaded in only one instance, a factor of 100 improvement over the best previous result.

Graphene has reinvigorated research into traditional metallic electron pumps by fabricating them out of graphene. Previous metallic SEPs made of aluminium are very accurate but pump electrons too slowly for a practical current standard. Graphene's semi metallic electronic structure allows electrons to transit on and off the quantum dot very quickly creating a near gigahertz frequency signal, sufficient for a current standard.

> *Tuneable-barrier electron pumps comprise a conducting channel etched into a two-dimensional electron gas. The entrance and exit gate electrodes cross the channel and create potential barriers when negative bias is applied. When a time dependent drive signal is applied to the entrance gate the barrier can be lowered or raised. If the exit gate barrier is kept high, electron tunnelling and thermal noise is suppressed. Multiple electrons,* n*, can be transported with each pump cycle of duration 1/f, but controlled by the height of the exit barrier resulting in current plateaus at* $I = nef$*. The best results so far were achieved by Giblin et. al. in 2012*[280] *and an upper limit for the accuracy of the pump of 1.2 ppm was estimated although achievable accuracy was predicted to be at the 0.01 ppm level.*

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[277] See eg. http://arxiv.org/pdf/1208.4030.pdf

[278] Rossi *et. al.*, " An Accurate Single-Electron Pump Based on a Highly Tunable Silicon Quantum Dot" Nano Lett., 14, 3405–3411 (2014) see http://arxiv.org/pdf/1406.1267v1.pdf

[279] S. P. Giblin *et. al*. "High-resolution error detection in the capture process of a single-electron pump" Applied Physics Letters (2016). DOI: 10.1063/1.4939250

[280] S. P. Giblin *et. al*. Nat. Commun. 3, 930 (2012).

Hybrid turnstile single electron transistors (SETs) based on a SINIS (Superconductor–Insulator–Normal metal–Insulator–Superconductor) devices utilize superconductivity. They are simple to design and operate and errors can be efficiently suppressed (eg. by lowering operating temperatures, modifying electronic band structure, improving device fabrication and optimising electric signal waveforms). Many devices can be put in parallel to achieve high currents, and recently a stack of 10 turnstiles has allowed demonstration of a current in excess of 100 pA. Currently accuracies of 1 in 10^4 have been achieved.

A refinement of SEPs as current standards would be accurate error counting. By measuring the charges at various points of more complex current sources with multiple pumps, it is possible to determine whether an electron was transported or not. The nominal value of the current is then corrected by the number of pumping errors. These self-referenced single-electron current sources are immature with pumping frequencies currently limited to ~ 30 Hz by the detection rates of the charge detectors.

Quantum dot pumps, with verified uncertainty of the 150 pA output current at the level of 1 ppm, and with theoretically predicted 0.01 ppm uncertainties, and SINIS turnstile devices are strong candidates for realising a future quantum standard of the Ampere. Because the electrons in SEPs also hold information about the electron spin, single electron pumps may find uses in quantum information processing because the spin encoded information can, in principle, remain coherent. Other - research - applications include single charge counting experiments to study energy fluctuation relations to increase understanding of steady state systems in conditions of non-equilibrium, testing fundamental statistical mechanics and thermodynamics of classical and quantum systems.

8.4.9 Imaging sensors for electromagnetic and electric fields

Imaging sensors for electric or magnetic fields can be made using periodic or non-periodic arrays. For example, it might be practical to replace the "skull cap" containing electrodes, or the more sophisticated SQUID[281] helmet mounted array, with an array of atomic vapour cells operating at room temperature to realise a brain imaging system.

Speculatively, one could envisage sprinkling a surface with diamond nanoparticles containing NV centres or endohedral fullerenes.[282] A laser could scan these and the fluorescence could be recorded using an imaging system. This would result in a number of spatially random data points. However, a clear representation of the underlying field could be obtained via an accurate knowledge of the scan position of each return and the reconstruction technique of compressive sensing.[283] With careful and precise engineering of the laser system the positioning of each data sample could be found automatically.

Bose-Einstein condensates trapped on an atom chip form the basis of a microscopic sensor that acquires high-sensitivity images of magnetic field maps acquired with single micron resolution. Different from conventional scanning probes, the image is obtained in a single shot (< 1 ms) in one

281 SQUID = Superconducting Quantum Interference Device (requires cryogenics)

282 These are buckyballs containing trapped atoms. The buckyballs act as cages and bestow specific properties on the trapped atom.

283 For a reasonably easy to understand article, see THIS.

dimension, so that a full two-dimensional image can be reconstructed from merely scanning along the remaining direction.

The Sussex group of Winni Hensinger pursues ion array sensors for static and oscillating magnetic fields, which could potentially find a use in medical diagnostics.

8.4.10 Imaging sensors for magnetic fields

Naturally occurring and man-made magnetic fields, measured in magnetic induction B, cover 29 orders of magnitude, see Table 6. Unsurprisingly, different methods are required to span this huge range. Here detection, and only imaging in the weak field regime, will be considered.

A SQUID (superconducting quantum interference device) is a very sensitive magnetometer used to measure very small magnetic fields. The devices use superconducting Josephson junctions, and are sufficiently sensitive to measure fields greater than 5 aT after a few days of averaged measurements; noise levels are as low as 2 fT $Hz^{-0.5}$. There are two main types of SQUID: direct current (DC) SQUIDS invented in 1964 and radio frequency (RF) SQUIDS invented in 1965. RF devices can work with only one Josephson junction which makes them cheaper to produce but at the cost of reduced sensitivity.

Optical atomic magnetometers (OAMs), sometimes called spin exchange relaxation free magnetometers (SERFs), are also sensitive magnetic field sensors. fT sensitivity is possible and, in addition, OAMs are vector magnetometers capable of measuring all three components of the magnetic field simultaneously. OAMs are potentially more sensitive than SQUIDs and do not require cryogenic refrigeration (which necessitates complicated handling and may incur heavy running costs for liquid He and maintenance) but are orders of magnitude larger in size (~1 cm^3) and must be operated in a near-zero magnetic field. They were first developed at Princeton University in the early 2000s but there are now groups around the world pursuing research.

OAMs measure magnetic fields by using lasers to detect the perturbations of vapour phase alkali metal atoms. Spin exchange relaxation, which usually randomises the orientation of atomic nuclear spins, is avoided in these magnetometers by using high (10^{14} cm^{-3}) densities of atoms and very low magnetic fields under which conditions the atoms exchange spin quickly compared to their magnetic precession frequency thereby preserving spin coherence. As well as cryogen free operation and equal or better sensitivity per unit volume than SQUIDs, all-optical measurement facilitates imaging and eliminates interference.

Order of magnitude		Example[284]	
10^{-18}	atto-Tesla	5 aT	SQUID magnetometers on Gravity Probe B gyroscopes measured fields at this level over several days of averaged measurement
10^{-15}	femto-Tesla	2 fT	SQUID magnetometers on Gravity Probe B gyros measured fields at this level in about one second
10^{-12}	pico-Tesla	≤ 1 pT	Magnetic fields in the human brain
10^{-9}	nano-Tesla	≤ 10 nT	Magnetic field in the heliosphere
10^{-6}	micro-Tesla	24 µT	Magnetic field near tape recording head
		31 µT	Strength of Earth's magnetic field at the Equator
		58 µT	Strength of Earth's magnetic field at latitude 50°
10^{-3}	milli-Tesla	0.5 mT	The suggested exposure limit for cardiac pacemakers by American Conference of Governmental Industrial Hygienists
		5 mT	Strength of a typical fridge magnet
10^{0}	Tesla	1.25 T	Strength of a modern neodymium–iron–boron rare earth magnet able to lift more than 9 kg and erase information on credit cards.
		2 T	Typical loudspeaker magnet or found in the core of a domestic mains transformer
		< 11.7 T	Strength of medical magnetic resonance imaging instruments
		23.5 T	Field strength of the magnet in a 1 GHz NMR spectrometer
		36.2 T	Strongest continuous magnetic field produced by non-superconductive resistive magnet.
10^{3}	kilo-Tesla	2.8 kT	Strongest (pulsed) magnetic field ever obtained in a laboratory (at VNIIEF in Sarov, Russia, 1998)
10^{6}	Mega-Tesla	< 100 MT	Strength of a neutron star
10^{9}	giga-Tesla	< 100 GT	Strength of a magnetar

Table 6: Naturally occurring and man-made magnetic field strengths. See appendix 8.5 for an explanation of prefixes.

Atomic co-magnetometers are sensitive atomic magnetometers which measure the nuclear spin precession of a medium containing two different nuclear spins, usually alkali and noble gas atoms. Their development is particularly active for applications as very sensitive gyroscopes and is discussed above in section 4.5.4

The electrical currents in muscles caused by depolarisation-repolarisation processes produce corresponding time-varying changes in the magnetic fields around the tissue. Detection of these electrical currents has become an important medical diagnostic technique, especially for cardiac problems. Electrocardiography (ECG) was an early diagnostic technique which is inexpensive, non-invasive and portable. However, it fails to provide critical information about the electrophysiological activity of the heart and for the detection of coronary artery disease is inadequate for accurate diagnosis. Magnetocardiography (MCG) measures magnetic signals and augments ECG by making visible current loops for which the ECG is blind and magnetic field imaging (MFI) is becoming a

284 See appendix 8.5 for an explanation of the abbreviations used for units in this table

valuable additional cardiac diagnosis method for instance in heart diagnosis to infer the risk of sudden cardiac death.

MFI uses sensitive devices, currently SQUIDs but likely to be OAMs in the future, to measure the epi-cardiac magnetic fields using a multichannel device, invert the data taking into account the electrical conductivity structure of the torso and produce images from which it is possible to locate the source of the magnetic activity, for instance sources of abnormal rhythms.

Early attempts at MCG required large coils placed over the chest, connected in opposition to cancel out the relatively large magnetic background. Heart signals were seen, but were very noisy. Subsequently, sensitive SQUIDs and magnetically shielded examination rooms have made MFI a practical diagnostic technique which is slowly being adopted around the world. Initially the focus is on cardiography but applications in brain imaging are emerging and uptake will accelerate with the development of OAM imagers which can operate at ambient temperatures.

8.5 Quantum imaging

Quantum Imaging uses quantum mechanics and the devices it inspires to make imaging systems and components that either surpass the performance of the state-of-the-art and/or provide functionality not hitherto possible.

Quantum Imaging falls into three broad themes:

- Enabled by quantum technology;
- Enabled by quantum physics;
- Quantum enhanced photonic imaging sensors.

Technology–enabled imaging techniques encompass photonic devices that are designed around single-photon measurement, including counting and timing. Quantum Technologies can both improve existing imaging systems and create new sensing modalities inaccessible to classical strategies. e.g.: imagers with single-photon and infrared sensitivity, extreme time-resolution, 3D profiling, hyper-spectral, ultra-low flux covert illumination, mitigation of aberrations, imaging beyond line-of-sight and imaging of local gravity fields.

Physics-enabled systems rely on the phenomenon of quantum correlation or squeezing, often created through quantum entanglement between optical fields. Such approaches improve the resolution, signal-to-noise or wavelength sensitivity of imaging systems.

Quantum enhanced photonic imaging sensors are conventional systems that use quantum technology to enhance key characteristics such as resolution or noise performance by harnessing phenomena such as entanglement.

Examples of quantum imaging technologies under development in the Glasgow-led Quantum Imaging Hub are:

- real-time imaging systems that can track objects moving around corners and beyond the line of sight;
- cameras that can see all colours and polarisation states simultaneously;
- camera systems that can use a low-cost visible sensor to record infrared images by illuminating the object at one wavelength and record images at another;
- mass-producible, low-cost gravity imagers with excellent performance;
- cameras that can see through fog, smoke and turbid media;
- cameras and sensors which are more sensitive, quicker and/or wider wavelength range than conventional technologies;
- sources of light which are noise-free for measurements in imaging and spectroscopy.

8.5.1 Future imaging capabilities

Imaging is pervasive to all aspects of everyday life, ranging from mass consumer markets, defence and security, medical through to scientific applications.

A wide range of imaging technologies is currently available on the market and, in some areas, new systems will have a high barrier to market entry and require a considerable amount of investment in research, development and innovation. Nonetheless, significant improvement to state-of-the-art imaging systems is highly desirable to a) enable completely new modalities, for example to image beyond the line of sight and b) improve existing systems, for example by reducing cost, size or power consumption and increasing performance (speed, dynamic range etc.). Such improvements require both the development of new and improved sensor and source technology and the development of better optics, cooling, data analysis and data inversion techniques.

Advances in sensor and source technology will also have broad applicability beyond imaging, especially in the field of single-photon detection and correlated photon-pair generation, which is an enabling technology for quantum communications and quantum computing.

Important application areas for quantum imaging innovation are focused around:

- Inexpensive IR imaging for ground or air-based, wide-area continuous surveillance;
- Low-cost airborne (hyperspectral) sensors for security, military, agricultural, oil and gas and environmental monitoring applications;
- Land-based, sub-sea, airborne and space-qualified high-performance and low-cost, miniaturised gravity sensors for gravity mapping and navigation;
- Covert ranging and 3D imaging;
- New modalities to allow imaging under-water, through turbid media and beyond the line of sight (through-building visualisation and tracking of moving objects around corners);
- Signal processing and data inversion techniques.

8.5.2 Imaging enabled by quantum technologies

8.5.2.1 Visible SPAD Arrays

Conventional cameras measure the light intensity but cannot resolve the distance of individual objects within the field of view. In addition to the intensity of each pixel, cameras based on Single Photon Avalanche Detectors (SPAD) arrays can measure the arrival time of the individual photons. When used with a pulsed illumination source this arrival time gives the time-of-flight from source to object and hence the range of objects at each individual pixel. The formatting of single SPADs into an array allows simultaneous recording of a 3D image.

There is a significant market for cameras that detect single-photons with high temporal resolution, high quantum-efficiency, and low-noise performance. Target applications are fluorescence microscopy, range finding, and low light-level surveillance. Commercially available cameras do not have all the desired features at once: EMCCD (Electron Multiplying Charge Coupled Device) cameras have a high quantum efficiency but relatively long exposures; ICCD (Intensified Charge Coupled Device) cameras provide very short exposure times and can be triggered at high repetition rates, but their single photon efficiency is very low. An attractive solution, combing the best of the two modalities, is a camera based on SPAD arrays.

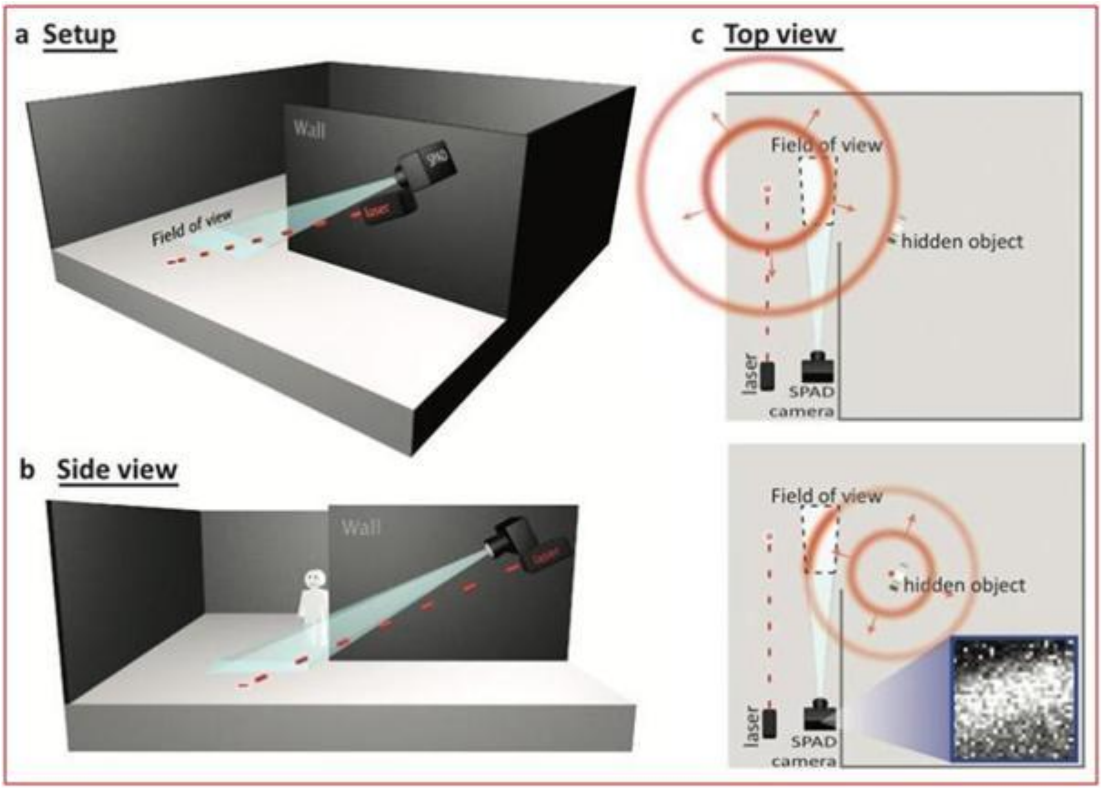

Figure 46: tracking hidden objects with a SPAD camera and pulsed laser Figure taken from Gariepy *et. al*. Nature Photonics, (2015). ***Reproduced with permission of Dr D Faccio***

An early demonstration of the capabilities of SPAD arrays in the visible range is to detect objects out of the line-of-sight, e.g. hidden behind the corner of a wall. A pulsed laser is used to illuminate a spot on the floor, some distance ahead of the camera. Light is scattered from this spot and strikes the object that is hidden. Light is then backscattered from the object back into the field of view of the camera where it is itself scattered (again) from a surface. The unprecedented single-photon sensitivity of the camera means that this triple-scattered light is still of sufficient intensity to be detected. The triple-scattered light is imaged as a curve on the last scattering surface, the centre of curvature indicating the position of the object (c.f. the ripples on a pond that identify where a pebble was dropped). Although recovering the detailed image of the hidden object is as yet beyond the computational power of the analysis, the size and speed of object or objects can be clearly identified.[285]

The ability to locate and track objects hidden around a corner or behind an obstacle could prove valuable in many situations, where it is dangerous or impossible to access an area. It would be a significant asset in rescue missions to locate and recover trapped people, in hostage situations to assess a crisis from afar and in automated driving to detect incoming vehicles from around a corner and avoid accidents. Although competitor techniques exist to reconstruct objects from around a corner, none of them have been able to locate in real-time the position of a target hidden from view in conditions where no access or control over the hidden area is possible.

Researchers at Heriot-Watt recently reported a method that locates hidden targets with fast enough acquisition to also detect their motion, with a technology that has the potential to be used in real-

[285] Gariepy *et. al*. Nature Photon 2015, 6, 6021 or see here for open source

life applications. The technique relies on the use of an ultrafast laser and a single-photon avalanche diode (SPAD) camera. In a proof-of-principle experiment, they used a femtosecond Ti:Sapphire laser and directed pulses at the floor, beyond the edge of a wall hiding a target to track. The target was a human form cut in a piece of foam, approximately 5x smaller than a person. When the laser pulses hit the floor, they are scattered as spherical waves, and part of the light travels beyond the obstacle to reach the hiding target. The target then scatters part of the light back onto the floor, which is then imaged with a SPAD camera. This camera is fast enough to detect the motion of light and sensitive enough to detect the very low signal scattered back by the hiding target. The spatial and temporal information contained in this signal is used to retrieve the position of the target behind the wall.

They were able to accurately track a target moving at 5 $cm.s^{-1}$, a meter away from the camera. One line of future work is focused on tracking large-scale objects e.g. humans and cars

8.5.2.2 IR SPAD Arrays

Semiconductor-based photon-counting detectors have risen to prominence in the last decade as new application areas, such as quantum technology, have emerged. Silicon-based SPADs were first demonstrated in the early 1980s, and since then they have come increasingly into widespread use for detecting ultra-low light levels with picosecond time resolution. Application areas include LIDAR[286] (including ground to low earth orbit satellites), fluorescence analysis, and quantum technologies, particularly in quantum communications, and quantum-enhanced imaging.

Si-based SPADS are insensitive to infrared wavelengths but there are many applications in this region of the spectrum that would benefit from single photon detection and accurate timing resolutions. Examples are quantum cryptography, eye-safe laser ranging, VLSI circuit characterization based on light emission from hot carriers in MOSFET[287]s and singlet oxygen detection for dosimetry in photodynamic therapy.

In the near-infrared, there are substantial issues with SPAD detectors, as their performance deteriorates at higher wavelengths due to the increased noise levels associated with the narrow bandgap semiconductors normally used. A new class of germanium-on-silicon SPADs will operate efficiently in the near-infrared, particularly at the strategically important telecommunications wavebands at wavelengths around 1300 nm and 1550 nm, and combine the advantages of low-noise Si single-photon avalanche multiplication with the infrared sensing capability of Germanium. These devices will also provide the much-needed compatibility with silicon photonics circuitry, enabling full on-chip detection in the infrared for the first time.

8.5.2.3 Avalanche Photodetectors

High resolution cameras imaging the visible wavelength range are now commonplace. Imagers in the infrared range (700nm - 1mm wavelengths) and especially in the medium infrared range (3 - 5 µm), however, are not yet widely available. Cooled indium antimonide (InSb) photodiodes (PDs) are the detectors of choice for many applications in the mid-infrared region, such as gas cloud imaging, astronomical and environmental observations, and medical diagnostics. By contrast InSb avalanche

[286] LIDAR = LIght Detection And Ranging, the optical equivalent of radar. Often referred to as LADAR in the US.

[287] Metal Oxide Semiconductor Field Effect Transistor which has become the most common transistor in both digital and analogue circuits replacing bipolar junction transistors.

photodetectors (APDs) will provide higher speed, lower noise and superior sensitivity. Fabrication on a Gallium Arsenide (GaAs) platform allows development of a monolithically integrated imager.

8.5.2.4 Single-Pixel cameras

Whereas modern cameras have many millions of pixels, cameras are being developed that have only one. Single-pixel cameras (SPCs) are much cheaper than multimillion pixel arrays, particularly in the infrared region of the spectrum where traditional cameras are expensive or even impossible to obtain. Imaging in the infrared has innumerable applications, for example it can allow firefighters to see through smoke and engineers to image gas leaks. In essence an SPC resembles a data projector where the light source is replaced by a single element (pixel) detector which measures the total power transmitted through the display as superimposed upon the scene. By 'displaying' a known series of complex masks and measuring the transmitted power associated with each mask, it is possible, by using data inversion techniques pioneered for Quantum Ghost Imaging, to deduce the image of the scene.[288]

Researchers at the University of Glasgow have used this approach to make a low-cost camera for imaging methane gas as it leaks from a pipe. The scene is illuminated with a few milliwatts of laser light at 1.6μm from a diode source similar to that found in a communication system. The single pixel camera images the back scattered light and overlays this gas cloud image on top of a full colour navigation image to guide the user to the source of the leak.

8.5.2.5 Gravity Imaging

Measurement of gravity enables the local mass density to be imaged. Gravity surveys are regularly used for oil and gas prospecting, environmental monitoring and security applications. Current state of the art instruments are high performance and high cost. There is a gap in the market for cheaper, highly sensitive devices that provide high-resolution gravity maps at a fraction of the current cost.

A relative gravimeter monitors the local change of gravity by sensing the position of a mass on a spring. Changes in the local gravitational acceleration, due for example to mass anomalies associated with oil reserves, change the vertical height of the mass. MEMS (Micro Electro-Mechanical Sensor) are all silicon micro-fabricated devices with a proof mass of 0.02 mg. Researchers at the University of Glasgow have fabricated a device[289] that can be read out with an optical sensor, enhancing sensitivity over traditional capacitive readouts and providing a system that is immune to electromagnetic interference. A long-term goal is to introduce correlated photons into the optical sensor in order to make the system more sensitive without overheating the sample.

8.5.3 Enabled by quantum physics

8.5.3.1 Correlated sources

Today, lasers are the cleanest source of light that is commonly used for optical measurement. However, these lasers are fundamentally limited in precision measurement applications by their inherent shot-noise (the noise inherent in the quantised nature of light). In addition, other common practical limitations arise, such as beam stability, detector noise and environmental noise sources. Both these practical and fundamental limits of noise in precision measurement can be overcome

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[288] Edgar *et. al*. Scientific Reports, 5:10909, 2015

[289] "Measurement of the Earth tides with a MEMS gravimeter" R. P. Middlemiss *et. al*. Nature 531, 614–617 doi:10.1038.

using quantum mechanics and quantum states of light. A single-photon source can be constructed to have the same key operational requirements as a laser, including long coherence length, directionality and single frequency, and they can also provide timing information. Unlike lasers, single photon sources have a reduced uncertainty on an intensity measurement, which results in a better signal to noise per unit of optical intensity. The quantised nature of light means that there is a binomial uncertainty in absorption measurements because there are only two possible outcomes: to detect either 0 photons or 1 photon. This results in a reduced uncertainty of measuring optical absorption. To overcome this limitation non-linear optics can be used to down convert a laser beam into two beams of frequency, time and momentum correlated photons. Detecting one of the photons "heralds" the presence of its twin, which we can then use for imaging or other sensing techniques such as range finding and spectroscopy. Sources of this type achieve a quantum-advantage over classical light in low light imaging and covert scenarios. Researchers at the University of Bristol have developed such a source based on periodically poled KTP converting the output of a diode laser at 405nm into twin photons at 810nm that can be efficiently coupled into single-mode fibres for relay and use elsewhere.

8.5.3.2 Sub shot-noise imaging

The heralding concept can similarly be applied to noise reduction techniques. In conventional illumination, the number of photons recorded in any one data bin (image or spectrum) is subject to a shot-noise variation equal to the square root of the number of photons recorded. This noise floor represents the quantum limit of classical measurement. The use of correlated beams allows this limit to be overcome. Since the shot-noise is identical on the two beams, dividing the number of photons measured in one beam by the number of photons measured in the other yields a unity ratio. This ratio is noise free. A slight absorption in one beam appears as a change in this ratio and hence can be detected even in the presence of shot noise. The extent to which this noise reduction can be implemented is critically dependent upon the measurement efficiency. Recent optical improvements in detector devices have allowed such noise reduction to be demonstrated but further work is needed to develop useful systems.

8.5.3.3 Ghost Imaging and Wavelength Transformation

Ghost imaging (or coincidence imaging) allows a high-resolution photon-counting camera plus an individual single-photon detector (the so-called “bucket” detector) to produce an image of an object that is out of the line of sight of the camera. The camera records photons from the source and the photon detector records photons scattered by the object. An image is formed computationally from correlations between photons arriving at the two sensors. Ghost imaging (see figure 47, below) was originally demonstrated as a quantum effect involving entangled photons, although later it was shown to be possible using only classical correlations. Subsequently, in DARPA supported work, the use of non-classical light was shown to improve the performance (i.e. resolution enhancement) and extend the scope of such a sensor provided a suitably large photon flux was used.

One example of Ghost Imaging is Wavelength Transformation. Conventional imaging systems rely on a) a light source to illuminate the object and b) a camera system to collect the back-scattered light after interaction with the object. In a conventional system the wavelength of the light illuminating the object is the same wavelength that is recorded by the camera, as it is indeed the same light. Quantum correlations make possible a wavelength transformation camera that allows illumination of the object with infrared light, but collection of the image using visible light. In the quantum regime, these two light sources are identical even at the level of individual photons (produced using a method called parametric down conversion). As a result, we can use a conventional high specification (visible) camera that is much more sensitive than its infrared equivalent, thereby allowing us to image at extremely low light levels. Systems are now operational to demonstrate the principles of this wavelength transformation but further work is needed to make their functionality accessible to a range of users.[290]

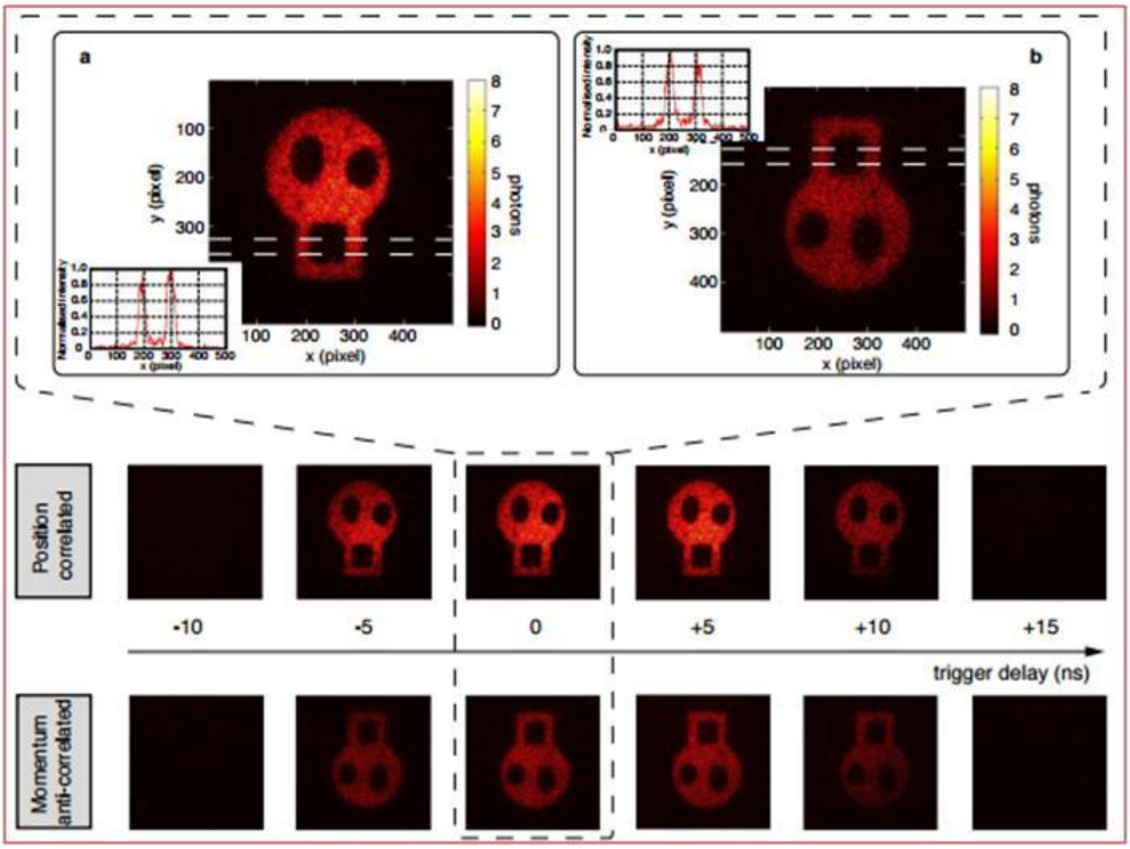

Figure 47: some of the recent ghost imaging results from the Glasgow QUANTIC hub ***Reproduced with permission of Prof Miles Padgett, Glasgow University***

Researchers at the University of Glasgow have used this approach to image the metal patterning evaporated onto a silicon wafer. The illumination of the wafer is at 1.5 µm yet the image is produced in the correlated beam at 460nm so that it can be imaged in the visible region of the spectrum where cameras are more sensitive and have lower noise. The improved camera specifications mean that an image can be produced from only a few tens of thousands of photons, a million times fewer than a normal imaging system.

290 Aspden *et. al.* Optica 2015, 2(12) 1049

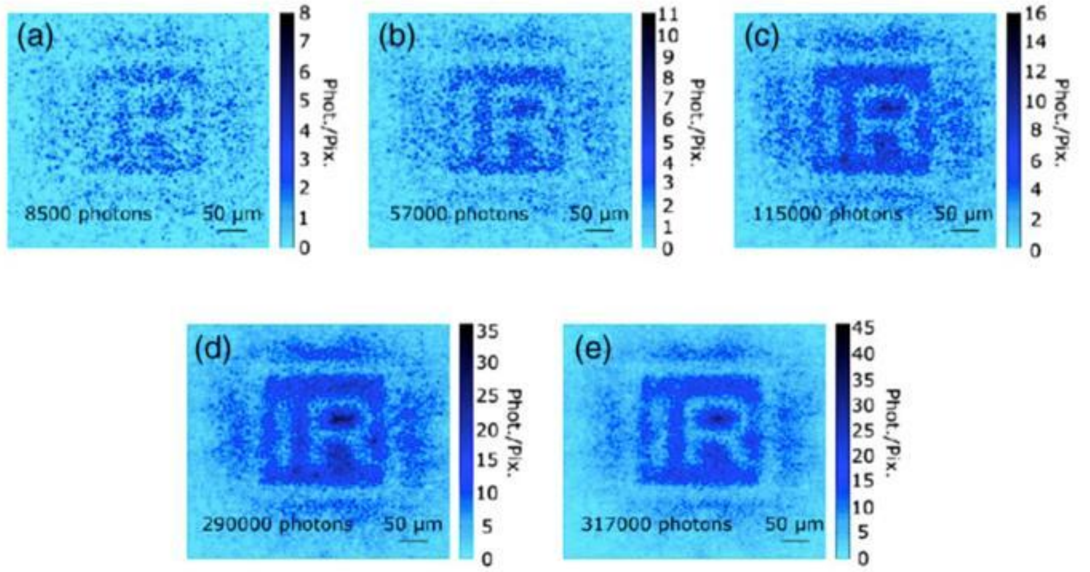

Figure 48: Image of a test object. A stencil of the letter "IR" obtained in visible light by an ICCD camera, even though the object was illuminated only by infrared radiation. The object is etched into gold deposited onto a 387 µm thick silicon substrate. For every infrared photon that probed the object and was detected by the heralding detector, the ICCD camera was triggered to record the position-correlated visible photon. The images were formed by summing over many photon-detection events as labelled.[275] ***Reproduced with permission of Prof Miles Padgett, Glasgow University***

The concept of wavelength transformation applies not just to imaging systems but to spectroscopy too. The sample is probed at one range of wavelengths yet the spectrum is recorded at shorter wavelengths where camera systems are more sensitive.

8.5.3.4 Quantum range finders

Laser range finders are commonplace both in the construction sector and defence applications. The time it takes for a laser pulse to reflect from an object and return to the source gives a highly accurate measure of distance. In the defence application it is desirable that the laser illumination is not detectable by anyone other than the sender. Achieving this covertness is problematic since, as anyone who has used a torch at night-time knows, the torch itself is visible from a much larger distance than that which the torch itself allows you to see. A solution is to use a highly efficient correlated source for a quantum rangefinder. As discussed above, the source emits two photons into two modes at exactly the same time. One of these photons acts as a trigger to the user, alerting them to the emission of a second single-photon. This knowledge of exactly when the photon is produced provides the additional information allowing the ranging of objects with ultra-low intensity. On the other hand, since the object has no knowledge of this emission time, they cannot distinguish the illumination from the thermal background. The ranging of the object then becomes covert.

8.5.3.5 Time Correlated Single Photon Counting (TCSPC)

This is being investigated at Heriot-Watt University[291] and at Selex-ES. This uses a single-photon laser source and very accurate timing to scan objects and identify them at distances of 1km and greater.

[291] A. McCarthy *et. al*. Kilometer-range depth imaging at 1550 nm wavelength using an InGaAs/InP single-photon avalanche diode detector, Optics Express, 21, 22098 (2013) Heriot-Watt research gateway

Heriot-Watt are using this approach for several application areas: examining target identification in free- space at kilometre distances; using remote multispectral depth information to extract foliage structural and physiological data,[292] and depth imaging in the highly scattering underwater environment[293] (see figure 49).

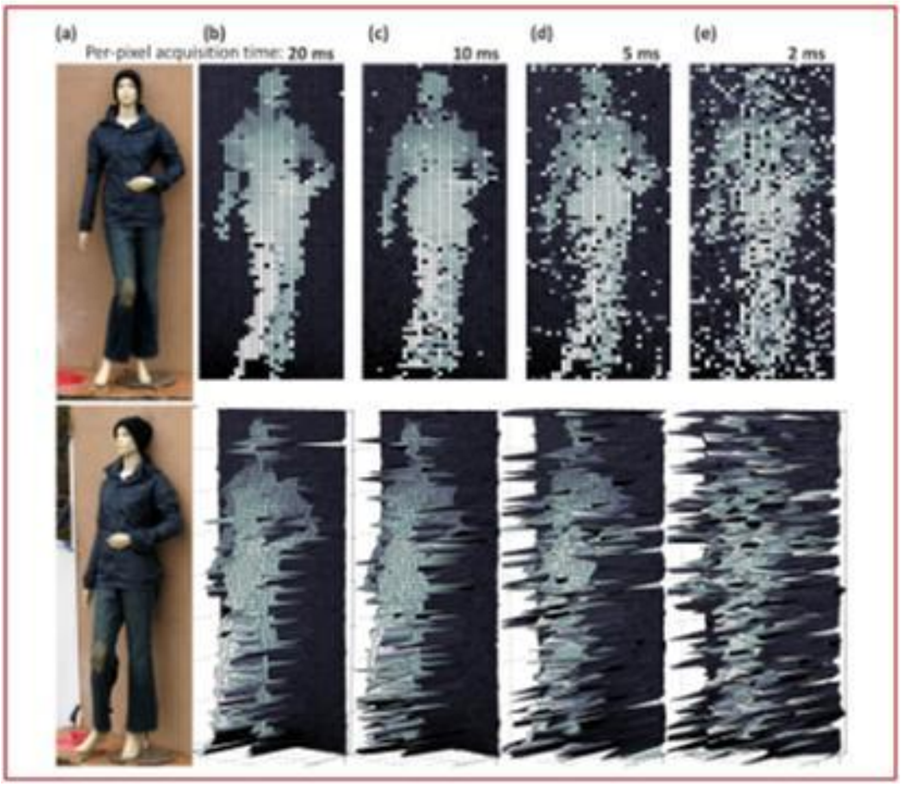

Figure 49 Single photon per pixel depth image at 900m ***Reproduced with permission of Prof Gerald Buller, Heriot-Watt***

An emerging and very promising technology for these ranging/imaging applications is single-photon avalanche diode (SPAD) detector arrays. These are cameras where each pixel is a single-photon detector with single-photon sensitivity and picosecond temporal resolution. Recent years have seen significant advances in the performance of such cameras. A particularly impressive advance has been made by Padgett *et. al*. at Glasgow[294] which combines several techniques to create photon sparse microscopy in the infra-red.

Silicon complementary metal-oxide semiconductor (CMOS) SPAD arrays can provide TCSPC capabilities such that each pixel can provide the time of arrival of a single photon with respect to a trigger to within a few tens of picoseconds. Current generations of SPAD arrays that operate in timing mode have around one thousand pixels (e.g. 32 by 32 pixels), and each pixel has a fill factor of a few percent. This is due to the electronics associated with the timing electronics for each pixel. Next generations of SPAD arrays will have formats of a few hundred by a few hundred pixels (e.g. 320 by 240) with fill factors of a few tens of percent (e.g. 20 to 30%). Typically, such SPAD cameras

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292 AM Wallace *et. al*., "Design and Evaluation of Multispectral LiDAR for the Recovery of Arboreal Parameters" IEEE Trans. GeoSciences and Remote Sensing, 52, pp4942 – 4954 (2014) Heriot-Watt research gateway

293 https://www.osapublishing.org/oe/abstract.cfm?uri=oe-23-26-33911

294 See http://www.gla.ac.uk/media/media_437525_en.pdf

do not operate in TCSPC mode but can be gated and can have exposure times down to around a few nanoseconds. Work in progress is transferring such arrays to full TCSPC mode, and are on the verge of implementation. Future generations of TCSPC SPAD array sensors that are based on vertically stacked manufacturing will have even larger fill factors and formats. Such sensors are currently in development as part of the UK's Quantum Technology programme (QuantIC), mainly via the University of Edinburgh group. Both TCSPC mode and gated mode SPAD arrays can be used for full-field single shot ranging, and this technology is currently being developed.

8.5.4 Inversion techniques

Central to all imaging systems is the reconstruction algorithm that converts the data recorded by the sensor to a displayed image. The community as a whole has taken a number of different approaches

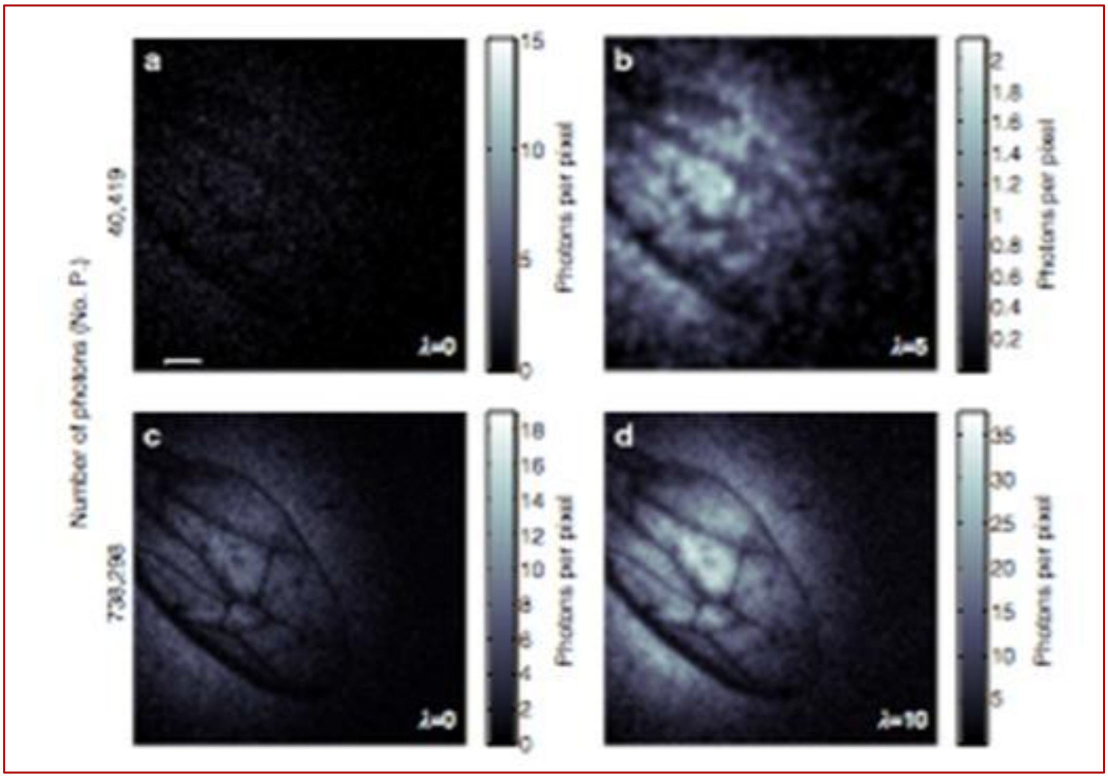

Figure 50: Images of a wasp wing. (a) A weakly absorbing wasp wing imaged using 40,419 detected photons and (b) the corresponding reconstructed image. (c) An image of the same wasp wing with a greater number of photons and (d) its associated reconstructed image. Scale bar, 400 mm. *Reproduced with permission of Prof Miles Padgett, Glasgow University*

to this problem, largely depending upon the nature of the sensor used. Central to many of these approaches is the recognition that real images are not a collection of random pixel values, rather that neighbouring pixels often show strong correlations between each other. This assumption is central for example to the familiar JPEG file format, which is based on sparsity, not in the image itself but rather in its Fourier-transform. In terms of image reconstruction, the same principle can be employed to recover images from noisy or incomplete data. In the quantum regime even a perfect system results in a noisy image due to the particulate nature of the light. Obtaining a high quality image from this noisy data is solved computationally by optimisation of the image to satisfy both the constraint set by the data itself and the sparsity constraint. In the quantum regime the noise is

Poissonian rather than Gaussian meaning that normal de-noising algorithms can be further improved.[295]

Figure 50 illustrates the approach and shows how image quality increases as the data density increases.

An emerging research area of interest is work examining the image processing of sparse photon data, for both two and three-dimensional imaging. Other work uses methods, such as Markov Chain Monte Carlo approaches, to examine images with less than 1 photon per pixel, on average.[296] These techniques promise much increased frame time and/or depth and spatial resolution for sparse photon imaging techniques.

8.5.5 Quantum enhanced photonic imaging sensors

LIDAR[297]s are well known classical sensors that can image terrain (and smaller scenes) to great accuracy, typically centimetres or millimetres. They work by scanning a beam rapidly over a defined area and measuring the time of arrival and strength of any return signal. There are many variants of the system implemented classically. In recent years, there has been increasing interest in LIDAR using single-photon detection, and the UK research is world class in this field. Also in the UK, work is proceeding in the fields of ghost imaging and covert imaging using entangled photon or correlated photon sources, although field work over long distances is yet to be established in either case.

There is a significant UK body of work addressing quantum enhanced multiple phase estimation. Datta *et. al.*[298] have developed a method of using multimode light for quantum enhanced imaging. The method can also be used for enhanced readout in other sensing systems such as the MEMS gravimeter in development by the QuantIC Hub. The same group have also developed a quantum enhanced method of measuring dephasing, which can be used to measure noise in quantum imaging sensors as well as atom accelerometers and gravimeters and to estimate heating very accurately at the quantum level.

8.5.5.1 Single-photon LIDAR sensors

There are several academic institutions involved in the development of Si CMOS detector arrays, including groups at Edinburgh University, Politecnico di Milano and Delft. The academic institutions are primarily focused on the development of silicon-based detectors using CMOS technology that are capable of detecting wavelengths in the spectral region of 400nm-900nm. Commercial III-V semiconductor SPAD array sensors based on InGaAs and InGaAsP absorber layers are capable of detecting infrared signals at 1.55µm and 1.06µm respectively and are commercially available from US company Princeton Lightwave. A variation of this aspect is using correlated photon pairs for range-finding imaging, heralding the measurement with one photon and performing the range measurement with the other photon, as demonstrated previously by Rarity *et. al.*[299]

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295 Sonnleitner *et. al*. Optica, 2(11), 2015

296 Y. Altman *et. al*., Lidar waveform based analysis of depth images constructed using sparse single-photon data, arXiv:1507.02511 (2015) To be published IEEE Trans. Image Processing (2016) http://arxiv.org/pdf/1507.02511v1.pdf

297 From Light and Radar, LADAR from Laser and Radar in the US

298 http://arxiv.org/abs/1605.04819

299 J. G. Rarity *et. al*., Experimental demonstration of single photon rangefinding using parametric downconversion, Applied Optics, 29, p2939 (1990)

8.5.6 Quantum secured imaging

Techniques similar to QKD have been proposed to secure reflected image data against an attack in which the returned photons have been intercepted and modified in order to present false information.[300] Polarised photons are sent to the target and any attempt to modify the reflection causes a change in the quantum state of the photons, depicted by a change in the false colour of the "spoof" image made up from four linear polarisation states.

8.5.7 Some exotic imaging sensors

8.5.7.1 Optical nano-probes

Merging of nanotechnology and photonic techniques has become a very active research area during the past decade. The confinement of light to sub-wavelength spatial distributions using nanoscale structures causes a number of unusual effects including ultra-tight optical confinement, field enhancement and extraordinary dispersion. This, together with efficient quantum based sources and detectors (particularly at 3 - 5 µm), creates new opportunities for manipulating light on the sub-diffraction-limited scale for applications including in optical communications, sensing, imaging and security.

This might allow biochemical fingerprints to be obtained at the cellular or sub-cellular level which conventionally would require the use of very short wave (damaging) radiation and would not yield the spectral data needed for analysis of lipids, amides, proteins etc. In the long term imaging *in vivo* at the sub-cellular level is expected. Deeper understanding of functions at a cellular level could eventually lead to bio-mimetic sensors (not necessarily quantum) that would deliver high sensitivity detectors for proteins and other chemicals and perhaps enable new medical treatments.

Spanish researchers[301] have observed ultraslow pulse propagation and backward propagating waves in a sub-wavelength-scale (135nm) slab of boron nitride, which exhibits hyperbolic optical properties at mid-infrared frequencies. The work lays the foundations for studying the precise manner in which light travels through complex optical systems at the sub-wavelength scale and may be a route to the future realisation of novel nano-photonic devices, perhaps for bio sensing or optical computing applications.

> *Nano-structured dielectric and metallic devices are being developed[302] to allow broad band, ultra-subwavelength (λ/19) Fano-imaging of the electric local density of states and phase modulation in two-dimensional photonic crystal nanocavities while avoiding the bleaching and strong tip-induced perturbations that degrade the high Q-factors of nano-resonators. Fano resonances can be used to probe directly the relative phases of cavity modes.*

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300 See for example http://arxiv.org/pdf/1212.2605v1.pdf

301 Yoxall *et. al.*, " Direct observation of ultraslow hyperbolic polariton propagation with negative phase velocity" Nature Photonics 9, 674–678 (2015) http://www.readcube.com/articles/10.1038/nphoton.2015.166

302 Caselli *et. al.*, " Ultra-subwavelength phase-sensitive Fano-imaging of localized photonic modes" Light: Science & Applications 4, e326 (2015) http://eprints.whiterose.ac.uk/86507/9/lsa201599a.pdf

8.5.7.2 Orbital angular momentum sensors

The orbital angular momentum[303] (OAM) series is an orthonormal basis[304] in which a wave field can be described. It may be thought of as a series of helices (see figure 51). The angular momentum is described as integral units of *m*, where *m*=0 represents a plane wave. Each value of *m* represents a separate channel for carrying information, and in fact this has been proposed as a way of increasing bandwidth for a given carrier frequency. OAM may, in principle, be used as a sensor, as each value can have different interaction regimes with objects and surfaces. It isn't very practical at optical wavelengths unless the target is very small as rough surfaces simply tend to mix the modes.

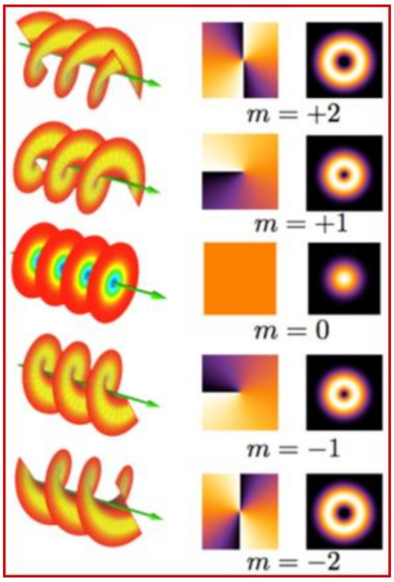

Figure 51: Illustration of some of the OAM states of light *E-karimi http://creativecommons.org/licenses/by-sa/3.0/*

However, recent experiments have shown that OAM may be applied to neutrons.[305] These may then be used to probe deep properties of solids, including superconductors.

All particles (including photons) may be *entangled* in OAM states. This results in some intriguing possibilities.[306] It has been suggested that IEDs could be detected using such schemes

8.5.7.3 Elementary particle sensors

Muons

The characteristics of elementary particles could, in principle, be used to "see" inside solid structures. The fundamentals of muon tomography have been known since the 1950s. Muons can penetrate solids much more deeply than X-rays. Muon sensors are not easy to deploy, although some of the uses have been:

- Monitoring sites proposed for carbon sequestration;
- Imaging magma chambers to predict volcanic eruptions;
- Finding materials with a high atomic number;
- Imaging of chambers in archaeological sites;
- Imaging of nuclear waste;
- Probing nuclear reactors.

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303 Orbital angular momentum is angular momentum over and above a particle's intrinsic spin. A useful but not quite correct analogy is the Earth's orbital momentum around the sun as compared to the once-a-day spin on its axis. Generally, a photon (light) field at a given wavelength may be completely decomposed in terms of, and completely described by, a series of OAM components.

304 i.e. a set of orthogonal axes in a mathematically defined framework (space).

305 For example, see this popular article.

306 See article on object identification or a more popular exposition of RF OAM.

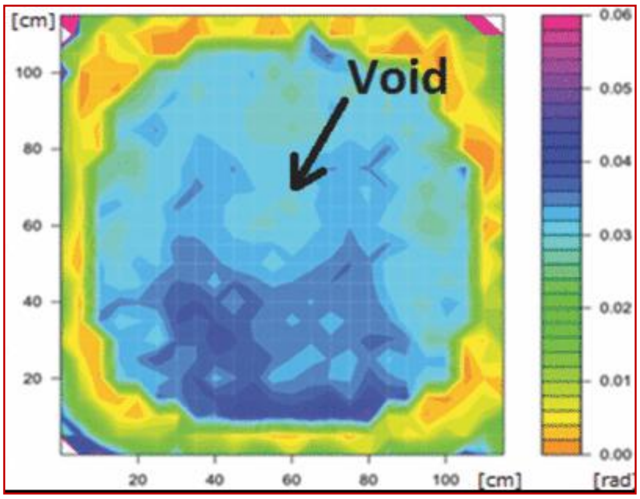

Figure 52: The Muon tomography image of void in reactor. This method has been proposed to locate the position of uranium fuel remaining in the Fukishima reactor. *Credit Haruo Miyadera http://creativecommons.org/licenses/by-sa/1.0/*

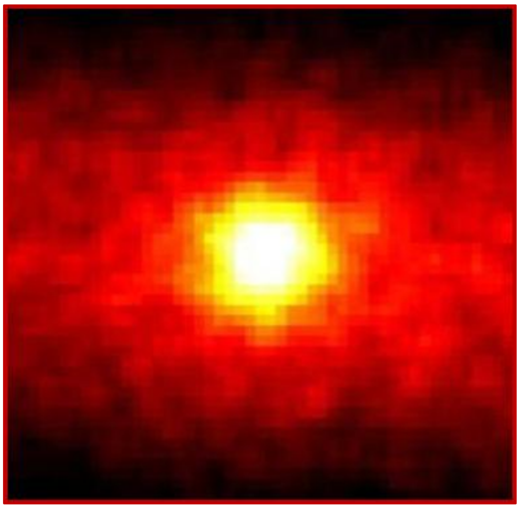

Figure 53: Image of the sun generated by neutrinos showing that the "fire" is still burning *Credit:* **R. Svoboda** *and K. Gordan*

Neutrons

Neutrons can be used to produce images, mainly based upon the attenuation properties of the object to be imaged. More recently, NIST[307] has developed a neutron microscope based on a Wolter lens, which consists of layers of nickel foil nested in the roughly into a shape like a shallot. This is a significant advance beyond the use of pinholes, and will eventually allow detection of phase variation to determine the structure of an object.

Neutrinos

Neutrinos are difficult to detect as they can (typically) travel through a light year or more of lead before any interaction takes place. They can be thought of as little more than a small piece of spin. however, with patience and a suitably large detector, they can be used to form images. Neutrinos are produced in prodigious quantities by reactors, particle accelerators and nuclear explosions. The image shown was taken on the *opposite* side of the Earth to the sun. It lays to rest once and for all any suspicion that the sun may have "gone out", we would not notice for a long time since photons take ~hundreds of thousands of years to travel to the surface from the core.

Coherent phonon sensors

Dr Charles Wang at Aberdeen university is a theorist who has been investigating the possibility of using an innovative concept that aims at circumventing the limitations, and exceeding the performance, of conventional sonar by implementing radically new sonar methodology at the fundamental quantum level. By sending and receiving coherent quantum acoustic waves, natural noise immunity could be obtained as the environmental incoherent acoustic noise can be distinguished and sifted.

Theoretically, the powerful photon counting and single photon detection technologies could be coupled to their acoustic counterparts by photon-phonon conversion leading to higher system

[307] See NIST (National Institute of Science and Technology (US)) article here.

sensitivity through detection of single coherent phonons via entangled pairs. The concept has yet to be experimentally verified; coherence has only been demonstrated across very small path lengths (i.e. only a few µm) so it is likely that the signal may get washed out.

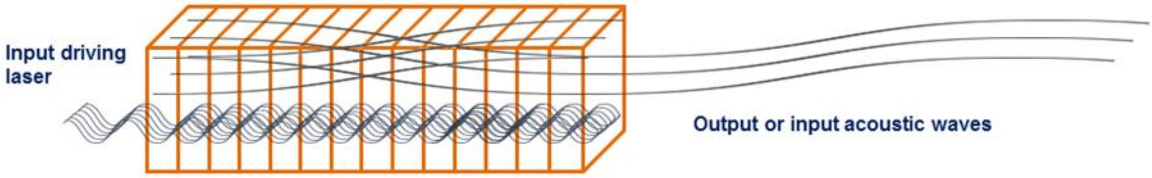

Figure 54 A crystal with macro-micro scales acting as a photomechanical cavity providing effective couplings and conversions between the resonant phonons whose half wavelength is the total length and the resonant photons whose half wavelength is the layer thickness of the crystal.

8.6 Sensors: Summary

8.6.1 Introduction

In the first quantum revolution the major technology driver was defence and security. Thus early computers, communications devices, sensors (such as CCD cameras, displays, night vision devices and radars) and enabling technologies (such as lasers, microwave sources, ...) were expensive, difficult or complex to operate and required trained personnel. Consequently, there was initially little penetration into civilian markets. Subsequent miniaturisation, development of hardware and software to allow simple operation by untrained individuals together with mass manufacture made ubiquitous the plethora of high tech devices in civilian use today. The same is extremely likely to occur again.

8.6.2 Applications

Gravity imaging systems, capable of detecting subterranean tunnels or voids or massive objects hidden in containers at checkpoints, obviously will confer military and security advantage on early adopters. Such systems will rapidly evolve towards low SWAPC and mature giving ease of use. However, because the ability to sense densities and structures under the Earth's surface is a key value adding technology, the systems will be rapidly adopted by industry. If gravity sensors are able to detect fossil fuel deposits (e.g. "oil bubbles" or salt domes) that have been left unexploited, the value is several trillion dollars per extra percent extracted from all known wells. (Typically, less than half of the oil present underneath a well can be extracted using current technology because the pockets remaining after initial pumping cannot be located.) There may be a "downstream" application for supervision of carbon sequestration.

An important application in the context of "sustainable cities" is in the civil engineering field. Survey of locations for foundations of dams, bridges and tunnels etc. will be an early civilian application. With higher resolution, imaging for reduction of roadworks (and avoidance of accidents) is possible by detecting "by first intent" pipes, cables, cellars, sinkholes and mine shafts and other "obstacles". Only 30 - 40% of services are accurately mapped in UK cities. One estimate of the benefit to the UK economy is ~£5 billion per year.

Sufficiently sensitive gravity sensors may also find application for detecting and predicting significant geological events, such as earthquakes and volcano eruptions.

Quantum inertial sensors have the potential to perform with orders of magnitude greater precision than conventional sensors and will have wide application, for instance for improved accelerometers and gyros. Engineering into ultra-precise navigation systems is a huge challenge but will enable GNSS independent navigation removing significant vulnerabilities and adding capability, eg. for underwater navigation. A driver for systems integration will be ever greater miniaturisation and cost reduction and this will facilitate uptake of quantum enabled navigation as a commercial application. When sufficiently small and cheap, autonomous vehicles (land, air, sea and underwater) could benefit immensely from the technology and will find early adoption in maintenance of underwater cables and pipelines, drilling of oil and gas wells and, perhaps, even surgery.

Quantum enhanced imagers, if they could be developed to a sufficient level of maturity, could offer military and security advantage in a number of scenarios:

- Single-photon enhanced LIDAR (laser version of radar) could allow a significant increase in resolution and noise performance of such systems. These would be realised as military systems in small numbers and are expensive with existing technology. However, as less expensive Si CMOS and narrow-gap semiconductor arrays are mass-produced, the cost will be significantly reduced;
- Covert ranging systems (e.g. using non-classical light) may be practicable, using single photon probes that cannot be detected by an adversary;
- Single-photon based approaches have been applied "seeing around corners", and this could be developed for urban warfare environments;[308]
- There have been reports of improved imaging through obscurants using entangled photon pairs, however these results have not been repeated in other laboratories. In any case, single-photon LIDAR techniques are ideally suited to imaging through highly scattering environments, such as underwater. Non interactive sensing (i.e. where vanishingly few photons interact with the object under scrutiny) might allow "stealth" imaging. This is unlikely to be practical with light, although it might perhaps be feasible with lower frequency quantum radar signals. The equipment required is not likely to be practicable or achieve acceptable cost/benefit within our target timescale;
- A certain level of protection against "spoofing" of return signals is possible by treating the imaging system as a communications channel and applying quantum techniques. Again, little experimental work has been performed, and major challenges remain.

In the commercial market, single pixel cameras will allow low-cost infrared imaging for detecting gas leaks, and for detecting intruders. Other applications of quantum enhanced cameras include seeing around corners for collision avoidance, fire and rescue services, monitoring the ripeness and health of fruit and vegetables, remote 3D imaging and non-invasive medical imaging. "Led-by-LED™ technology will be an enabling LED based technology[309] for smart lighting systems, Internet of Things, optical wireless communications and medical instrumentation. Sub shot noise visible, near infrared and long wave imagers will enable new or improved bio imaging and healthcare diagnostics as well as precision manufacture.

As with computing and clocks, there will be a wide variety of applications in the scientific market, both for terrestrial use and in space, for most families of quantum sensors. Health monitoring applications, already a strong driver of traditional CMOS based technologies, could be an early adopter of quantum enhanced spectroscopy for example.

Electromagnetic sensors may be useful for environmental sensing where sensitivity is key, however, consideration needs to be given to noise in the form of ambient fields.[310] They could find use for law

[308] QuantIC Annual Report 2014-2015, see https://quantic.ac.uk/quantic/wp-content/uploads/2016/04/QUANTIC-ANNUAL-REPORT-2015_LowRes.pdf

[309] LEDs are capable of modulating their light output to at least tens of MHz, leading to the possibility of novel communications networks (see here for example)..

[310] Electric field sensors could also be useful to predict geological activity. The phenomenon of animals becoming agitated before an earthquake is often due to a strong electric field being produced by rocks being compressed before a fault "gives"; it is detected through their fur. Infrasound also probably plays a part in some cases.

enforcement, e.g. tracking individuals by perturbations in the local electric field or residual charge deposited on objects or in the environment.[311]

Chemical and spectroscopic sensors relying on quantum effects could be used as part of law enforcement, where packets, substances or the environment need to be sensed with greater sensitivity. They could also be used for prospecting for natural resources (e.g. gases and trace elements), although they would have to deliver sufficient added value over classical or earlier quantum techniques already in use. These could be miniaturised using quantum optics (for example) and eventually find a mass market at the "mobile phone" level of implementation.

In life sciences, nano- and micro- scale magnetometry, electric field measurement and thermometry will enable a step change in managing chronic diseases such as Alzheimer's and cancers. "Magnetic helmets" that are highly sensitive and not reliant on cryogenics will become available for 3-D dynamic imaging of brain functions. Diamond nanoparticles with NV centres and atomic vapour cells interrogated with lasers are quite likely to be a viable technology.

The ability to analyse cells and their chemical components in detail *in vivo* will make a significant contribution to sustainable healthcare. This is potentially an immense market, as healthcare costs are rising rapidly in the developing world, and ways are being sought to make sophisticated diagnoses and monitoring cheaper and more efficient.

8.6.3 Synopsis

The subject of Quantum sensors has many branches that are extending, developing and maturing rapidly. The measurement of most physical parameters can be enhanced by using a quantum approach. The challenge then becomes one of practically using a quantum device in a *system* to make a useful product or service to deliver.

The main branches of quantum sensors can be defined by the quantum system used to make the detection. These are atoms (or their waves) interrogated by light and the results passed to electronics, or photons that are detected and subsequently interpreted by electronics. A summary of the parameters that can be detected is shown in Table 3 (in section 4.5.1).

The main thrusts of sensor development are becoming close to maturity. The Birmingham hub is centred on inertial sensors, and the Glasgow hub on photonic sensors, although there is some complementary activity in each.

The number of applications for quantum sensor technology is immense, and not yet fully known. As the devices become mature, and reduced in size, weight and power, many more applications will be found. Typically, they will include:

- Civil engineering;
- Disaster relief;
- Geology and natural resources;
- Military;

[311] Clearly success will depend on the amount of moisture present, although if the environment is dry deposited charge can remain for many hours or even days.

- Security;
- Medicine;
- Space technology;
- Enabling technologies and frontier physics;
- ...and many more.

The UK is in a pre-eminent position, with many industrial partners on board for development and marketing. It is now extremely important to capitalise on our position.

8.7 Quantum simulation and computing

In this section we review (at a basic level) the principal genres of quantum computing and quantum information processing. We will also deal with some of the misconceptions that bedevil the subject. We will include both special and general purpose quantum computers.

After an introduction to key concepts, we will discuss first the paradigms and then the technologies used in quantum computing. Quantum computing and simulation is a very large, expanding, highly specialised and complex field. We will not attempt to explain the more abstruse technicalities as they could fill (and have filled) books.

8.7.1 Introduction

Richard Feynman first proposed a basic model for a quantum computer in 1982. It would be able to simulate the evolution of a quantum system where, in general, a classical machine of sufficient complexity could not. In 1985 David Deutsch extended the concept to a universal quantum computer, analogous in a sense to the universal Turing machine[312].

This resulted in the "circuit model" of quantum computing, a quantum analogue of a classical computer, usually used as a paradigm for such machines.[313] Proposals to realise quantum computers have been many and varied, and demonstrations of rudimentary examples have been produced. After the year 2000, several families of quantum computer have been proposed, some are equivalent to the circuit model, some are (arguably) not. The classes of problem that a quantum computer may be able to solve which a classical machine (realistically) cannot are not yet fully understood. The explanation lies in the field of computational complexity theory.[314] A full description is beyond this paper although we show a much simplified view of the problem complexity hierarchy in figure 55. The field of computational complexity is itself not yet fully understood and it is an active field of research. Quantum computers can only reach the solution of problems more rapidly where an appropriate quantum algorithm is available. Quantum algorithms are an active field of study.

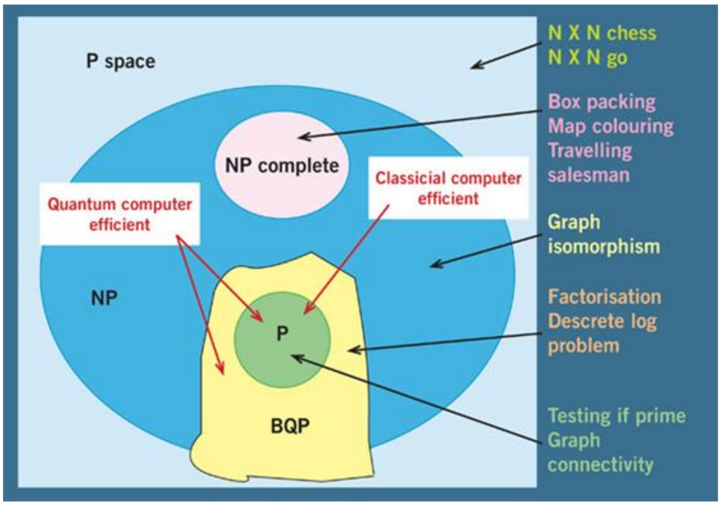

Figure 55 A simplified view of the concept of computational complexity

312 A Turing machine, first described by Alan Turing, is a hypothetical (but realisable) computing engine analogous to all classical computers. A program on one machine can be converted for use on any other via an additional program known as a cross compiler. A *universal* Turing machine (UTM) can simulate any other machine by reading both the description of the machine being simulated as well as the data to be processed.

313 Note that this way of thinking attempts to impose our traditionally classical mind set on to quantum physics. This is not necessarily an optimal approach as the quantum world is conceptually deeper with far richer implications.

314 This is a very specialised and complicated mathematical subject, see THIS poster for example.

Below we will discuss and comment on principal families of quantum computer and some general challenges before briefly describing areas where we understand they have a distinct advantage over classical machines.

8.7.2 Misconceptions

Misconceptions abound in the field of quantum computing. Some of the most prominent examples are:

- *Quantum computers are fast.* In fact, they are not necessarily fast at all.[315] They just have the property that they can solve problems that are inherently more difficult than those that can be solved by a combination of arithmetic and logical functions. The timing of their operations, for most examples, usually has to be very accurate. In the context of taking less time to solve certain problems, they could be described as being "fast to reach a solution"

- *Quantum computers can solve many problems simultaneously*. They can't, they just often exhibit the *appearance* of using many parallel processes to yield an answer. They will produce only one answer with a finite probability of it being wrong

- Quantum computers can solve "huge" problems that are inaccessible to normal machines. This isn't automatically true and the issue is one of complexity rather than size. An example is that a normal problem such as the effort to multiply two numbers doesn't grow inordinately quickly as the size of the inputs increase. The opposite process[316] does. It is an algorithm that requires a doubling of computing power (or worse) each time a single bit is added to the input. It is an example of an algorithm that could be addressed far more efficiently by a quantum machine;

Figure 56: An intuitive indication of what a quantum computer can do. An easy problem is represented on the right: unravel a ball of wool. On the left, unravelling is more of a challenge as the problem is inherently more complex. Neither problem is "bigger" than the other in the sense that no more movements of one's hands may be necessary. The problem on the left could be said to belong to a higher complexity class.

- *Quantum computers can solve any problem*. That simply isn't true, in the same sense that "a classical computer can solve any problem". A technical example of a problem class that

[315] In fact, true adiabatic quantum computers would have to operate more and more slowly as their size (i.e. complexity) is increased. Arguably, a sufficiently large size to be useful might never be practical.

[316] I.e. finding the prime factors of a number.

quantum computers would find very hard is a class of problems that are known to be "super-exponential", one member of which is the determination of Ramsey numbers.[317] Often, a quantum computer might offer an advantage over conventional methods, but by only a small amount, meaning that it would not be sensible to employ one. And there are instances where a quantum computer could in principle find an "answer" more rapidly than a classical machine, but practical factors might prevent it from doing so. Examples could include problems that grow super-exponentially with input (such as the determination of Ramsay numbers)[318].

8.7.3 Classical and quantum information

Classical information is a configuration of a classical system that can be duplicated and stored in many different forms. For example, footprints contain information regarding someone who has previously walked on a surface. The basic (whole) unit of classical information is now widely accepted as a "bit" of information and takes the form either of a "1" or a "0".[319]

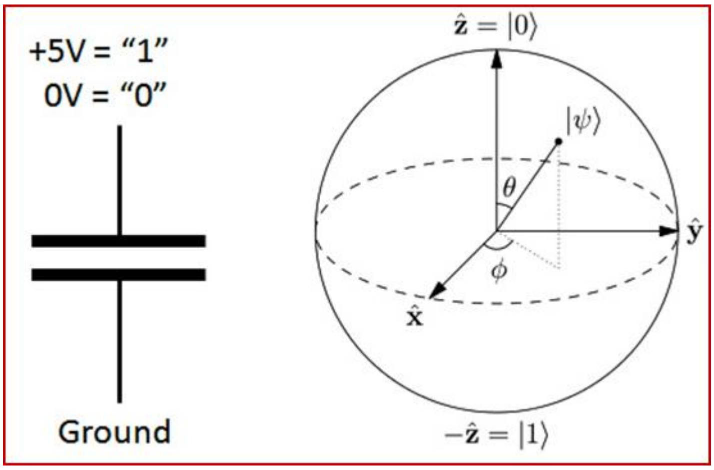

Figure 57 Conceptual representation of a classical bit (left) and a quantum bit (qubit) right *http://creativecommons.org/licenses/by-sa/3.0/*

Quantum information is physical information that is inferred to be held in the quantum state of a system. It is never fully accessible to classical interrogation and is conceptualised, in general, by a density matrix.[320] The basic unit of quantum information is the qubit. Conceptually, the qubit is a vector of radius 1 that can be represented as any point on a sphere, where the "north pole" is equivalent to a "0" and the south pole is equivalent to a "1" (or vice versa in some descriptions). Unlike the classical case, such a system can be in a *superposition* of the two states at once. A qubit cannot be completely read.[321] When read, it will become definitely either a "1" or an "0", with a probability related to the

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317 Simplistically, Ramsey numbers R(m,n) are represented by the minimum number of party guests that need to be invited before m of them will definitely know each other or n of them will definitely *not* know each other. The problem appears simple but grows surprisingly quickly with an increasing number of guests and only a few such numbers are known with any certainty.

318 Super exponential problems would typically grow as exp(e^x) of input size x. See here for an explanation of Ramsay's theorem and Ramsay numbers.

319 Technically, information usually represents disambiguation. Before measurement, a bit can be considered a symbol rather than a value. If "0" was a priori as likely as "1", then the symbol represents a bit of information. If "0" was a priori ten times more likely than a "1", then the "1" represents rather more information than the "0". So "classical information" is "about" how prior and posterior distributions are related. By comparison, "quantum information" is "about" how prior and posterior density operators are related.

320 Loosely speaking, a density matrix is a statistical ensemble of several possible quantum states that exist within the qubit. It is a general form of a quantum state, known as a "mixed state".

321 There is a large technical field dedicated to "weak measurements" that have minimal impact upon quantum states.

square of the angle θ the vector makes with the "north-south axis". An arbitrary *quantum* state, however, cannot be copied[322].

Quantum information may be processed by quantum gates in much the same way that classical bits are processed by the Boolean gates of classical logic. A significant difference is that, as described above, quantum bits are fundamentally probabilistic, i.e. do not have a definite value until measured.

It is important to understand that although the "size and power" of a quantum computer are popularly defined by the number of qubits in a machine, that is not the only important factor. The mechanism for operating the qubits, or the connections in the machine that define the interaction between the qubits (depending on the type of computer) are equally important, as is the fidelity to which the information is maintained.[323] An analogy is to label the power of a classical machine with the number of switches (or transistors) without regard for the interconnections.[324] Good fidelity in classical machines can be thought of as the result of effective error correction.[325]

8.7.4 Paradigms of quantum computing

The paradigms of quantum computing are not always separable from the technologies. For example, certain technologies may favour one or the other paradigm in terms of ease of implementation. An important consideration is that quantum computing is reversible in a thermodynamic sense. That means that as a fundamental process it does not dissipate energy in a way that produces heat[326]. (Most classical operations need not do so, they do because it is far easier to construct machines in the way that we do).

8.7.4.1 Circuit model quantum computers

Circuit model quantum computers are the most often used to explore the potential of quantum computing. Their operating principles may or may not ultimately be seen as the most appropriate paradigm as the ideas are derived from considering the operation of classical digital computers. These in turn are (usually!) derived from the paradigm of Boolean logic, arithmetic, and switches and relays. Those are familiar, but do not necessarily sit well with the behaviour of quantum objects.

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322 This is governed by the "no cloning theorem", although some "weak measurements can be made.

323 There is also the issue of entanglement, which is used as a resource and manipulated in quantum computers

324 In classical computing and communications, the connectivity and its use of power are rapidly becoming the parameters that will limit future progress. It is interesting in this context to note the exceptionally dense connectivity of the human brain.

325 In a classical dynamic random access memory (DRAM), the bits are regularly extracted and re-written within their decay lifetime. Interestingly, an analogous process can be implemented in a quantum memory to prevent decoherence.

326 Most classical computation does not *have* to produce heat, it is just that it is far easier to build machines that do e.g. by resetting registers to zero thus dumping charge held on the gates to ground.

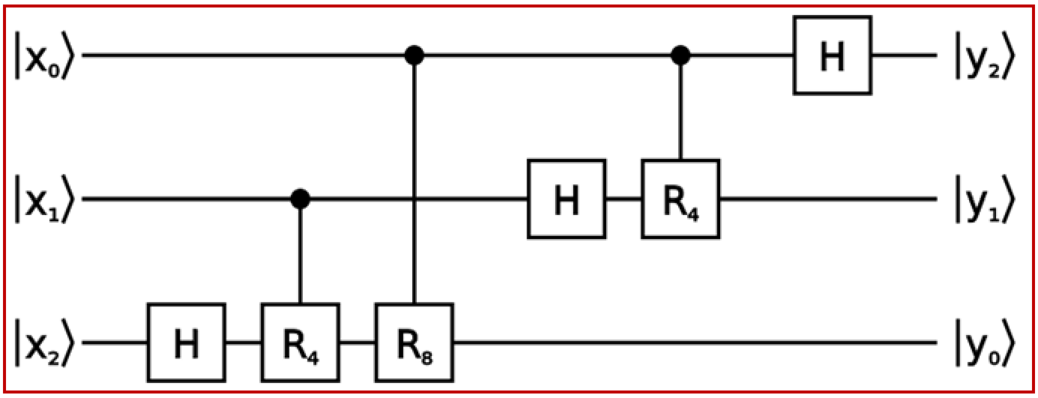

Figure 58 Representation of a typical quantum "circuit" for three qubits
http://creativecommons.org/licenses/by-sa/3.0/

In a classical machine, the information is stored as bits of information that are subject to a sequence of operations that may be reduced (ultimately) to a complicated set of interconnected one and two bit operations. A quantum circuit model takes an array of qubits and subjects them to a series of precisely timed interactions via an arrangement of what are known as "quantum gates". These may be broken down into primitives of one or two qubit operations.[327] The machine needs to be set up with a structure that provides the appropriate interactions and measurements at the right point in the calculation. That arrangement can be very complicated. The operation is typically represented by a diagram such as that in figure 58 where the progress of the qubits |0> and |1> is from left to right and the operations defined by the boxes.

8.7.4.2 Measurement based quantum computing (MBQC)

This genre of quantum computing is also known as the "cluster state model" and has no direct classical paradigm. Therefore, it can be very difficult to understand by the non-specialist. Clusters of qubits in a highly entangled state are generated and used for computation. Some variants are also known as "one-way quantum computing" i.e. the Raussendorf and Briegel variant. This method is seen as an attractive way forward by workers in the field[328] and proof of principle demonstrations have been carried out.

The standard circuit model approach assumes the ability to perform any quantum operation from a universal set of gate primitives.[329] This is difficult to achieve practically, particularly in multi-qubit

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327 It is beyond the scope of this paper to provide a deeper explanation, however there is plenty of good material in Wikipedia, for example in http://en.wikipedia.org/wiki/Quantum_computer

328 Technical note: Qubits still propagate forward in time as with the circuit model, but all the multi-qubit operations happen up front when the cluster state is built. Thereafter, qubits only interact with classical bits: that is, qubits are separately rotated by certain amounts specified by the measurements of previously-measured qubits, before themselves being measured. By keeping all the qubit-qubit interactions away from the actual “computing” part of the process, one may be able to reduce the amount of unwanted interactions during the computation.

329 There are more of these than in the classical case, where all operations may be constructed using "NAND" gates.

configurations. In an extended computation, in realistic conditions, the quantum state being acted upon would most likely be rapidly corrupted and the calculation would fail (see issues and challenges, in section 6.9.10 below). That is one reason why gate fidelity is so important. Whilst error correction can correct the fault it introduces a significant overhead in terms of qubits required. It is possible to address many of these problems by using the MBQC model instead.

Knill, LaFlamme, & Milburn[330], following Gottesman and Chuang, invented measurement based quantum computing using linear optics and requiring only single qubit gates plus so-called Bell basis measurements or Bell measurement gates. Technically, it was shown using this approach that universal quantum computation is possible with only linear optical elements and photodetectors. Two Bell measurement gates can move an arbitrary 2-qubit state between two locations using a process known as "teleportation" (see section 6.3.6) and, given the assumed ability to store instances of an entangled state, provide the basis for a more complex machine to perform any feasible quantum operation.

Later, an alternative approach was proposed by Raussendorf and Briege[331], more often known as "one way" quantum computing; only single qubit measurements are required. The system is prepared in an initial, highly entangled, state called a cluster state. A set of measurements is made on single qubits and the order and choice of basis for these measurements defines the computation, the path chosen relying on the results of previous measurements. It is a "one way" scheme because, as the computation is performed, time asymmetry is introduced and the computation can only be run forwards. The approach is attractive because the technical challenge becomes that of preparing the initial cluster states rather than executing the subsequent single qubit measurements: these are assumed to be straightforward. In reality this may not quite be the case, since the single qubit measurements are required not to affect neighbouring qubits and this limits possible architectures. Whether this is the best approach is arguable and depends on the physical implementation.

8.7.4.3 Topological quantum computers

These, if they prove possible to build, are probably a long way off. More exotic possibilities arise in the physics of particles confined to move in only two dimensions, particularly at very low temperatures and in the presence of very strong magnetic fields. A topological quantum computer is a theoretical system most often employing anyons. Anyons are two dimensional quasiparticles (i.e. excitations that usually exist on surfaces) whose world lines (trajectories) form braids in two-dimensional space plus time. As time proceeds, the calculation takes place via interactions between these anyons. The system is thought to be comparatively robust due to the stability of these braids (they possess structures similar in concept to knots).[332]

The idea behind Topological Quantum Computing is to encode information into topological degrees of freedom which are intrinsically error free (in a suitable thermal environment) in terms of error avoidance rather than error correction. Topology is a mathematical discipline concerned with geometrical properties which are not affected by continuous deformations including stretching and

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330 https://arxiv.org/pdf/quant-ph/0006088v1.pdf

331 See http://arxiv.org/pdf/quant-ph/0301052v2.pdf

332 See for example http://iopscience.iop.org/1367-2630/focus/Focus%20on%20Topological%20Quantum%20Computation

bending. (Hence, a tea cup is considered to be topologically the same as a doughnut because of its handle).

Such machines would be similar in computing ability, power and capability to circuit models of computation, although certain problems may map more or less easily on to their structure. None of these machines have yet been demonstrated, although work has commenced on some of their building blocks. Experimental evidence for the existence of some types of anyons was observed in 2005. The type of anyons required for topological quantum computing are thought to exist in rotating Bose Einstein condensates, quantum spin systems and superconductors.

More recently, Microsoft have been investing in this technology, and braiding has been demonstrated by Charlie Marcus in Copenhagen. Microsoft say that the advantage is that the qubits are quite spatially large (as they are quasi particles made up of multiple real particles) which means that the errors are much fewer and that qubits are almost naturally fault tolerant.

8.7.4.4 Adiabatic quantum computers

Adiabatic computation is a well-represented field of study. Experimental implementation is mostly at a relatively primitive stage.

The principle of operation is allied to quantum annealing but the process is driven as near to being quasi-static[333] as possible. A system is prepared in a low energy state using a simple energy "surface". Points on this hypothetical surface are (usually) considered to be in a one-to-one correspondence with the set of system configurations. The surface is then slowly (adiabatically) distorted into the shape that represents the problem, where its lowest point represents the state of the system that provides the "answer".

A useful (if simplistic) analogy is that of a ball on a dimpled surface, not moving because it is in its lowest energy state i.e. dent. The dimpled surface is then slowly distorted into a more complicated landscape and the problem is to discover the lowest point. Normally, the ball will roll downhill but if the surface is very complicated it might get "stuck" in a local minimum i.e. not at the very bottom. In a classical machine, the difficulty of getting stuck is ameliorated by jiggling the ball around using various algorithmic prescriptions, however, this can be a long process requiring a lot of processing effort, and frequently does not yield the best answer. The jiggling together with its prescription is known as "simulated annealing" as it mimics the annealing of solids by slow heating and cooling.

A quantum adiabatic machine will solve such optimisation problems without getting stuck - provided that the surface is distorted slowly enough. Our metaphor of a ball rolling downhill now allows the wave function of the machine to pervade the landscape with the greatest amplitude assumed to be at the "lowest point"[334]. These "surfaces" can be multidimensional and very complex. As the scale of the machine increases, undesirable energy levels get closer and to follow an ideal "trajectory" the computing process has to occur ever more slowly. One conceptual model implies tunnelling between minima to reach the lowest point; another is that the wave function extends across all minima with the amplitude at its highest at the lowest point.

[333] I.e. so slowly that changes are imperceptible; a theoretical construct often used in thermodynamics to invoke the concept of reversibility.

[334] Recently, the high efficiency of photosynthesis has been attributed to such quantum computing type activity.

Many problems can be converted into such an optimisation problem. However, neither classical methods (simulated annealing) nor quantum adiabatic methods could be said *always* to find the global minimum; this is an NP hard problem (figure 55). Theoreticians are still exploring the question of whether quantum annealing (QA) is likely to be useful for anything other than modelling the QA that actually happens in reality, e.g. chemistry.

8.7.4.5 D-Wave

D-Wave is a machine produced by a private venture Canadian company of that name. It uses a chip containing a cryogenically cooled array of magnetised loops isolated as much as possible from the electromagnetic environment. This array contains a network of connections between the qubits and is designed to settle into a state that represents the solution to an optimisation problem based on pre-set qubit biases and programmable coupling constants.

Although it used to be referred to as an adiabatic quantum computer, it is said to use "co-tunnelling" to access its lowest energy state, and is not a universal machine[335]. Its processes occur far too quickly to be described as "adiabatic" in the sense of 6.5.4.4 (above). A "quantum annealer" would be a better description. We have chosen to separate out D-Wave as the technology is a technical *tour de force* and well advanced, although, strictly speaking, it does not represent a distinct computing paradigm in its own right. There is a great deal of controversy in the community as to whether or not it makes good use of quantum effects, although it has recently been shown that evidence for entanglement has been found within, and between (adjacent), unit cells of 8 qubits. (There does seem to be a degree of misunderstanding of how the term "entanglement" is used in this context).

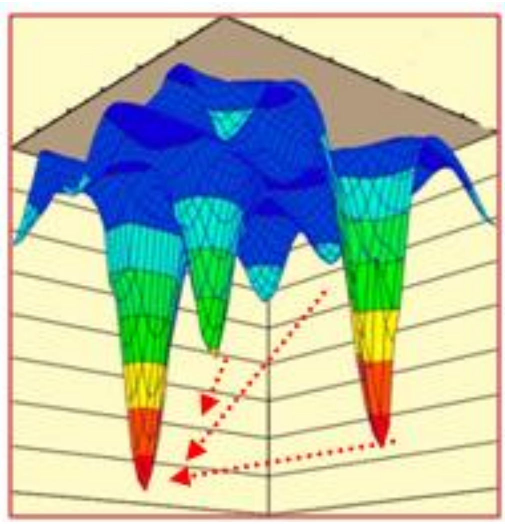

Figure 59: Finding the lowest point on an energy surface. Co-tunnelling implies the system can find the lowest point and not get stuck in a local minimum.

D-Wave claim that the machine works using "co-tunnelling" (figure 59) of the qubits into the lowest energy state,[336] and that the efficacy of this mechanism can be increased by a small amount of noise. Both D-wave and conventional algorithms may claim to provide "good enough" rather than the best solutions, especially as the answers, in complicated scenarios, can be very hard to check. Although a full programming cycle currently takes 100ms, the machine can perform 10,000 "runs" of a program each second, and such repeated operation may (in appropriate cases) be used to arrive at a probability distribution that represents the "answer". There is extensive literature available,[337] though we do not have the space to review all of it here.

The respected Google quantum AI team[338] has found a

[335] A universal machine would be capable of performing a full set of functions offered by a generalised circuit model. Technically, the D-wave machine is capable of solving (i.e. minimising for E) equations of the type known as QUBO or Quadratic Binary Optimisation problems.

[336] For a useful technical article on the computational value of finite range tunnelling see here, or for a more glossy tech times article here.

[337] See the D-Wave site http://www.dwavesys.com/en/dw_homepage.html,or or for an independent view (with useful references) http://physics.aps.org/articles/v6/105

very significant speed up (over a single core conventional machine).

As currently realised, D-Wave is an optimising machine with many of the characteristics of an adiabatic quantum computer. Overall though, the functionality of the D-wave machine is limited compared to that of a universal quantum computer, i.e. able to solve all problems in BQP.[339] In principle, some difficult problems (such as bi-prime factorisation) *could* be cast in a form that it can tackle but the complexity of the problem must be reflected into the required structure within the machine. This may prove to be impractical for large problems. However, D-Wave say that there are many possible design variations and report that they run ~8 design cycles each year. The acid test, though, is whether a suitably optimised and coded $10M conventional machine will be significantly outperformed by D-Wave.

8.7.4.6 Hamiltonian computation

There is a useful and generalised higher-level view of several of these variants of quantum computing. We usually consider quantum computing in a setting directly analogous to ordinary digital computing, with qubits instead of bits, and quantum gate operations instead of classical gates (AND, OR, CNOT, etc.). Instead of discrete gate operations, the input state of the qubits can be evolved to the final state in a continuous-time process. This continuous time process can be specified in terms of time-dependent quantum Hamiltonians and a coupling to a low temperature environment (i.e., open quantum system).

In particular, adiabatic quantum computing, quantum annealing, computation by continuous time quantum walk, and most proposals for "special purpose" quantum simulators all fit this model. In adiabatic quantum computing and quantum walks, the coupling to the environment is zero, and for quantum walks and quantum simulation the Hamiltonians are not time-dependent, however these are clearly special cases of the same scheme.

To complete this higher level picture, see figure 6o, continuous-variable quantum computing encodes the data into a continuous variable instead of qubits, but still uses discrete gate operations (e.g., beam splitters), while quantum versions of analogue computing would use both continuous data and continuous time evolution. These latter two are less useful because encoding into continuous variables (unary encoding) is not as efficient as binary encoding, and indeed, an encoding of qubits into continuous variables is often discussed to avoid this. However, continuous time evolution of qubits is computationally efficient, and therefore important to consider in the development of quantum computing technology. In particular, the same hardware can be designed to perform all of these types of continuous time quantum computing, which have been called “Hamiltonian computation”. Moreover, hybrid strategies combining elements of adiabatic, quantum annealing and quantum walk computation allow for optimal algorithms to be developed for different types of problems.

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338 The Google quantum AI team has discussed its evaluation here,

339 BQP = Bounded error Quantum Polynomial time, a measure of computational complexity.

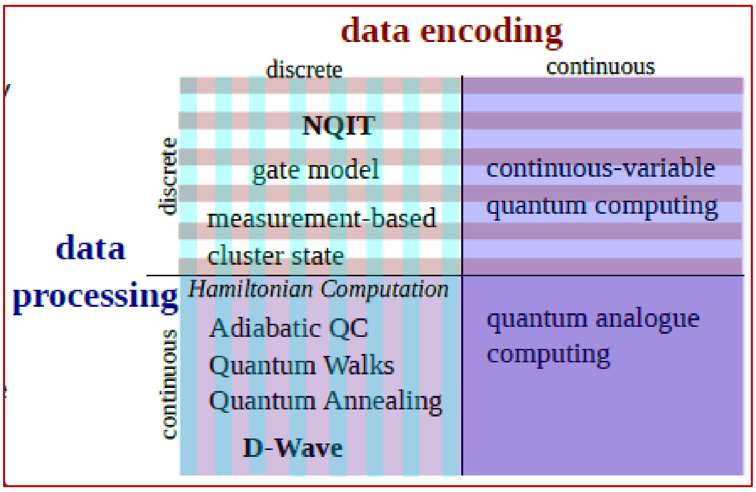

Figure 60 A generalised view of quantum computing *courtesy of Viv Kendon, Durham*

Our current theoretical understanding is that this type of computation is universal in the sense of universal quantum computing (depending on the available Hamiltonians in any given instance), but better suited to some types of problems than others. Examples include optimisation problems and quantum simulation. Using Hamiltonian computers for subroutines in hybrid classical-quantum algorithms has been explored theoretically. This is a promising route to extending the power of optimal classical algorithms into the quantum regime as soon as suitable small quantum computers become available. The D-Wave architecture fits into this model, but is limited in what it can do. This is because the low temperature environment dominates the time evolution, severely limiting the range of computations it can perform. It also has a limited range of time-varying Hamiltonians it can be programmed with. Nonetheless, the progress made by D-Wave shows the potential of this type of quantum computing.

Developing hardware with better coherent quantum control over the continuous time evolution and characteristics of the low-temperature environment (an essential component of quantum annealing to remove unwanted excited states) will allow the full range of Hamiltonian computation to be exploited. Proposals for special purpose quantum simulators, in which the Hamiltonian of interest is implemented directly, should be examined for the possibility of widening their application to more general Hamiltonian computation. This could provide the fastest route to deployable quantum Hamiltonian computers, since the connectivity required between qubits (local, but non-planar graph) is similar in all cases.

Hamiltonian computation requires further theoretical development for full exploitation, but the unifying approach across several established types of quantum computation is building on firm foundations. The hardware is aligned with special purpose quantum simulators, which are expected to provide the first useful quantum computers. We think that it is important to support future work in this direction, especially since the idea has recently originated in the UK and we currently have a head start for exploitation.

8.7.4.7 Boson sampling computers

The principle of the "boson sampling computer[340]" has been known for well over a decade, although it has only recently attracted significant interest and experimentation after detailed analysis by Scott Aaronson.[341] It can be considered to represent a paradigm which is an "odd one out", set apart from the mainstream effort in quantum computing. It is not a universal quantum computer and even

340 see http://arxiv.org/pdf/1406.6767v1.pdf or for those with chronic insomnia there is a truly excellent paper by Scott Aaronsen HERE

341 A detailed technical *tour de force* can be found at: http://www.scottaaronson.com/papers/optics.pdf

simple classical arithmetic is out of scope.[342] Approximately, the output is the answer to "how many belong to this set" rather than "is there a member of this set present". It is considered to be impossible for a classical machine to emulate a boson sampling computer if 20 or more bosons (e.g. photons) are used.

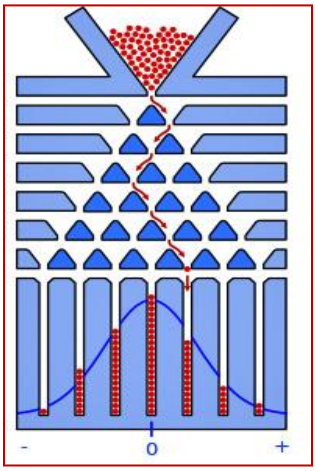

Figure 61 A Galton board

Bosons are elementary particles with integer spins; photons are chosen as being suitable candidates. A number of photons are suitably prepared (i.e. indistinguishable and with precise overlap) and sent into a network of optical couplers. The probability distribution detected at the output ports represents a computation that is (loosely speaking) equivalent to finding the permanent of a matrix.[343] Although this is not a universal quantum computer, the computations represent a complexity class generally thought to be inaccessible to classical machines.[344]

A very simple classical analogy to a boson sampling computer is a Galton board. This is a board laid out similarly to a game of bagatelle or pinball. The example in figure 61 shows such a board set up to calculate a normal (Gaussian) distribution.

Recently, a small machine has been demonstrated by Ian Walmsley and Joshua Nunn at Oxford, and Peter Smith at Southampton.[345] They are now engaged in a project with the aim of realising a 24 photon machine. This is proceeding according to plan with a record number of steps achieved in a time domain quantum walk. Soon, multi-photon quantum walks will be demonstrated. The device might be able to act as a quantum co-processor to help simulate quantum chemistry. Whether boson sampling computers will be able to solve a wide enough range of problems to make them useful as commonplace processors is a matter of debate.[346]

8.7.4.8 "Analogue" quantum computers

There are a number of approaches to what might be termed "analogue" quantum computing. This concept is similar to electronic analogue computers, that use continuous values of current and / or voltage to perform a computational task rather than "1"s and "0"s. They would principally be used for simulation. Some examples are:

8.7.4.9 Continuous variable quantum computing[347]

In this form of quantum computer, the information is stored as eigenstates[348] of a continuous variable such as position or momentum. It is essentially a theoretical construct with few followers. It could, for example, be used to determine the allowed values of fields at certain points. There is

342 Technically, the boson sampler accesses only a subset of what a standard quantum computer (BQP machine) accesses.
343 The permanent of a matrix is like a determinant except that the signs do not alternate between the terms in the formula. This is much harder to calculate than the determinant as short cuts have been discovered for the latter.
344 The complexity class is P# rather than BQP (bounded quantum polynomial time).
345 See http://www.orc.soton.ac.uk/publications/57xx/5716.pdf
346 One possible application might be the "monomer - dimer problem".
347 http://www.iqst.ca/events/csqic05/talks/travis.pdf
348 These are basic, separable states of the system that are the only ones that can be found as a result of a direct measurement.

some overlap with the concept of computing with cluster states.[349] It could be argued that CVQC is a separate paradigm in its own right.

8.7.4.10 Optical lattices

Optical lattices consist of an interference pattern, i.e. standing waves of photons, generated by intersecting laser beams. These are arranged such that there is a one, two or three-dimensional grid of energy minima ("dents") in which trapped ultra-cold atoms can sit, see figure 62. It can be thought of as an egg box like structure with control over the depth of the dents. The array needs to be held in an ultra-hard vacuum,[350] where cryogenics are not necessary.[351] By varying the potentials of the field structures in the lattice (the dents), and its contents, the system can in principle be used to emulate fundamental systems by dint of its energy "landscape" (known as the Hamiltonian). These energy landscapes can be set up to mimic the behaviour of solid state systems or even some of those that can never be produced on Earth, such as magnetars (stars with exceptionally strong magnetic fields).[352]

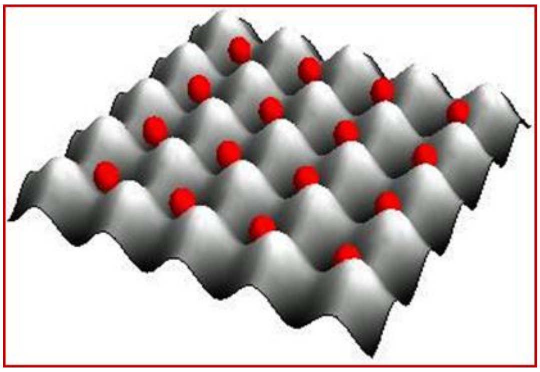

Figure 62 Conceptual representation of 2-D optical lattice ***Credit Sakurai2***

The world leader in the field of optical lattice control and measurement is Immanual Bloch at LMU Munich, who has succeeded in observing and manipulating such lattices atom by atom and lattice site by lattice site.[353] This is a necessary pre-condition for atoms in a lattice to act as qubits in a *digital* quantum computer. Needless to say there are immense practical technical difficulties. His more recent work has focussed on fundamental studies.

Meanwhile Blatt at Harvard has demonstrated[354] low noise, stable lattices for long term trapping of ultra cold (fermionic) ^{6}Li[355].

8.7.4.11 Frequency combs

Quantum frequency combs have recently been proposed as a mechanism for scalable quantum computing[356] . These would rely on the manipulation of the different frequencies within an optical comb together with the manipulation of time bins to generate many qubits on chip. The work is in a very early stage.

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349 See for example http://arxiv.org/pdf/1001.2215v1.pdf

350 At least 10^{-10} Torr, preferably 10^{-12} Torr, where 760 Torr ≈ 1 atmosphere pressure

351 If the excitation states of the atoms are well above the most energetic thermal radiation in the environment, the atoms won't "see" it.

352 For a UK leader in the field, see http://mpa.ac.uk/muarc/people/kaibongs.html

353 For an excellent introduction see 2010 article https://www.en.uni-muenchen.de/news/newsarchiv/2010/2010-bloch.html

354 See http://arxiv.org/pdf/1505.00758v2.pdf

355 This means the isotope lithium 6 (3 protons and three neutrons); fermionic means spin value of 1/2.

356 See http://live.iop-pp01.agh.sleek.net/2016/05/20/quantum-combs-light-up-computing/

8.7.4.12 Atomic clocks

Recently, atomic clocks have been proposed as simulators, e.g. for quantum magnetism.[357]. NIST and the University of Colorado discovered that a lattice clock (*op. cit.*) containing approximately 2,000 neutral strontium atoms could, in certain conditions, interact like atoms in magnetic materials. This could be used as a variety of optical lattice computer.

8.7.4.13 Bose Einstein Condensate

These have been proposed for communicating quantum information inside a quantum computer[358] and for analogue computation.[359] They have also been seen as a paradigm for holding quantum information.[360] As yet, these ideas are outside the mainstream of research.

8.7.5 Principal quantum computer technologies and UK strengths

8.7.5.1 Ion traps

Ions, i.e. charged atoms, may be confined in three dimensions using oscillating magnetic fields. Initialisation, manipulation and measurement of their states may be performed by lasers. The qubits may be defined by a pair of hyperfine levels (hyperfine qubits), a ground state and an excited electronic state (optical qubits), or spin states (spin qubits).

UK has good strengths in ion traps. There are two very large worldwide groups (Wineland, Blatt), but UK has now also developed a world-leading position in quantum computing with trapped ions. For example, Lucas's group (Oxford) has focused on delivering world-leading levels of precision in control of one- and two-qubit gates as well as hybrid quantum gates between two ion species.

Meanwhile, Hensinger's group (Sussex) develops novel ion chip technology (figure 63) and a new method for entanglement generation using microwave[361] radiation (rather than lasers). Hensinger's

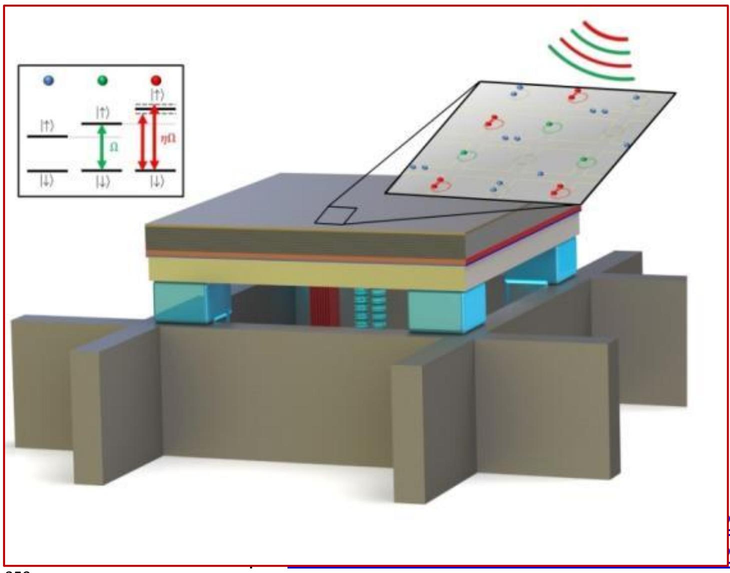

Figure 63: Schematic drawing showing the blueprint for the microwave trapped-ion quantum computer being constructed at the University of Sussex *courtesy of Professor Winfried Hensinger*

group has already demonstrated a new type of microwave two-qubit gate with fidelity close to the fault tolerant threshold. This is particularly suited to build in large scale quantum computers and quantum simulators. As part of the NQIT hub, two trapped-ion quantum computer demonstrator devices are currently being constructed in the UK. The 20-20 engine[362] being constructed at Oxford

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359
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long-wavelength radiation, S. Weidt, J.
itsch, W. K. Hensinger, Phys. Rev. Lett. 115, 013002 (2015) or Public domain arxiv version http://dx.doi.org/10.1103/PhysRevLett.115.013002

362 See 'Freely Scalable Quantum Technologies using Cells of 5-to-50 Qubits with Very Lossy and Noisy Photonic Links, Naomi H. Nickerson, Joseph F. Fitzsimons, Simon C. Benjamin; Phys. Rev. X 4, 041041 (2014)' Public domain arxiv version

utilizes individual modules that are connected via photonic interconnects. This approach is highly modular using both photonic and trapped-ion technologies making use of heralded entanglement links between modules. The two-node microwave quantum computer, being constructed at Sussex,[363] uses a new microwave entanglement approach to remove the very substantial overhead in laser or microwave fields which would usually be required to power a large scale quantum computer. It also replaces photonic interconnects (as a means to link individual modules) with ion transport between modules substantially simplifying the engineering required to build a large scale quantum computer.

Both demonstrator device designs are complementary and highly promising with the first large scale demonstrator devices scheduled to be completed in 2020. Richard Thompson's group at Imperial College is purported to have the best control of ions in a Penning trap in the world.

8.7.5.2 Photonic quantum computing

Photonic quantum computers use photons as "flying qubits". Typically, they could consist of a combination of sources, couplers, detectors, switches and gates. There are many possible architectures. Recent results include the realisation of this technology on a microchip. A long term vision is to integrate fully optical quantum information processors with microelectronics.

Photonic quantum computing has provided pioneering results in implementations with a few qubits. Whether this technology on its own can be readily scaled to larger numbers of qubits to construct a large scale universal quantum computer is not clear and subject to debate.

UK has excellent presence in this area. With Thompson's group at Bristol and the Walmsley led groups in Oxford, the UK has world-leading strengths both in purely photonic systems and in the approach of photonic "qubits + matter" memories. Competitors include White (Australia) and the Walter group in Vienna.

8.7.5.3 Superconducting qubits

Recently relocated to the UK are some strong researchers previously associated with the NEC effort, including: Pashkin (Lancaster), Leek (Oxford), and Petrashov (Royal Holloway). The UK therefore has a growing strength here, although we should note that there are massive existing strengths in Yale and others. Martinis (University of California) has teamed up with Google to do some very interesting work on chips with 40 qubits. Decoherence times are thousands of times longer than gate times, and measurement fidelity is extraordinarily high.

8.7.5.4 Cold atoms and molecules

In this area there is a heavy international presence from e.g. Bloch and Zoller etc. There are, however, strong UK efforts. Implementing operations between elements is the recognised challenge; solutions are either (a) use cold molecules rather than atoms (for example Hinds in Imperial) or Rydberg atoms (e.g. Adams at Durham).

8.7.5.5 Solid state spin systems

- GaAs quantum dots, electrostatically defined, electrically controlled: efforts in UK include, Elzerman (who performed seminal spin-readout experiments on these systems) recently

[363] See 'Blueprint for a microwave ion trap quantum computer, B. Lekitsch, S. Weidt, A.G. Fowler, K. Mølmer, S.J. Devitt, Ch. Wunderlich, and W.K. Hensinger, arXiv:1508.00420 [quant-ph] (2015)'

relocated to UK (UCL) and Pepper (UCL). The Cambridge group of Richie is considered a UK leader in this technology. International competitors include Yacoby (Harvard), Marcus (Copenhagen) and Kouwenhoven (Delft).

- Optically active, self-assembled GaAs dots: Good UK strength and activities with Atature (Cambridge), Rarity (Bristol), Skolnick (Sheffield) and Shields (Toshiba). A whole quantum circuit can be fabricated based on this technology, and this is the subject of a programme grant and topic of research at Toshiba. International strength includes the groups of Vuckovic (Stanford), and Imamoglu (ETH).

- Impurities in Silicon: This offers the longest measured coherence times of any system (up to 3 hours for the nuclear spin at cryogenic temperatures), and among the highest single-qubit 'quality factor' (i.e. decoherence time / single qubit gate time). This is 10^8 for the electron spin and 10^9 for the nuclear spin). Seamless integration with classical CMOS technology is another important advantage, it is therefore seen as “an approach with a complete solution (memories, processing etc.)”. UK has world-leading strength in a number of aspects of this platform, including fabrication at the atomic scale (Curson, Schofield, UCL), coherent control of electron and nuclear spins (Morton, UCL), orbital states (UCL, Surrey), electrical measurements of donors and dots in silicon (Cambridge and Hitachi). International leaders include Simmons's new group in Oxford, and Morello and Dzurak, University of New South Wales.

- Diamond NV centres: One of the few systems with realistic prospects for room temperature operation, however there are advantages to operating them at cryogenic temperatures. The relative ease with which single centres can be measured has led to a number of near-term applications, especially with regard to sensing (see above). Specific UK strengths are in e.g. cavities (Smith, Oxford), registering NV centre to other technologies (Rarity and O'Brien, Bristol), exploring different kinds of impurity (Atature, Cambridge) etc. However, there is very heavy international competition in the form of Wachtrup (Stuttgart), Jelezko (Ulm), Awschalom (Chicago), Lukin (Harvard), Hanson (Delft).

8.7.5.6 Adiabatic systems

In UK there is a significant effort at UCL (largely funded by industry) toward this class of architecture and its direct applications to learning and optimisation problems in computer science. There also remains a strong collaboration with the University of Chicago on underpinning experiments. Loughborough (Samson) also has an interest, and expertise in superconducting qubits will be needed if the (highly controversial) D-wave machine emerges to be genuinely useful for a wide variety of practical problems.

8.7.5.7 Hybrid quantum systems

Interfacing different quantum systems to create 'hybrid systems' is important for:

- Addressing the challenges of building a quantum computer by using the relative strengths of different systems (e.g. different systems for memory and processing);

- Building interfaces between 'static' and 'flying[364]' qubits to connect quantum processors, potentially in a secure way;
- Specific devices such as quantum memories and quantum repeaters, or quantum transducers (e.g. between optical and microwave ranges);
- Generally, the coupling of matter systems, whether atomic or solid-state, to photons is a UK strength that may be important in achieving scalability. The UK has, therefore, the opportunity to become a world leader in this field and much can be achieved if we foster collaborative work between groups. For example:
    - Trapped ion and superconducting qubits, e.g. the trapped ion is a memory for the superconducting qubit (Hensinger at Sussex is developing this technology as part of the IQIT consortium[365]);
    - Trapped ion/atoms and photons (Kuhn (Oxford), Keller (Sussex));
    - Rydberg ensemble atoms as interface between optical and superconducting systems;
    - Spins and superconducting circuits (Morton, UCL; NPL);
    - Quantum dots and trapped ions (Atature, Cambridge).

8.7.6 Quantum simulation

Part of our brief has been to identify suitable "stepping stones" on the route to the highest impact quantum technologies. This is particularly difficult for quantum computing and information processing in general, where achieving sufficient scale is an issue. One important stepping stone is a clear idea of which quantum algorithms would be of most immediate use. The theory in this space is immature, and only comparatively recently have people begun seriously working out the interesting algorithms for chemical simulation, etc.

However, physicists' understanding of the maturity of quantum chemical techniques for elucidating the electronic structure of molecules and the simulation of reactions is poor. Routine calculations on ensembles of thousands of atoms to so called "chemical accuracy" can be run routinely on laptops. State of the art methods and hardware allow simulations on ensembles of *billions* of atoms. Initial applications of quantum simulation to chemical and bio-chemical systems will be aimed at niche areas, for instance where many body electron effects are critically important.

Hence, full scale, general purpose quantum computing in a commercially viable sense remains a long term goal. However, special purpose computing may be feasible in the medium term, most likely in the form of simulation. This is analogous, at least partially, to the development of classical machines. There are two types of quantum simulator; analogue and digital.

Analogue simulation is possible using a variety of systems and is a particular strength of cold atoms where the exact *number* of atoms is not an issue but having complete system control is. Therefore, one can aim to exhibit limited control and mimic the system of interest, usually by means of shaping the Hamiltonian (energy landscape) of the system.

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364 "Flying" qubits is a term often used for photons when they carry quantum information
365 See http://www.iqit-research.eu/home/

Analogue simulators do not need to be very large to access classically intractable regimes of certain problems. The Hilbert space spanned by 10 ions including their motional degrees of freedom is sufficiently large to allow for certain quantum simulations that may be out of reach of a classical computer. An estimate of the time required to develop a working demonstrator (with sufficient resources) is four years (Charles Adams, Durham). Examples of applications include:

- Simulation of misaligned layers of graphene to enable a new generation of electronics;
- Energy transfer in thermo-electrics (e.g. Lambert's work (Lancaster));
- Energy transfer in synthetic photosynthesis systems;
- Semiconductor / organic materials interfaces;
- Medical applications, e.g. design of new drugs or simulating cellular functions;
- Design of materials e.g. to discover new high temperature superconductors.

The development of "digital" simulators is more difficult and the issues align with those of quantum computing in general. However, digital simulation is extremely powerful, since, in principle, it can permit the simulation of *any* system. Thus, for example, there is the possibility of discovering completely new chemistry purely by simulation.

Porras (Sussex) is a world-leading theorist in the field of quantum simulations with trapped ions and collaborates with Hensinger (Sussex) on the practical realisation of large scale ion trap quantum simulators.

O' Brien estimated that a device suitable for specific problems lying outside physics (e.g. chemistry and biology) delivering ~ 100 qubits might be developed in about five years given sufficient funding.

8.7.7 Quantum computers for the simulation of chemical systems.

In this section we present a technical perspective on when a quantum computer may or may not be advantageous for certain types of simulation.

> *Quantum chemistry (the first principles description of the structure, properties and chemistry, that is reactivity, of ensembles of atoms) requires solution of the appropriate Schrodinger equation and all known efficient methods (ignoring the many semi-empirical approaches, methods include Hartree-Fock; post Hartree-Fock techniques of Configuration Interaction; Møller-Plesset Perturbation Theory; Density Functional Theory (DFT); Quantum Molecular Dynamics, ...) to achieve this require either truncation of the Hilbert space and/or approximations whose effect can be sometimes difficult or impossible to estimate. Theoretical considerations suggest that these restrictions are not just shortcomings of the algorithms but arise from the inherent difficulty of simulating quantum systems.*
>
> *The rate limiting step in this process is the evaluation of the electron-electron exchange-correlation energy. ("Correlation" is chemistry speak for entanglement.) Density Functional Theory (DFT) has become a popular technique during the past two to three decades and, although it is not an* Ab Initio *method, nonetheless it can provide accurate predictions of properties for systems in excess of 1,000,000 atoms*[366] *- that is systems with dimensions of the*

[366] For example, CONQUEST, a linear scaling DFT code; see https://en.wikipedia.org/wiki/CONQUEST

order of microns (easily resolvable with magnifying optics). However, such calculations are not trivial, require massively parallel super-computers and specialised (linear scaling) algorithms.

It has been claimed[367] *that the simulation of an ensemble comprising about 100 atoms is beyond conventional simulation (because exact quantum chemical calculations scale exponentially with the size of the problem), but that such a simulation could be performed on a quantum computer with roughly the same number of qubits as atoms in the molecule. Clearly, this claim is not true, at least at the DFT level, although it may be that quantum computers will ultimately allow routine calculations on very large systems or much more accurate calculations than possible with DFT on intermediate size systems.*

The use of a quantum computer to solve a quantum chemical calculation goes back to Feynman, usually credited as the first to envision the possibility for a universal quantum computer, and was demonstrated in 2010 for the hydrogen molecule.[227] *A major advantage which is claimed is that there is little overhead in the number of qubits required to simulate the molecule, compared to the size of the molecule itself (as opposed to, say, factoring a large number). This implies there exists a certain fixed physical system - in this case a number of entangled photons - which is capable of simulating the dynamics of another physical system (in this case H_2). The 2010 paper reported the complete energy spectrum of H_2 (in a minimal basis) to 20 bits of precision and discussed how the technique might be expanded to solve large-scale chemical problems.*

The practicalities involved in a quantum simulation of an atomic ensemble are 3-fold:

- *prepare the initial state of the model in which the wave-function of the target ensemble is to be encoded; Usually one wishes to encode the target ground state as defined by some Hamiltonian. Solving for a complete description may be a hard problem, for instance in terms of the number of parameters required, but it is often claimed that if the target exists in nature it must be possible to efficiently prepare the initial state model;*

- *Adiabatic evolution is the preferred approach to evaluating the ground state but the dynamics of the model may be quite different to those of the target and implementing the Hamiltonian, driving it towards the state chosen to represent the target's ground state, may not be trivial. Also, it may not be possible to code targets not known to exist naturally. Increasingly, quantum chemistry is used to answer "what if?" questions thereby limiting the use of quantum computing for materials discovery, for instance;*

- *Finally, measurement may require huge numbers of gates and this implicitly requires models with long coherence times.*

Despite these difficulties, the quantum computing and simulation communities remain optimistic although the many years of determined efforts by computer scientists to find

[367] " Towards quantum chemistry on a quantum computer" B. P. Lanyon, J. D. Whitfield, G. G. Gillett, M. E. Goggin, M. P. Almeida, I. Kassal, J. D. Biamonte, M. Mohseni, B. J. Powell, M. Barbieri, A. Aspuru-Guzik and A. G. White, Nature Chemistry 2, 106 – 111 (2010)

effective quantum algorithms suggest "Quantum" quantum chemistry is truly hard. A review of the computational problems which arise in performing chemical simulations is available on the arXiv server.[368]

8.7.8 Software and theory

The literature describing software, theory and error correction is extensive but has often followed, in an academic sense, the most interesting or revealing trajectory of research rather than being closely coupled to the immediate needs of the experimentalists. The full potential of quantum computing is not yet understood and will be difficult to discover - especially given our propensity to stick to classical paradigms. For example, the potential role that quantum discord[368] could play is controversial and not easy to envisage. The mathematics used to explore the subject is not trivial. The general opinion seems to be that software will be lagging behind what the physics might offer when the outstanding challenges have been met.

The scope for quantum computing to outperform classical computing by a very significant factor currently appears to be limited to comparatively few algorithms, although most are agreed that the scope for simulation (both "digital" and analogue) of quantum systems is significant. However, this whole area is a subject of intense study and breakthroughs continue to be made.[369] One of the latest is concerned with evaluating certain characteristics of systems of simultaneous linear equations[370], possibly using a hybrid classical / quantum approach.

Applied quantum technology theory is nevertheless a significant UK strength; UK results are quoted and used in groups worldwide. Examples include Imperial (Kim, Rudolph), UCL (Bose, Browne), York (Spiller), Durham (Kendon), Oxford (Benjamin, Jaksch, Vedral) who have teams looking at modelling, architectures and thresholds. Our ongoing pan-national quantum technology partnership would benefit from a thorough survey of UK theory activity, especially *vis-a-vis* UK experimental expertise.

A brief survey finds that many universities host good but small quantum technology theory groups. However, there are a number of universities that have multiple teams of quantum computing theorists working on applied issues. These universities comprise Imperial College, UCL, Oxford, Leeds, York, Sussex and Durham:

- Kim (Imperial) - Atom/optical theory;
- Rudolph (Imperial) - "Blind" QIP, loss tolerant encodings relevant to photonic QIP;
- Bose (UCL) - spin-chains for quantum technology;
- Browne (UCL) - ‘magic state distillation’ for fault tolerant QIP;
- Fisher (UCL) [mainly quantum materials];
- Benjamin (Oxford) - fault tolerant architectures for quantum technology, energy flow calculations;

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368 Quantum discord is a measure of non-classical correlations between quantum systems. Entanglement is a subset of quantum discord. See here for a comprehensive technical article.

369 A reasonably comprehensive exposition can be found in the form of the "quantum algorithm zoo" see http://math.nist.gov/quantum/zoo/

370 One needs to be careful. A quantum computer will yield an expectation value associated with the solution rather than the solution itself. An interesting paper on the subject can be found here.

- Jaksch (Oxford) - simulation of quantum systems;
- Vedral (Oxford) - thermodynamics of quantum systems;
- Pachos (York) - Topologically protected quantum computing;
- Kendon (Durham) - Ancilla based QIP;
- Beige (York) - Atom/optical theory;
- Spiller (York) - Optical QIP, superconducting and few qubit systems;
- Dunningham (Sussex) - behaviour of rotating superfluids (entanglement population and interactions);
- Datta (Warwick) - is developing new methods on verification of quantum simulation. This is essential to ensure that quantum simulators are doing what they are meant to do. Applications include quantum chemistry, boson sampling, materials modelling, and all Q2020 simulations being developed by the Oxford hub.

Bristol and Cambridge have a number of quantum theory groups whose foci are either abstract quantum information or quantum materials.

8.7.9 Summary of progress since 2000

A complete view of progress is not possible given our time constraints and the proliferation of approaches and paradigms used by the worldwide quantum community. This summary focuses on the practicality of implementing two qubit deterministic gates.

Many of those approaches focus on the number of qubits made available by a machine. However, (arguably) an equally important characteristic, apart from the connectivity, is the "fidelity" of a gate. This defines the effort and resources required for error correction, which rise very steeply as the fidelity is reduced.

Figure 64 (below) shows the "best" reported 2 qubit gate errors in two technologies currently able to perform deterministic 2-qubit gates (i.e. trapped ions and superconducting Josephson junction qubits). It is a little out of date (recent NIST, Oxford and Sussex unpublished results are now better), but the general trend is the important thing: there is no evidence of progress slowing down. More importantly, the progress is roughly logarithmic, i.e. the gate error has been halving every couple of years or so. The consensus is that "practical" QC (i.e. without forbidding overheads in the number of physical qubits required) requires errors below 0.01%, so there is still some way to go. Neither technology appears to have a fundamental physical limitation that has been identified so far.

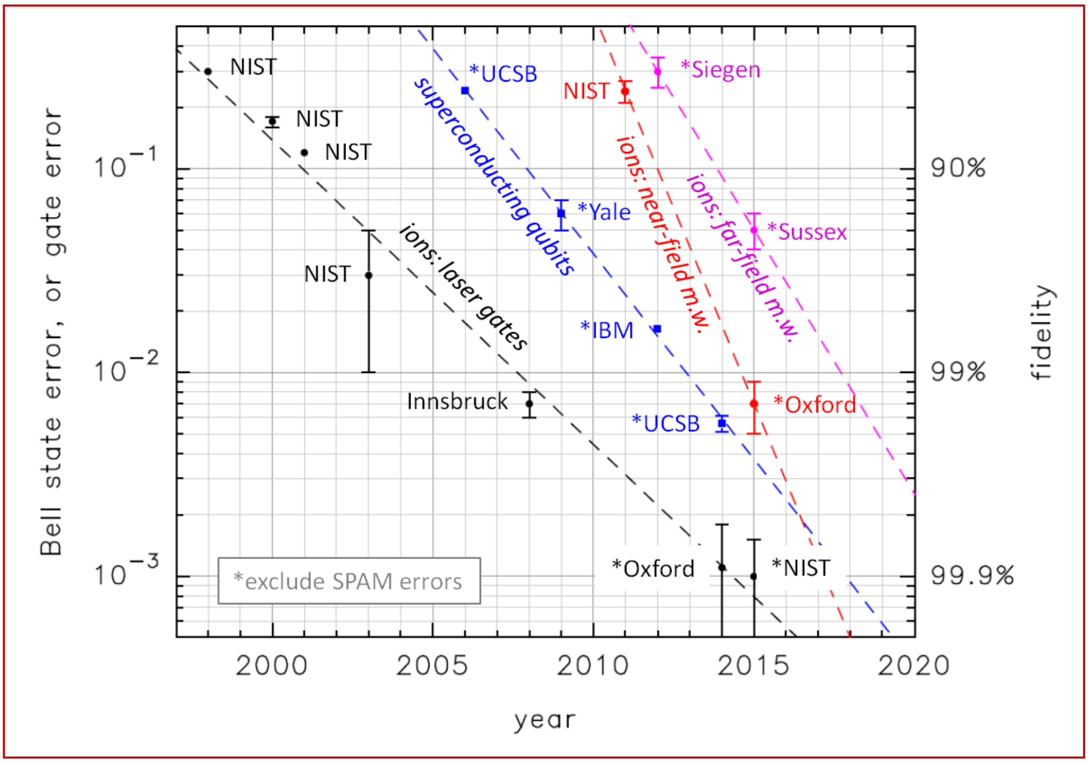

Figure 64: 2 qubit gate history. Note that only the "best" gate is plotted for any particular year. Some numbers have been "normalised" for the sake of a consistent representation. ***courtesy of Professor David Lucas Oxford University***

8.7.10 Issues and challenges

There are a number of issues with quantum computing, most of which need to be resolved before any significant value-adding computational activity can take place.

- Decoherence. To exercise its computational power, a quantum system needs to maintain a superposition of its states. Superposition is by nature extremely fragile and is immediately destroyed when tested (= measured) by any interaction with the environment. In that situation the qubits in the quantum computer cannot continue to evolve in a coherent manner. Therefore, the elements of the system performing the computation have to be completely separated from the environment and no information exchange can take place. This becomes a rapidly increasing challenge as the scale of the system increases, somewhat akin to attempts to maintain wave-like properties in objects of increasing size.
- Thus: Scalability – difficulty of realisation increases rapidly with size. Large machines (> 10^3 qubits plus suitable interaction schemes) are needed for most significant applications.
- The exact benefits of QC are not always well defined and are more limited than most people realise.[371] The current range of applications should be clearly defined by mapping existing quantum algorithms to problems of significant interest. Emphasis should be placed to find more algorithms with, potentially, highly significant or disruptive effects There is a great deal of misunderstanding as to which problems could be usefully addressed by a quantum computer. For example, it would not be advantageous to use a quantum computer to perform ordinary arithmetic[372], although it would be possible.
- Misconceptions: there are many misconceptions about what quantum computing is, how it works and what problems it can solve. See section 6.9.2 for more detail;
- There is a fundamental engineering conflict in the underlying physics between the requirement for complete isolation and the need to interface to inputs and outputs at will. However, recently, we have engineering solutions available that cater for both requirements simultaneously. In trapped ions, for example, turning on the detection laser allows for detection by coupling to the environment, while off-resonant laser fields or microwave fields are used for coherent manipulation whilst not coupling the system to the environment
- Irreducible problem complexity causes trade-off between difficulty of preparing physical states and difficulties in software preparation. This is analogous to the trade-off in classical machines between the complexity of the instruction set and that of the program. It is a "coding" problem in the Shannon sense;[373]
- There is a multiplicity of potential approaches, each with significantly different characteristics and foibles. To explore them all would significantly dilute R&D effort.

[371] A universal quantum machine is able in principle to do anything a conventional universal Turing machine could do, it would just be extremely inefficient to use it for most ordinary tasks

[372] Significant killer apps are likely to offer an "superpolynomial" (loosely, exponential) speedup, i.e. quickly enter a regime where conventional (classical) computing would find the problem impossible with increasing problem size while the quantum computer would not. Many quantum algorithms offer a much more modest speed gain (see The NIST quantum algorithm zoo; most have arguable real world application)

[373] Computing can be viewed as a communication channel between input and output, where the instruction set defines the symbols that are used to translate the information.

Therefore, a compromise must be made between "picking a winner" and the risk of spreading resources too thinly;

- Lack of classical paradigm for many models and concepts makes the area difficult to understand and slows progress;
- Usually, there's a finite chance of getting the wrong "answer". This needs a setup strategy and a verification strategy. Can the answer be verified easily? Are there many similar answers returning the same, or almost the same, measure of success? Note: to measure "how many" rather than "finding" is often in a higher computational complexity class (see notes on boson sampling computers in section 6.9.4.6).
- Error correction and its effect on complexity and scale. Error rate is very strongly determined by gate fidelity, with error correction resources rising sharply when gate fidelity drops below 99.9%. (See Figure 64).

The comments above are generalisations and refer to the physics and engineering challenges. Others, general to all quantum technologies, will be discussed later in this document.

Some of the issues (above) could be mitigated by having a distributed quantum computing system. That would consist of a number of small machines connected by a quantum information network[374].

8.7.11 Synopsis

A demonstration of the technological realisation of quantum computing in scalable, repeatable form (in the context of the conventional "circuit model") is most likely years away. Some argue that a realisation of a fully flexible machine tens of thousands of qubits in size or more is impossible; the answer is not yet known. The Oxford quantum technology hub NQIT[375] aims to demonstrate their "2020" processor by the end of 2019. This would consist of 20 units each of size 20 qubits connected by fibre. Although it will not initially be a universal quantum machine[376] it is planned to demonstrate all the principles required to make large scale, general systems.

A solution based on new technology or new physical insight could emerge at any time. The D-Wave machine represents an heroic engineering effort that has had some success and it is capable of addressing certain optimisation problems. However, it is yet to be definitively demonstrated that it will do any better than an optimally programmed[377] top of the range PC, or be scaled effectively to a size where it can address very important challenges. The boson sampling computer could probably be realised on a significant scale within 5 years, however, it would seem to be limited to addressing a very narrow class of useful problems.

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374 There may be a useful analogy here with parallel (classical) processors in terms of problems that benefit from a networked CPU approach.

375 NQIT = Networked Quantum Information Technologies

376 "Universal" means it will be capable of addressing all BQP (Bounded Quantum Polynomial) problems in real time, i.e. all problems that a quantum computer could address commensurate with its size.

377 This is a very loose concept. An "elegant" program is the shortest possible program that could be written to output a given result. A general test for elegance is impossible to realise in practice and is at least in the NP-hard complexity class. Any deterministic computation can, of course, be done in a single step, but in general the memory required would be 2 to the power of the maximum length of the input string.

Trapped-ion quantum computing demonstrator devices are currently being constructed in the UK (Oxford and Sussex) incorporating technology that in principle *enables* a universal architecture. Both devices are designed with a view of eventually being able to perform the full spectrum of currently known quantum algorithms and digital quantum simulation.

Overall, the potential of quantum computing is powerful but may be limited in its applications, although the full range is not yet fully understood. Some academics are of the opinion that the software, theory and experimental groups need greater coherence.

8.7.12 Applications notes:

Quantum computing has many scientific applications. Some of the most important involve emulation of quantum systems, which will lead to increased understanding and possibly new physics. The study of quantum algorithms is an emerging field that might yield industrial applications in a number of areas. The analysis and manipulation of Big Data may eventually become a significant application, as might expert systems, medical and other image analysis, although these are likely to require very large machines. There is an emerging field studying the utility of quantum information processing for the financial sector, however, it is too early to understand fully the opportunities and limitations.

A number of companies, such as Airbus, Google, Microsoft, Lockheed, have become interested in quantum computing, having already made significant investments in this field. This gives some indication of the type of early adopter that could be expected for quantum computing systems.

8.8 Materials and Nanotechnology

8.8.1 Introduction

Many quantum applications overlap significantly with micro-/nano-technology fabrication and materials science (design, synthesis/fabrication and properties). A full treatment of these large subject areas is beyond the scope of this report, however, there are some potentially disruptive technologies based on solid state and molecular research that are important enough to consider briefly as part of our process.

Silicon, III-V and other "electronic" materials (such as II-VIs, diamond, sapphire, garnets etc.), coupled with the enormous progress in micro- and nano-device fabrication, were two pillars of the first quantum revolution and will play a similar role in the second quantum revolution. In addition, with the explosion in quantum opto-mechanics, stiff structural materials, including silicon and polymers, have become technologically important in this area. In the past 3 decades there has been a huge explosion in the fabrication, understanding and exploitation of new materials including carbon nano- materials (graphene, fullerenes, carbon nanotubes, ...) and soft materials with a host of applications in sensing. Bio-materials have also become of huge interest for sensing devices, in part because of the exquisite specificity possible for molecular recognition, making application to medical diagnostics particularly attractive. Lancaster's Quantum Technology Centre is very active in this area.

Non-covalent materials functionalisation (via π–π interactions, Van der Waals forces, ionic interactions, and hydrogen bonding) of graphene and its oxide and graphene analogues (such as MoS_2 and WS_2) is allowing fabrication of materials with engineered properties. Bio-molecules, polymers, metals and metal oxide-based nano-particles, quantum dots, magnetic nanostructures and carbon allotropes (fullerenes, nano-diamonds, and carbon nanotubes) have all been used. The materials have applications including energy materials, solar cells and water splitting.

In a pure sense, nanotechnology is the application domain and quantum mechanics the science domain although, more practically, nanotechnology is the manipulation of matter on an atomic, molecular, and supra-molecular scale. The US National Nanotechnology Initiative (NNI) defines nanotechnology as the manipulation of matter with at least one dimension in the range 1 to 100 nm. Quantum mechanical effects are important at this scale. Points ("dots"), lines or wires and thin sheets are often called zero, one and two dimensional structures (0D, 1D and 2D) and this "quantum confinement" strongly affects the behaviour of electrons within the structure. Because of the great number of potential applications, governments have invested billions of dollars in nanotechnology research: in 2012, through the NNI, the US has invested $3.7 billion, the European Union $1.2 billion and Japan $750 million.[378] The advances in nano-fabrication have not just enabled new technology but have also demonstrated previously unconfirmed ideas; the effects of one particle on others in a one-dimensional line are much greater than in if arranged in two- or three-dimensions (a "Luttinger liquid").[379]

[378] http://www.thedailystar.net/news-detail-230436

[379] "1D-1D Coulomb Drag Signature of a Luttinger Liquid " D Laroche, G Gervais, M P Lilly, and J L Reno, Science, 343, 631 - 634 (2014) preprint publicly accessible: http://arxiv.org/pdf/1312.4950v3.pdf

8.8.2 Energy generation and recovery

Energy generating and energy saving technologies are crucially important in the commercial sector and could become a source of immense economic benefit. Here, we refer to significant advances in "conventional" quantum technology as well as those potentiated by new thinking. Such systems are governed by non-equilibrium thermodynamics. This allows assessment of the performance of energy-converting devices, such as thermo-electrics or photo-electrics, including determination of the role of quantum effects. These theories are believed to be a valid design paradigm for systems weakly interacting with their surroundings, although for strong system-reservoir interactions, finding definitions for heat, work, entropy and entropy production is a much harder and as yet unsolved problem. Further theoretical work is needed.

Power harvesting devices which harness ambient surrounding energies to produce electricity are a good solution for charging or powering small and medium sized electronic devices. They have small SWAPC parameters and are ecologically safe. Most of these power harvesting devices are realised by utilising MEMS and NEMS fabrication techniques. For example, recent research has demonstrated the possibility of assembling, at the nano-scale level, highly efficient devices that will be able to deliver electrical power from waste heat.[380]

This technology will create a new generation of highly efficient thermoelectric materials and devices by exploiting quantum interference at a molecular level. Proof of principle has already been demonstrated in C_{60} junctions. It is likely to become extremely important if it can be realised on a significant scale. To date, conventional systems have been relatively inefficient and mainly used for minor applications. There is a UK gap in experimental capability, which will need multi-disciplinary collaboration. Maturation of these technologies is still a long way off, possibly circa 20 years for large scale devices?

8.8.3 Displays

Third generation photo-voltaic devices are being designed to achieve high light to electricity conversion efficiencies. These utilise various quantum effects in semiconductor nanostructures, for example via uniform periodic quantum dot (QD) arrays, or multiple exciton[381] generation. 0D QDs have traditionally been fabricated from silicon but lead selenide and cadmium sulphide are also used. Hybrid devices using self-assembled aromatic monolayers (eg. of 4-nitrobenzoic acid), are being designed to achieve higher efficiencies through improved band alignment at the electrodes, and metal oxides are frequently used in hybrid devices to simplify their processing. 1D zinc oxide nanowires with cadmium selenide QDs have been shown to exhibit 60% internal quantum efficiencies. Graphene QDs have been blended with organic electronic materials to achieve high efficiencies in photovoltaic devices at lower cost.

LED technology for displays is convenient because LEDs can be fabricated on a silicon substrate allowing straightforward integration onto standard CMOS circuits or MEMS devices. One research

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380 See for example http://arxiv.org/pdf/1305.3229v1.pdf (molecular wires) and "Engineering the thermopower of C_{60} molecular junctions" Evangeli *et. al.*, NanoLetters (2013)

381 An exciton is a bound state of an electron and an electron hole (absence of an electron from a place where it "should" be) which are attracted to each other by the electrostatic Coulomb force. It is an electrically neutral quasiparticle that exists in insulators, semiconductors and in some liquids.

thrust is to improve the efficiency of light emission in the IR, visible and UV in compact, miniature units. However, the emission colours of QDs can be tuned from the visible throughout the infrared and can create almost any colour in the CIE colour space[382] providing more colours and better rendering than possible with filtered LEDs. QD photon emission is achieved either via photo excitation with a primary light source LED (typically blue or UV LEDs are used) or by direct electrical excitation.

8.8.4 Optical nanoprobes

Optical nanoprobes are optical devices made by precise shaping of an optical fibre to a tip ~ 100 nm wide. Usually the tip is coated in nanoparticles, such as silver, whose surfaces enhance Raman scattering of the light (Surface Enhanced Raman Scattering SERS). The scattered light is modulated by the characteristic vibrations of the object being probed giving, essentially, a spectrum which can be used to identify the object. These SERS nanoprobes produce higher electromagnetic fields enabling higher signal output and accurate detection and identification of samples at low concentrations.

The nano-fabrication profiling of the fibre confines light to sub-wavelength spatial distributions, and together with efficient quantum sources and detectors (particularly at 3 - 5 μm), is expected to allow biochemical fingerprints to be obtained at the cellular or sub-cellular level. To achieve such a level of detail using conventional optics would require the use of very short wave (damaging) radiation and would not yield the spectral data needed for analysis of lipids, amides, proteins etc. Ultimately, in the long term (15-20 years), it is expected that imaging will be achieved by similar or related methods at the sub-cellular level *in vivo*.

8.8.5 Mechanical sensors

Quantum mechanical effects become significant at nano-scales and a well-known example is the presence of Casimir forces at close ranges; these are not yet fully understood and may enable novel technologies, especially in non-trivial geometries where the vacuum modes are constrained by reflective boundaries.

This is a comparatively recent (though extensive) field of research that couples mechanical motions or forces to a read-out system, usually electronic in nature. Nano-mechanical oscillators may exhibit quantum behaviour e.g. assume a superposition of states, and certain mechanical modes may be used for cooling. Some examples of such sensor systems are:

- The interaction between mechanical spin and vibration allows electron spin flips within molecules to be detected via recoil of a nanostructure or carbon nanotube,[383] which subtly changes its conductance. Strong spin–phonon coupling between a single-molecule magnet and a carbon nanotube nano-electromechanical system has been demonstrated[384] and is expected to enable coherent spin manipulation and control of quantum entanglement. In 2015, coherent control of spin transitions in NV centres in diamond using sound generated

[382] https://en.wikipedia.org/wiki/International_Commission_on_Illumination

[383] See this for a popular account

[384] " Strong spin–phonon coupling between a single-molecule magnet and a carbon nanotube nanoelectromechanical system" Ganzhorn *et. al.*, Nature Nanotech. 8, 165 - 169 (2013) see http://www.neel.cnrs.fr/IMG/pdf/Nature_Nanotechnology_8.pdf for publicly accessible version.

by a macroscopic diamond resonator was demonstrated.[385] Likely applications include magnetic field sensing, inertial motion sensing and quantum information processing;

- Quantum nanomechanical cantilevers to perform RF / optical conversion on a single photon level;
- Optomechanical cantilevers for magnetic field detection, atomic force microscopy ("remarkable" displacement sensitivity up to 20 MHz bandwidth), electrostatic actuators etc.;
- Quantum acoustic sensors (e.g. trace gas sensing), mechanical oscillators as quantum coherent interfaces between incompatible systems;[386]
- NASA has demonstrated a metal-oxide-polymer sensor based on tunnelling that changes its voltage-current characteristics when a mechanical force is applied. This is expected to become a self-powered or ultra-low power sensor of exceptional sensitivity;
- Vibrations in graphene have been measured by using strong quantum vacuum interactions to shift the frequency of a quantum optical emitter;
- "Quantum microphone" single phonon detector i.e. detecting sound waves at the quantum limit (an emerging capability). Also, the possibility of single phonon emission is being researched.

This is a field that is likely to grow significantly over the next decade, with more applications becoming apparent as research progresses.

8.8.6 Quantum nano-opto-mechanics

This field has seen a massive expansion in theory and experiment during the past 10 - 15 years. The goal is to control the motion of mechanical resonators at the level of single quanta using optical or electrical means. Applications include determining the fundamental limits of high precision measurements of mass, displacement and force sensing as well as testing some of the fundamental aspects of quantum mechanics.

One of the leading groups working in this area in the UK is at York. Their focus is understanding laser cooling of, and dissipation in, mechanical resonators. Their studies of mechanical dissipation include dissipation and decoherence of high-quality mechanical resonators and vibrational decoherence induced by soft phonons[387], for instance excitons in single-walled carbon nanotubes which may provide an alternative to radiation for transferring energy between sub-systems in a nano-structure (optical nanotransduction). Other work includes investigation of quantum effects in nanoresonators caused by geometric nonlinearities and their associated instabilities.

8.8.7 Synopsis

Nanotechnology is in itself a burgeoning field and the overlap with quantum technology is extensive. We can't cover all of it in this document.

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385 Fuchs *et. al.*, "Coherent control of a nitrogen-vacancy centre spin ensemble with a diamond mechanical resonator." Optica, 2, 233-238 (2015) - preprint at http://arxiv.org/pdf/1411.5325v2.pdf

386 See for example http://www.physics.utoronto.ca/~colloq/Talk2011_Lehnert/Lehnert.pdf

387 Soft phonons have decreased frequency due to a loss of order, usually a decrease in crystal symmetry associated with a phase transition, typically in a crystal that has more than one form of lattice.

Most key areas are not within the envelope of hub activity (James Watt Nanofabrication Centre is an exception).

When mature, nano structured materials will make a significant technological impact, although most are at an early stage of development (typically TRL 1-3). Examples are thermoelectrics, photoelectrics and (possibly) room temperature superconductors. Nanomaterials designed at the atomic or molecular level by quantum computer could possibly have an immense impact, although little is known and development needs to await mature quantum computing.

Nano-mechanical sensors and devices could result in high impact technologies in the long term, especially if they can be fabricated in bulk or as arrays.

9 Conclusions and recommendations

9.1 Conclusions

The quantum technology hubs have made excellent progress since their work started 18 months ago. The UK is leading the world in many aspects of turning quantum physics into technology. International engagement is proceeding and needs to be reconciled with the wealth creation agenda. Skills development has accelerated significantly, with universities attracting some of the best students and world class staff.

The MOD's complementary programme provides a "first adopter" approach for some of the most sophisticated, high risk systems. This will provide impetus in areas where commercial investors and developers would otherwise be reluctant to engage.

Industrial take-up leading to wealth creation is beginning. Some very promising developments are:

- Enabling and supporting technologies (e.g. MOTs, lasers and vacuum components);
- Miniature atomic clocks;
- Portable gradiometers and gravimeters;
- QKD systems;
- Companies wishing to purchase *systems* to provide *services* (e.g. surveying, prospecting and secure networks).[388]

In the medium term we expect a variety of imagers and other sensors to appear on an inventory of wealth creating products, and in the longer term for quantum computing and quantum information technology to become a practical and valuable output.

As the technologies are created and refined we can expect enabling and underpinning technologies to follow, while further opportunities will follow[389] in their wake.

However, at Chicheley 2016, the greatest challenges identified as we approach the midpoint of the first phase are:

- To access and grow markets (with preliminary test examples)
- The knowledge base is still mostly in universities. This needs to be disseminated to the technology exploiters
- For the academics to become yet more flexible
- Focussed investment by research councils (in the basic science) and focussed innovation investment by IUK, once the whole ecosystem has been understood
- "Crystallisation" of supply chains and a complete ecosystem (e.g. chip packaging)

388 For commercial reasons we avoid naming manufacturers and service providers

389 By this we mean that once a very challenging technology is realised, less demanding items become comparatively easy to design and manufacture. This could be described as a "low technology tail". For example, experience in building leak proof vacuum systems at 10^{-7} atmospheres will enable the production of reliable components for other applications.

Quantum physics is still a rich and rapidly advancing field with much yet to be discovered and explained. Completely new opportunities for technological development are likely to arise over the next 20+ years or more.

9.2 Recommendations

9.2.1 Global recommendations

It is important to maintain the "momentum" of our technical developments and their industrialisation. Continuity and commitment by our sponsors is important. Periodic establishment of profitable product lines or new businesses will bolster confidence and bring new actors into the quantum business ecosystem.

Early successes are likely, with new business lines being proposed by companies not previously engaged with quantum technology. The first of these are enablers (such as specialist laser diodes) and subsystems (such as vacuum based technology).[390] As much as possible needs to be done to encourage their take up by industry.

As confidence improves and new "quantum products" are successfully marketed, we need to engage with large scale investors, both as individuals and organisations. For that to be successful we will also need to maintain a pipeline of emerging products and demonstrate that we have a good grasp of applications.

Meanwhile, innovation activities (principally through IUK) are oversubscribed and we recommend that more resource is made available for translation to marketable technology.

Engagement with users and markets should be strengthened to ensure commercially successful products are developed. Potential users need to be made aware of new capabilities that QT could provide, and when it might do so. Some funding should be directed at understanding market needs, and then ensuring appropriate products are developed.

The UK is not a world leader in *every* aspect of quantum technology, and in some areas it may even be seriously lagging. A more detailed analysis of international activity[391] would be helpful to assess the potential of global markets and our position in the race. This would also ensure commercialisation is directed at technologies where the UK does have a strong position and a realistic chance of a large commercial return.

As the rest of the world struggles to catch up, we recommend benchmarking our progress against foreign activities on an ongoing basis.

Capabilities and their implications need to be explained in simple terms that non-technical people can understand, together with benefits resulting from the applications.[392]

390 We can't be specific here since there is commercial sensitivity surrounding new product development and marketing.

391 I.e. conversion of quantum research output into technology

392 Benefits should be separated from features. Loosely speaking, benefits are of core utility and importance to specific customers and will fulfil a need, whereas features do not directly service a requirement.

Some of the conventional markers of success are not as available to graduates, PhDs, PDRFs and academics working in the field of quantum technology. They will probably publish some papers, but as their primary mission will be to work on wealth creating activities, they will need alternative forms of recognition. We must find a way to give them such recognition, and to ensure that well paid and prestigious career paths are available to the best.

It is important to see a virtuous circle formed by the end of the programme, where money and other resources can be fed back into basic research and development physics. This will ensure our technological pre-eminence in the longer term and boost morale and dedication in the fields of fundamental "seed corn" physics. Cost cutting would be very damaging to the medium and long term future.

Specific opinions expressed at Chicheley 2016 were that:

- More attention needs to be given to cross cutting technologies and enablers;
- We should consider picking races rather than winners. In the case of quantum computing and information processing, keep superconducting technology in reserve;
- We need to implement parallel rather than serial development of supply chains;
- We need to understand the whole of the quantum technology ecosystem and its infrastructure;
- Where possible, accelerate development and exploitation;
- We should note that it is too early to redesign the hubs and their structures. We need to build on, and mature, our new way of engagement and structure the bid for phase 2 around our successes and existing outputs and requirements;
- We should discuss the establishment of an industry and supply chain hub, for which we will need entrepreneurs.

9.2.2 Industry recommendations

On the 7th July 2016 the KTN quantum technology special interest group (SIG) held a workshop with industry to understand their recommendations (in the form of a Wish List) for the next phase of the UK national quantum technology programme. The output is summarised as follows:

- Money needs to be invested to develop supply chains;
- We need explicit support for SMEs ... put aside a separate allocation;
- We should avoid using any funding mechanisms which *only* fund academia;
- We need to (Financially) involve OGDs to develop demonstrators (this will likely require identification/creation of public procurement instruments);
- Invest to develop value propositions;
- Continue to fund new quantum science;
- We need to maintain a “drumbeat” in funding calls via Innovate UK;
- Fund some big (~ £10 million) projects - perhaps 3 to 5 over the lifetime of phase 2;
- Attract more globally recognised experts to the UK bringing with them networks, collaborations and funding;

- Co-locate (some of) the research effort;
- Cross-disciplinary funding through to users (including benchmarking);
- Create a central facility for VVUQ[393];

There were also some comments relating to the current structure:

- When funding is renewed the existing Hub structure should be (mostly) retained;
- Consider creation of a fifth Hub - perhaps an industry led packaging Hub or a KTN led "widget" showcase Hub;
- Create a strong executive function - a single, accountable decision making board in place of multiple funding agencies (EPSRC, IUK, Dstl, ...).

393 VVUQ = Verification, Validation and Uncertainty Quantification

10 Appendices

10.1 National programme strategic advisory board membership

Current membership comprises:

- **Professor David Delpy, CBE, FRS, FMedSci, FREng.**
  He Chairs the UK National Quantum Technologies Programme Strategic Advisory Board and is a world-renowned researcher specialising in the development of techniques for the physiological monitoring of patients and especially the imaging of neonatal brain function. He spent most of his academic career at University College London (UCL) where in his research he worked closely with many companies who have marketed the devices developed by him and his team. Most notably, he collaborated for more than twenty years with Hamamatsu Photonics, who have developed market-leading infrared spectroscopy monitoring and imaging technology based on his work. At UCL, he was Head of the Department of Medical Physics and Bioengineering and Vice-Provost for Research. He has served as Chief Executive of the EPSRC and currently Chairs the Defence Scientific Advisory Council.

- **Dr John Bagshaw, FInstP**
  An independent member with extensive experience in engineering RF and Electro-Optic systems, including sensors, photonics, and displays. He has led teams of scientists and engineers responsible for R&D for a number of platforms including spacecraft and aircraft, successfully translating science from early demonstrations of initial concepts to application of the delivered hardware in operational systems.

- **Dr Trevor Cross**
  Trevor Cross is Group Chief Technology Officer at e2v based in Chelmsford, Essex. He is experienced in technology and business development with a focus on technology translation and commercialization. He has held the board level role of Director for Space and Communications and Technical Director and has played a key role in e2v's University engagement programs. He chaired the Technology Strategy Board led Electronics, Sensors and Photonics KTN from 2009-14

- **Professor Peter Dobson, FInstP, FRSC**
  After careers at Imperial College and Philips Research laboratories he was appointed to a University Lectureship and College Fellowship at the Queen's College Oxford and subsequently a Chair, conducting research on nanoparticles, nanostructures, optoelectronics and biosensors. He is currently a Principal Fellow at Warwick Manufacturing Group. He has experience in commercially exploiting university research covering a wide range of applications, from sunscreens to fuel additive catalysts and bio-labels. He built up the Begbroke Science Park to accommodate 24 start-up companies and created new laboratories for University research groups. He holds 30 patents covering a wide range of subjects and has been the Strategic Advisor on Nanotechnology to the Research Councils in the UK and currently sits on several EPSRC panels and committees.

- **Mark Hughes**
  He is CEO of BT's security enterprise, which brings together experts from several parts of BT. Mark is responsible for BT's international security. He ensures that BT has the right policies and procedures in place to safeguard all types of assets. Previously he was commercial director of MWB Business Exchange, where he was responsible for projects including a partnership with the UK Government for the Criminal Records Bureau in Scotland. He is also a member of the Senior Strategic Steering Group of the Centre for the Protection of National Infrastructure (CPNI).

- **Professor Sir Peter Knight, FRS**
  He is Senior Fellow in Residence at the Kavli Royal Society International Centre at Chicheley Hall and immediate past-President of the Institute of Physics. Previously he was Deputy Rector (Research) at Imperial College with responsibility for research strategy and a member of the Imperial College Management Board and Council. He retains his Professorship of Quantum Optics at Imperial with research centring on theoretical quantum optics, strong field physics and especially on quantum information science. He is a Past-President of the Optical Society of America, a Thomson-ISI 'Highly Cited Author' and knighted in the Queen’s Birthday Honours List in 2005 for his work in optical physics. He has chaired the UK Ministry of Defence's Defence Scientific Advisory Council. He has been a member of the Science and Technology Facilities Council and continues to be involved in advising government on science issues. He has been Chief Scientific Advisor at the National Physical Laboratory and currently chairs the Quantum Metrology Institute there. He has won a number of prizes and awards including the Thomas Young Medal and Glazebrook Medal of the Institute of Physics, the Royal Medal of the Royal Society and the Ives Medal of the Optical Society of America.

- **Roger McKinlay**
  After reading Engineering at Cambridge, he has worked in the defence, aerospace, maritime and rail industries. He is a chartered engineer, Fellow of the Institution of Engineering and Technology, Fellow of the Royal Aeronautical Society, Fellow of the Institute of Directors and Immediate Past President of the Royal Institute of Navigation. He started his career as a programme manager on satellite communication and navigation projects, moving on to Avionics when he joined Thales Ltd, where he later became Head of Engineering.

- **Professor Gerard Milburn**
  He obtained a PhD in theoretical Physics from the University of Waikato in 1982 for work on squeezed states of light and quantum nondemolition measurements. He was appointed to a postdoctoral research assistantship in the Department of Mathematics, Imperial college London in 1983. In 1994 he was appointed as Professor of Physics and subsequently Head of Department at The University of Queensland. He is currently Director of the Australian Research Council Centre of Excellence in Engineered Quantum Systems. He is a Fellow of the Australian Academy of Science and The American Physical Society. He has worked in the fields of quantum optics, quantum measurement and stochastic processes, atom optics, quantum chaos, mesoscopic electronics, quantum information and quantum computation, and most recently in quantum nanomechanics and superconducting circuit quantum electrodynamics.

- **Rt. Hon. Baroness Pauline Neville-Jones, DCMG**
  She is a member of the Engineering and Physical Sciences Research Council and has been Minister of State in the Home Office responsible for Security and Counter terrorism and a member of the National Security Council. After leaving government she became the Prime Minister's Special Representative to Business on Cyber Security until March 2014. She has a background in government and the private sector. She has been a career member of the Diplomatic Service (including Head of the Foreign Affairs and Defence Secretariat in the Cabinet Office), Chairman of the Joint Intelligence Committee and Deputy Secretary to the Cabinet. She has served in Washington DC, the European Commission (as Chef de Cabinet to a British Commissioner) and Germany and, as Political Director in the Foreign and Commonwealth Office (FCO) she led the UK delegation to the Dayton Peace negotiations on Bosnia. She became Managing Director for business development at NatWest Markets, the investment banking arm of the NatWest Group and has been non-executive Chairman of the defence technology group, QinetiQ. She became David Cameron's National Security Adviser in opposition and was responsible for the creation of the National Security Council.

- **Neil Stansfield**
  He is Head of the UK Ministry of Defence's newly formed Centre of Excellence for Technology Innovation: the Knowledge, Innovation, and Futures Enterprise. The Centre is focussed on three modes of 'challenge led activity': Grand Challenges, tackling important and complex issues for Defence and Security; embracing future Challenges of and from Science and Technology and the Internal Challenge to ensure that the £1-2 billion translational research investment from MOD is effectively targeted. The early part of his career was spent in scientific research in countering the use of weapons of mass destruction, including supporting the United Nations Special Commission inspections in Iraq following the Gulf War and developing IT methodologies to support these inspections. He has been involved in ballistic missile defence programmes, supporting the negotiation of the Chemical Weapons Convention, ratified in The Hague and was the UK lead in the demilitarisation of old and abandoned chemical weapons. He has also led operating departments providing advice to MOD in chemical and biological defence and subsequently across the maritime domain. He is a graduate of the Royal College of Defence Studies, MOD's flagship development opportunity for senior leaders. Working at the strategic level, he broadened his expertise in wider security matters, and developed a worldwide network of contacts, as well as receiving an MA in International Relations. Before his current role, he was Head of the Delivery Unit for CONTEST, the UK Government's Counter Terrorism Strategy and Head of the Science and Technology Unit.

- **Professor Ian Walmsley, FRS** (current SAB representative of the Hub Directors)
  He is Pro-Vice-Chancellor for Research and Hooke Professor of Experimental Physics at the University of Oxford and Director of the NQIT (Networked Quantum Information Technologies) Hub within the UK National Quantum Technology Programme, which is led by the University of Oxford. He was elected a Fellow of the Royal Society for his contributions to quantum optics and ultrafast optics, including his development of the spectral phase interferometry for direct electric-field reconstruction (SPIDER) technique.

10.2 Strategic capital investments

The Quantum Technologies Strategic Capital investments are held by:

- **Professor Maurice Skolnick, University of Sheffield**

This grant will fund advanced crystal growth equipment to enable the growth of nanometre-scale semiconductor quantum dots with world-leading properties. These properties include emission limited only by fundamental properties of the dots unaffected by the surrounding environment, and ordered arrays of dots, critical to enable scale-up and to translate the science of quantum dots to highly competitive Quantum Technologies.

- **Professor Andrew Briggs, University of Oxford**

Quantum technologies require complex control systems and packaging to ensure that the quantum effects that they use are not corrupted by their environment or external disturbances such as magnetic fields. Complex simulation tools, which allow a 'virtual' prototype of the control and packaging to be created are beginning to be applied to these systems. The aim of this project is to build on this, and develop standard methods that allow detailed simulation of a wide range of quantum technologies. These models and methods will be evaluated by using a test platform to measure the performance of the 'real' hardware against the simulated prototype.

- **Professor Oleg Astafiev, Royal Holloway University of London**

Superconducting Quantum Technology (SuQT) - a state-of-the-art electron beam lithography (EBL) system that will enable the exploration and exploitation of a new generation of SuQT including quantum meta-materials, coherent quantum phase slip (with consequent potential for a redefinition of the unit of electrical current, the Ampere), microwave quantum optics and quantum limited amplification as well as further development of multi-qubit devices. As world leaders in the field Royal Holloway's team will build on its strong collaboration with the National Physical Laboratory and initiate a further collaboration with JEOL, the world-market leaders in EBL systems to form a consortium that can offer SuQT nanofabrication facilities.

- **Professor John Morton, UCL**

Quantum Engineering of Solid-State Technologies, or QUES2T- to address the capability gap in quantum solid-state technologies and ensure the UK is in a strong competitive position in some of the most high-impact and scalable quantum technologies. QUES2T will focus on three solid-state platforms which are poised to make significant commercial impact: i) silicon nano-devices, ii) superconducting circuits and iii) diamond-based devices.

- **Professor Mark Thompson, University of Bristol**

This grant will establish a UK quantum device prototyping service, focusing on design, manufacture, test, packaging and rapid device prototyping of quantum photonic devices. QuPIC will provide academia and industry with an affordable route to quantum photonic device fabrication through commercial-grade fabrication foundries and access to supporting infrastructure. QuPIC will provide qualified design tools tailored to each foundry's fabrication processes, multiproject wafer access, test and measurement, and systems integration facilities, along with device prototyping capabilities.

- **Professor Tim Spiller, University of York**

This grant will connect BT Research and the major ICT and telecommunications cluster at Adastral Park, Martlesham, to the UK Quantum Network (UKQN) being built by the Quantum Communications Hub. This will enable new and direct collaborations between companies at Adastral Park and the Hub partners, accelerating innovation. It will offer QKD and trial quantum-encrypted data services to a large cluster of companies in the very important telecommunications sector. It will enable major Showcase and Demonstration events for quantum technologies, utilising the outstanding facilities at Adastral Park.

- **Professor Richard Curry, University of Surrey**

This grant will allow installation of the world's first single ion implantation tool with 20nm lateral beam focus, with the ability to implant any species from gas or solid source. The tool will serve the UK need for an open access user facility for academia and industry in QTs.

10.3 Quantum technology fellowships

10.3.1 Established career fellows

- **Professor John Rarity, University of Bristol**

Spin-photon systems for scalable quantum processors. This Fellowship will develop technologies that address both classical and quantum applications using single atom-like light emitters embedded in wavelength scale optical cavities (or waveguides) configured as either attojoule optical switches or high-fidelity efficient spin-photon entangling gates;

- **Professor Peter Smith, University of Southampton**

Quantum Integrated Nonlinear Technologies for Enabling Stable, Scalable, Engineered Commercial Exploitation (QuINTESSEnCE). This Fellowship will provide support to build a research team to address industry and academic led challenges in Quantum Technologies. Professor Smith has also recently been elected as a visiting fellow to Dstl;

- **Professor Gerald Buller, Heriot-Watt University**

Next Generation Imaging using Sparse Single-Photon Data. This Fellowship will bridge the gap between the enabling quantum technology and practical image processing to improve the scope and overall performance of next generation imaging systems based on quantum technology;

- **Dr Elham Kashefi, University of Edinburgh**

Verification of Quantum Technology. This Fellowship will deliver an end to end investigation of the verification and validation of quantum technologies, from full scale quantum computers and simulators to communication networks with devices of varying size and complexity down to realistic "quantum gadgets". This goal represents a key challenge in the transition from theory to practice for quantum computing technologies;

- **Professor Douglas Paul**

University of Glasgow: Engineering Quantum Technology Systems on a Silicon Platform. This Fellowship will develop practical quantum technology for the accurate measurement of electrical currents and to develop high sensitivity detectors for gases such as carbon dioxide, methane (the gas used to heat homes) and carbon dioxide. Professor Paul has also recently been elected as a visiting fellow to Dstl.

10.3.2 Early career fellows

- **Dr Jonathan Matthews, University of Bristol**

Photonic Quantum-Enhanced Sensors. This Fellowship will integrate revolutionary quantum-enhanced sensing capabilities and photonic chip scale architectures to enable capabilities beyond the limits of classical physics for absorbance spectroscopy, lab-on-chip interferometry and process tomography (revealing an unknown quantum process with fewer measurements and fewer probe photons);

- **Dr Earl Campbell, University of Sheffield**

Towards fault-tolerant quantum computing with minimal resources. This Fellowship seeks to find a software solution for practical fault tolerance thereby improving the scalability of technologies for quantum computing;

- **Dr Alessandro Fedrizzi, Heriot-Watt University**

QuigaByte-Gigahertz-clocked telecom cluster states for next generation quantum photonics. This Fellowship will accelerate current state-of-the art quantum photonics and deliver gigahertz clocked photonic "quantum bytes"- 8-photon cluster states for telecommunications;

- **Dr Jose Verdu Galiana, University of Sussex**

Quantum Microwave Sensor. This Fellowship will unite atomic physics and cryogenic research to establish the Geonium Chip as a pioneering, practical quantum technology;

- Dr Jonathan Pritchard,[394] University of Strathclyde

A Hybrid Atom-Photon-Superconductor Quantum Interface. This Fellowship will combine three different technologies to create a novel hybrid quantum interface to store, process and generate highly entangled states of photons for quantum networking and cryptography applications, overcoming the short coherence time associated with the scalable superconducting circuit systems.

10.4 ITAR[395] issues

10.4.1 Background:

ITAR is a set of United States government regulations which control the export and import of defence related articles and services on the United States Munitions List (USML) by implementation of the provisions of the Arms Export Control Act. A summary of the USML may be found at the first URL in the footnote [289] below. ITAR's goal is to safeguard U.S. national security and further U.S. foreign policy objectives.

Recent government initiatives are particularly sensitive to ITAR issues because:

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394 Not the author of this paper.

395 ITAR = International Traffic in Arms Regulations:
see https://www.pmddtc.state.gov/regulations_laws/itar.html The US also has the Export Administration Regulation (EAR) that controls lesser risk technologies:
see http://www.bis.doc.gov/index.php/regulations/export-administration-regulations-ear (Note: this link may take several seconds to connect)

- There is an aspiration to exploit quantum technology for UK civil purposes, with UK BIS having assigned over £270M, and the UK MOD over £30M, for exploitation purposes. In this context constraints such as ITAR might prove particularly damaging.

- There is collaboration between UK Universities and various US research institutes, including Lockheed Martin's Sandia Labs (funded by the US Department of Energy) and US DOD laboratories (AFRL, ARL and NRL[396]).

- There is a concern that US technology might be inadvertently built into UK civil and military systems, leading to UK systems also facing ITAR constraints because they have incorporated US knowledge (particularly if US subcontractors are involved in development). There is an additional risk, that US sourced components or materials may be incorporated and this could lead to export constraint should the US so chose.

- The US system is strict, and the incorporation into a system of a single screw sourced from the US and exported to certain designated countries can attract a lengthy prison sentence. UK citizens have been charged and extradited to the US for inappropriately exporting US controlled technology.

The UK has a similar system known as "export control" and there is little difference in principle to the US ITAR, except that the US has an extraterritorial element not present in the UK controls. Generally, these systems are governed by the "Wassenaar" arrangement.[397] This has been established in order to contribute to regional and international security and stability. This promotes transparency and greater responsibility in transfers of conventional arms and dual-use goods and technologies, thus preventing the destabilising accumulation of technology. It provides a list of agreed items, although the control systems are up to the individual countries concerned.

Our programmes and activities also need to heed UK guidelines, which are driven by intelligence led risk assessments and such activities as "Project Alpha", led by King's College London, which is also a source of good advice.[398] Economic considerations are not to be taken into account when considering trade or export restrictions. Contacts within Government can be requested from the authors of this paper and see footnote.[399]

10.4.2 Minimising the ITAR risk: the issues

Several circumstances commonly trigger an ITAR problem:

1. UK may inadvertently incorporate US ideas protected by patent.[400] This is a 'normal' risk which can arise in any development and industry will be alert to such an issue. Patent searches are a routine activity undertaken prior to product development and in the event of

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396 ARL=Army Research Laboratory, AFRL = Air Force Research Laboratory, NRL = Naval Research Laboratory

397 See http://www.wassenaar.org/introduction/index.html

398 See https://www.acsss.info/

399 Further information regarding export control may be found, for example, at: http://bis.ecgroup.net/Publications/EuropeTradeExportControl/ExportControl.aspx

400 Not all of these are in the public domain. At the end of 2010, according to the US Patent and Trademark Office, there were 5,135 inventions that were under secrecy orders invoked via the Invention Secrecy Act of 1951.

an issue industry can either adapt designs or come to a commercial agreement with the patent holder. In the particular case that the patent is held by the US or UK governments, it may be used by the US or the UK for defence purposes, free of charge, under the 1953 agreement. This would not include export for commercial uses as that would not constitute UK defence use;

2. UK may be passed US owned intellectual property (IP) under an agreement between the bodies concerned, and then wish to use it beyond the scope of the agreement. Should this occur it would be a breach of the agreement and the IP owner would have the usual range of legal remedies available. In addition, the US government could apply ITAR restrictions to UK components and systems incorporating that US technology. In particular, 'Technical Assistance Agreements' and hardware exported under DSP83[401] are examples of ITAR controls likely to lead to constraints on use;
3. The UK may be passed US owned IP without constraint, but without appropriate export approvals. In this case the US citizens involved would have committed an offence, and additionally (2) might apply. This is a hazard for academics in particular;
4. The UK may use openly published US technology. In such a case there is no constraint on its use as ITAR does not apply, however, there may be secondary risks as described elsewhere in this list. Evasion strategies such as publishing US technology may be addressed by court action or denial of future access to ITAR technologies;
5. A component or system may contain US sourced components or materials which, should they so wish, the US could choose to restrict. This is most likely to occur when its initial use is within a military system, or exported to certain named countries, and where there is no other source. Therefore, attention should be paid to sole source risks attached to essential components, subsystems and materials initially to be procured outside the US;
6. A system or component sourced completely in the UK and sent via the US can have ITAR control imposed. (The reverse scenario is known as "transit" or "transhipment");
7. Knowhow and IP can inadvertently be exported via movement of students and academic staff. In part, this risk is mitigated by the ATAS scheme;[402]
8. Documents containing information related to ITAR restricted items transferred across a border by any means, including in a laptop or via the internet where US servers are inadvertently involved, (e.g. Google, Drop Box etc.), can be deemed to breach ITAR restrictions covering re-transfer of information. This is illegal under US law. Academics may be particularly susceptible to this issue;
9. Specially designed software is also subject to control and this is often overlooked;
10. One should be aware of the possibility of designers or engineers working on an ITAR product making subsequent designs or products that could be deemed subject to ITAR. This could be

[401] See ITCI (International Trade Compliance Institute) http://www.tradecomplianceinstitute.org/index.php

[402] ATAS = Academic Technology Approval Scheme, see https://www.gov.uk/academic-technology-approval-scheme#overview

whether related to the original or not, due to the potential for knowledge transfer. How much basis there would be for a valid claim is arguable.

Some guidance may be obtained by considering the technology readiness level (TRL[403]). At low maturity levels (TRL 1-3), information is more *likely* to be open source science, above TRL 3 it is more likely to be considered as technology development with accompanying restriction of intellectual property (IP) and proliferation. The boundaries are blurred, however.

10.4.3 Actions:

- The universities, NPL and industrial partners have been made aware of the issues and risks associated with ITAR and intellectual property. A knowledge of UK export control was included. Education and appropriate action has become a responsibility of the hubs, promulgated to all participating universities and their partners;
- A strategy for staff and students etc. employed on the projects or leaving for overseas needs to be decided and implemented. Potentially, workers could be UK nationals, EU citizens, of US origin or even from countries banned from receiving US technology;
- Sessions have been held on the topic, initially at the hubs' directors' meeting in early 2015;
- Annual training to be instituted in the hubs and their partners as appropriate. Larger companies are already expected to participate in mandatory ITAR and export control training;[404]
- Those working on quantum technology projects need to be aware of US sourcing (if there are no alternatives available) and identify these to the relevant PI. Planning for alternatives needs to take place wherever possible;
- IUK has conducted a patent search, with relevant findings being made available to all involved in the quantum programme;
- That a central, top level strategy for ITAR and IP[405] is generated, with the hubs assuming responsibility for its implementation. Arrangements need to be agreed for individual projects before they commence. Project staffing needs to form part of the strategy where there may be sensitive issues;
- It is key to differentiate between USA IP and UK IP that happens to overlap an ITAR item. Therefore, in key projects, we need to make sure that we can demonstrate where *knowledge* originated. In important hub projects we need to ensure traceability.

403 See, for example, the NASA definition at http://esto.nasa.gov/files/trl_definitions.pdf
404 This is available from BIS, see for example https://www.gov.uk/strategic-export-control-training-for-exporters
405 Useful guidance concerning IP may be obtained from the BIS IP office at Newport, see https://www.gov.uk/government/organisations/intellectual-property-office

10.5 Scientific notation

Scientific prefixes and suffixes

Prefix		1000^m	10^n	Decimal
Name	Symbol			
yotta	Y	1000^8	10^{24}	1 000 000 000 000 000 000 000 000
zetta	Z	1000^7	10^{21}	1 000 000 000 000 000 000 000
exa	E	1000^6	10^{18}	1 000 000 000 000 000 000
peta	P	1000^5	10^{15}	1 000 000 000 000 000
tera	T	1000^4	10^{12}	1 000 000 000 000
giga	G	1000^3	10^9	1 000 000 000
mega	M	1000^2	10^6	1 000 000
kilo	k	1000^1	10^3	1 000
hecto	h	$1000^{2/3}$	10^2	100
deca	da	$1000^{1/3}$	10^1	10
		1000^0	10^0	1
deci	d	$1000^{-1/3}$	10^{-1}	0.1
centi	c	$1000^{-2/3}$	10^{-2}	0.01
milli	m	1000^{-1}	10^{-3}	0.001
micro	µ	1000^{-2}	10^{-6}	0.000 001
nano	n	1000^{-3}	10^{-9}	0.000 000 001
pico	p	1000^{-4}	10^{-12}	0.000 000 000 001
femto	f	1000^{-5}	10^{-15}	0.000 000 000 000 001
atto	a	1000^{-6}	10^{-18}	0.000 000 000 000 000 001
zepto	z	1000^{-7}	10^{-21}	0.000 000 000 000 000 000 001
yocto	y	1000^{-8}	10^{-24}	0.000 000 000 000 000 000 000 001

NB: 10^{12} (for example) is often written as 10^12. Aficionados of Fortran may even write it as 10**12

10.6 Some notes on navigation and GNSS

10.6.1 Introduction

Until the 18th Century, navigation over long distances used the stars, compasses, Logs and sextants. Accurate determination of longitude was solved by John Harrison's invention of the marine chronometer for which he won the Longitude Prize in 1773.

10.6.2 Global positioning system (GPS)

Navigation by observation of stars was impossible during daytime and in poor weather. The concept of Artificial Stars, seen through cloud and in daytime, was invented to augment natural stars.

ARPA, the forerunner of the US Defence Advanced Research Projects Agency (DARPA), played a role in developing TRANSIT (also called NavSat) in 1959. From 1973 a joint effort between DARPA and the Johns Hopkins Applied Physics Laboratory began to improve the TRANSIT system and the first Global Positioning by Satellite (GPS) launch occurred in 1978. GPS has subsequently evolved into a space-based navigation system that provides location and time information in all weather conditions, anywhere on or near the Earth where there is an unobstructed line to four or more GPS satellites. Full operational status was achieved by 1995 using a constellation of 24 satellites.

GPS capabilities comprise absolute location, relative movement and time transfer and have become essential to both civilian, scientific and military communities. Uses include:

- Astronomy: for positional and clock synchronization in astrometry and celestial mechanics calculations;
- Autonomous vehicles: for determining locations and routes;
- Cartography;
- Cellular telephony: clock synchronization enables time transfer, which is critical for synchronizing spreading codes with other base stations allowing inter-cell handoff and supporting hybrid GPS/cellular position detection for mobile emergency calls and other applications;
- Clock synchronization: the accuracy of GPS time signals (±10 ns) is second only to the atomic clocks on which they are based;
- Disaster relief/emergency services: for location and timing capabilities;
- GPS-equipped radiosondes and dropsondes: to measure and calculate the atmospheric pressure, wind speed and direction up to 27 km from the Earth's surface for weather forecasting and atmospheric science;
- Fleet tracking: to identify, locate and maintain contact reports fleet vehicles in real-time;
- Geofencing: vehicle tracking systems, person tracking systems, and pet tracking systems;
- Geotagging: applying location coordinates to digital objects;
- GPS aircraft tracking;
- GPS for mining: centimetre-level positioning accuracy has improved mining operations such as drilling, shovelling, vehicle tracking, and surveying;
- GPS data mining: data from multiple users allows understanding of movement patterns;
- GPS tours: location determines what content to display;
- Navigation: uses precise velocity and orientation measurements;
- Phasor measurements: for highly accurate timestamping of power system measurements to compute phasors and synchronise generators on the grid[406];
- Recreation: geocaching, geodashing, GPS drawing and waymarking;
- Surveying: for absolute locations to make maps and determine property boundaries;
- Tectonics: fault motion measurement of earthquakes and estimation of seismic strain build up for creating seismic hazard maps

10.6.3 Other GNSS systems

In addition to GPS, other systems are in use or under development.

The Russian Global Navigation Satellite System (GLONASS) was developed at the same time as GPS, but complete coverage of the globe was not achieved until the mid-2000s. Development of

[406] The consequences of mismatched phases are severe, e.g. a generator could turn into a motor and cause a runaway situation where the 500kV power breakers are tripped and the generator's angular momentum is dumped into a lake or suchlike. (This shows what happens sometimes when the lights flicker before a power failure).

GLONASS began in the USSR in 1976. The constellation was complete by 1995 but subsequently allowed to decline until re-invigorated from 2001 onwards. By 2010, GLONASS had achieved 100% coverage of Russia's territory and in October 2011, the full orbital constellation of 24 satellites was restored, enabling full global coverage. The system has comparable precision to GPS.

The European Union Galileo positioning system currently has 12 of 30 satellites in orbit and operational capability will be offered during 2016.

India's Indian Regional Navigation Satellite System (IRNSS) is used to provide accurate real-time positioning and timing services over India and up to 1500 km around India. IRNSS comprises 3 satellites in geostationary orbit and 4 satellites in geosynchronous orbit.

China's BeiDou Navigation Satellite System consists of two separate satellite constellations – a limited test system of 3 satellites that has been operating since 2000, and a full-scale global navigation system of 35 satellites that is currently under construction with a completion date of 2020.

The Japanese Quasi-Zenith Satellite System is a proposed four-satellite regional time transfer system and Positioning System that will be receivable within Japan. The first satellite launched in September 2010 and the four-satellite system is planned to be operational in 2018.

10.6.4 Drivers to augment GNSS

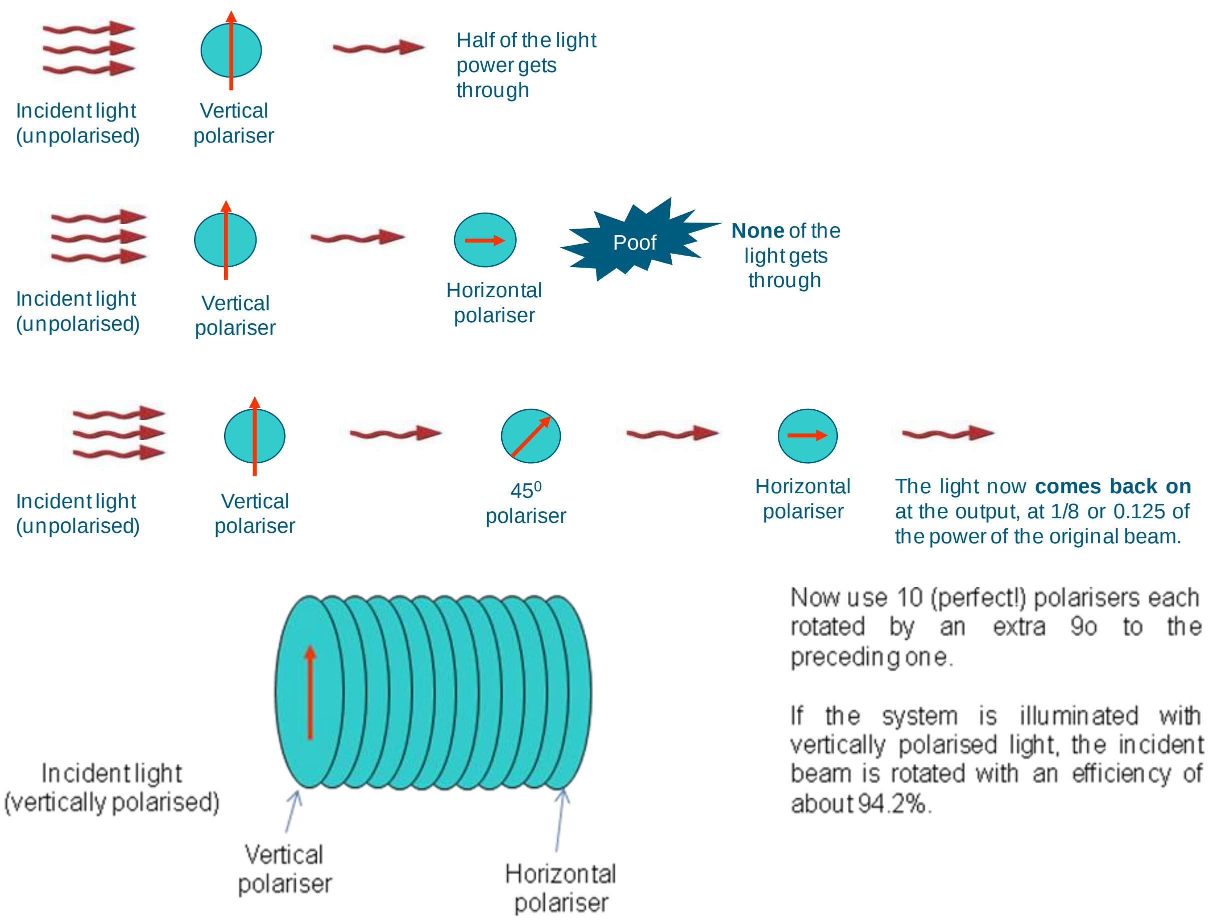
GNSS does not work where there is not a direct line of sight to at least 4 satellites. This denies positioning and timing synchronisation service underwater, in Space, underground or in buildings and can be critical to business function.

In Defence, this vulnerability to loss of service is a major concern as is local jamming or spoofing of GNSS signals. Precision warfare completely relies on precision navigation and timing and loss of GNSS implies reversion to earlier area destruction weapons, rather than precision guided munitions.

Resilient navigation and precision synchronisation might also be achieved by high power terrestrial signals, like eLORAN. Inertial navigation using state of the art classical inertial sensors (accelerometers and gyros) together with clocks and devices to measure local gravity and altitude (and increasingly magnetic field) at best allow a navigation accuracy of no better than 2 km/day and the strategic grade systems required are expensive.

10.7 Illustration of the quantum Zeno effect

The quantum Zeno effect has a number of counter-intuitive consequences. We illustrate one example below:



10.8 Glossary and abbreviations

Term	**Definition**
A	Amp, or Ampere, a unit of current
Al	Aluminium (element)
Analogue	A physical analogy, as opposed to digital, which represents a system with binary numbers
ASG	Atomic Spin Gyro (gyroscope)
ATM	Automatic Teller Machine (cash machine)
BB84	The original QKD protocol described by Bennett and Brassard in 1984
BEC	Bose-Einstein Condensate - a state of matter very close to absolute zero temperature where the atoms act together as a single quantum mechanical wave
BIS	Department of Business Innovation and Skills
Black body radiation	The characteristic spectrum of electromagnetic (heat) radiation emitted from an item
Bohr model	The model of the atom proposed in 1913 where electrons orbit the nucleus like planets around the sun (they don't)
Cantilever	Rigid or semi-rigid structural element anchored at only one end
CCD	Charge Coupled Device, sensitive low power device used for detecting photons, especially in modern electronic cameras
CDT	Centre for Doctoral Training
CMOS	Complementary Metal Oxide Semiconductor
Correlated	Loosely, sharing information or a tendency to be synchronous
CPT	Coherent Population Trapping - refers to ensemble of atoms used in an atomic clock to produce the timing signal
Cryogenics	Conventional apparatus for cooling of systems, usually operating at 0.002-tens of degrees absolute (Kelvin)
Cs	Caesium (element)
CSA	Chief Scientific Advisor
CSAC	Chip Scale Atomic Clock
Dark fibre	Fibre link(s) not yet in service for carrying bulk traffic
DARPA	Defence Advanced Projects Agency (US)
Diode	Component arranged to let electrical current flow in only one direction
DOF	Degree Of Freedom
Doppler shift	Characteristic rise or fall of a received wave frequency depending on the speed of approach or departure of the emitting object
DOS	Denial Of Service
Dstl	Defence Science and Technology Laboratories (MOD)
DTC	Doctoral Training Centre
E or Eo	Unit of gravitational gradient. At the Earth's surface, the gradient is approximately 10^{-7} Gal per metre.
E91	An advanced QKD protocol using entanglement proposed by Artur Ekert in 1991
Eigenstate	A definite, separable and observable state of a system

E-LORAN	Enhanced-Long RANge Navigation - a system instituted in the second world war for navigation by timing signals emitted by a network of transmitters, now largely superseded by GNSS
Ensemble	Well defined collection or group (in a non-mathematical sense)
Entanglement	Non local connection between quanta
EPSRC	Engineering and Physical Sciences Research Council
FPGA	Field Programmable Gate Array - complex microelectronic circuit whose functionality can be programmed by software. It is more general and fundamentally versatile than a microprocessor.
FRS	Fellow of the Royal Society
GaAs	Gallium arsenide - semiconductor compound
Gal	Unit of gravitational field strength, defined as 0.01 metres per second per second (equivalent to an acceleration
GCHQ	Government Communications Headquarters
Getter	A substance that absorbs certain kinds of contaminants in vacuum chambers to help maintain the vacuum. Used extensively in thermionic valves.
GNSS	Global Navigation Satellite System
GPS	Global Positioning System (US GNSS system)
Gravimeter	Device for measuring gravitational field strength
Gravity gradiometer	Device for measuring the local *gradient* of a gravitational field
Hub	One of four lead universities for quantum technology development
Hyperfine splitting	Very small splitting of energy levels in an atom
IARPA	Intelligence Advanced Projects Agency (US)
IMU	Inertial Measurement Unit
Interferometer	An instrument that operates by interfering waves
Ion trap	A trap containing a charged atom, built from electromagnetic fields
IUK	Innovate UK - a government organisation tasked with stimulating the development of new business and technology
J	Joule, a unit of energy. Do not confuse energy with power. Power is the *rate* of energy delivery.
KTN	Knowledge Transfer Network
KTN	Kelvin, a measure of temperature. 0K is absolute zero on this scale
Lattice	Regular 1, 2 or 3 dimensional array
LED	Light Emitting Diode
LIDAR	Light Detecting And Ranging (standoff imaging device)
MEMS	Micro Electro Mechanical System
MIT	Massachusetts Institute of Technology
MIT	Massachusetts Institue of Technology (US)
MOD	Ministry of Defence
MOT	Magneto-Optical Trap. An ultra-high vacuum trap for the containment of cold atoms
NDFIS	National Dark Fibre Infrastructure Service
NEMS	NanoElectroMechanical System
NIST	National Institute of Science and Technology (in the US)

Noise	Not usually audible noise. Refers to a random perturbation or distortion, often caused by background low level thermal effects
Non classical light	Light that can't be described by classical electromagnetism i.e. Needs a quantum vacuum description
NPL	National Physical Laboratory
NQIT	Networked Quantum Information Technologies (Oxford hub)
NQTP	The UK National Quantum Technology Programme
NV	Nitrogen Vacancy. Usually refers to diamond, where a pair of carbon atoms in the lattice may be replaced by a nitrogen atom and a gap, resulting in a "colour centre"
OAM	Orbital Angular Momentum. A free photon or electron can possess this characteristic as well as its intrinsic spin. It can be thought of as a corkscrew-like phase profile.
OGD	Other Government Department
PDRF	Post-Doctoral Research Fellow
Photon	Quantum of light, or other electromagnetic radiation
Pixel	Smallest area of a display, usually square or rectangular. Some may have three or more components (e.g. Red, green and blue)
POG	Programme Operations Board (for the NQTP)
Polymer	Substance made from aggregates of similar molecules chemically bonded together to form chains or other structures
QD	Quantum Dot
QDS	Quantum Digital Signature
QDS	Quantum Digital Signature
QKD	Quantum key distribution (for encryption)
QMI	Quantum Metrology Institute at the National Physical Laboratory
QUANTIC	UK quantum hub in quantum enhanced imaging
Quantum	Smallest, indivisible fragment of physical unit, particle or wave
Quantum 1.0	Predominantly 20th century quantum technology
Quantum 2.0	Technology arising mainly from recent developments in quantum physics
Quantum dot	Nanoscale semiconductor features that that tightly confine either electrons or holes (absence of same) in three dimensions. They are often referred to as "artificial atoms".
Quantum logic	Quantum analogy to classical logic but containing counter-intuitive entities (e.g. The square root of "NOT")
Quasi particle	A combination of effects or quanta that behave as a particle, e.g. a phonon is the smallest "particle" of sound in a solid
Qubit	Quantum analogy to the classical "bit" of information
Rb	Rubidium (element)
RBB	The Research Building Block - the MOD research budget
RNG	Random Number Generator
Rydberg atom	An atom in a fragile state where the outermost electron is an unusually distant from the nucleus
SAB	Strategic Advisory Board (for the NQTP)
SERS	Surface Enhanced Raman Scattering

Shot noise	The noise caused by single electrons, as an electrical current is not infinitely divisible
Shot noise	Quantisation of a signal caused by the quantisation of the underlying carrier, for example shot noise in a circuit is caused by electrons moving one by one
SIG	Special Interest Group (usually refers to the quantum SIG of the KTN)
SPAD	Single Photon Avalanche Diode
SRL	System Readiness Level
SRL	Strontium (element)
Stark shift	Splitting of atomic energy levels in an electric field
Superconducting	A cooled regime in which the resistance of a substance has fallen to zero
Superposition	Existing in two or more places, or with two or more values, at once
SWaP	Size, Weight and Power
SWAPC	Size, Weight, Power and Cost
TCSPC	Time Correlated Single Photon Counting
Tesla T	Unit of magnetic field strength succeeding the Gauss, which is 100 μT. The Earth's field is approximately 32 μT
TRL	Technology Readiness Level - from 1 (conception) to 9 (fully mature)
TSB	Technology Strategy Board, now known as Innovate UK (IUK)
Tunnelling	The ability of a quantum wave to escape an energy barrier or container (see main text)
UKQN	UK Quantum Network - a test bed for integration of quantum and conventional communications
UTC	Universal coordinated time, an international standard for the "right time"
VVUQ	Verification, Validation and Uncertainty Quantification
W	Watt, a measure of power i.e. Joules (J) delivered per second
W or Watt	A measure of power, i.e. Energy delivered per unit time
Yb	Ytterbium (element)
Yb	Ytterbium (element) (not to be confused with Y (yttrium))
Zeeman effect	Splitting of atomic energy levels in a magnetic field

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