Government
Office for Science

Technology and Innovation Futures 2017

Foreword

The promise of technology – in medicine, transport, construction, communications, entertainment and many other areas – dominates the modern world and its discourse. In this digital age, a slew of technologies hold out the prospect of greater health, freedom, security and convenience.

We can never be certain, of course, about which technologies will eventually have the greatest impact on growth, on our society or further afield, as we confront global challenges. Part of the value of horizon scanning lies in anticipating a range of possible outcomes, as well as identifying potential risks.

Nevertheless, the key insight from this report is that increasing interactions between technologies and between data sets will create opportunities to make the UK more productive and our public services more efficient.

This country already has a range of bodies which enable interactions, but we can do more to reinforce the UK's place at the vanguard of innovation: demonstrator facilities, standards for technological interoperability and coordinated effort within government itself all matter.

We shouldn't leave these mechanisms to chance. We're creating UK Research and Innovation: a single organisation that will facilitate greater collaboration across scientific disciplines and internationally to make the UK the best place in Europe to develop new technologies. By harnessing clear domestic strengths in pure and applied science – by combining existing technologies as well as innovating from scratch – we can position the UK at the forefront of new markets, industries and delivery models.

JO JOHNSON
Minister of State for Universities,
Science, Research and Innovation

Organisation

This report comes in two parts.

The first, "Findings" (page 4) sets out the context for the research project and its conclusions.

The second, “Convergence and disruption” (page 13), expands upon the central messages of the first part. It explores how technological interaction is occurring (page 14).

It then highlights opportunities (page 18) created by that interaction in health, food, living, transport and energy.

Findings

The invention and adoption of technologies continues to transform our world. This is most readily apparent in our latest modes of communication and consumption. Facebook alone connects over one and a half billion people each month. We tweet 500 million messages every day – in addition to the billions of texts. We order what we want online – increasingly via smart phones – and often receive those goods and services the same day, sometimes within the hour. Indeed, certain digital products and applications arrive almost instantaneously, and can be stored on remote servers for use on demand.[1]

"Just 10 years ago, sequencing an entire genome required tens of millions of dollars; it can be done today for under a thousand"

Less visible but still significant, advanced manufacturing is entering a new era. Machine intelligence is disrupting time-honoured methods, offering cheaper goods that can be more easily customised, greater productivity and an explosion of associated services. Components for aircraft and high-performance racing cars are already being made on 3D printers. Such developments are challenging the model of labour-intensive factories and complex supply chains; long delays between prototype and product are no longer inevitable.

In other spheres, the past 20 years has seen technological advances driving a renaissance in space exploration, from the surface of Mars to the first ever comet landing. Satellite technologies continue to enable new communications and navigation capabilities. In the life sciences, we have sequenced the genomes of multiple organisms, including our own. Just 10 years ago, sequencing an entire human genome required tens of millions of dollars; it can be done today for under a thousand.[2]

Government interest in next-generation technologies is fourfold.

- It is looking for potential enablers of long-term economic growth and productivity in the UK.
- It is seeking the means to improve the delivery of public services.
- It wants to understand opportunities to enrich the lives of our citizens, as the internet has done, while mitigating risks associated with technology.
- Finally, it is interested in ways that technology might enhance and inform policy development within government itself, particularly by gathering better and more detailed evidence.

1 newsroom.fb.com/company-info; www.internetlivestats.com/twitter-statistics. (All web links working in January 2017.)
2 www.nature.com/news/technology-the-1-000-genome-1.14901.

This report aims to inform longer-term policy thinking and investment decisions in science, technology and innovation – as well as to highlight the challenges that government as a whole is likely to face in seeking to reap the full benefits of emerging technologies. It has been produced by the Government Office for Science (GO-Science), as part of its role to maintain a watching brief on such technologies. This report is a deliberately broad survey that complements the in-depth analyses that GO-Science also produces on individual technologies and domains. For example, GO-Science has most recently issued reports on the applicability of forensic science methods beyond the courtroom setting with which they are most commonly associated, on distributed ledgers, artificial intelligence and quantum technologies.[3]

The TIF series

This report represents the third iteration of the Technologies and Innovation Futures (TIF) exercise, the first of which was carried out in 2010. The previous report in 2012 (TIF2) identified a number of significant, multi-use technologies, subsequently classified as the Eight Great Technologies:

- Advanced materials
- Satellites
- Energy storage
- Robotics and autonomous systems
- Agri-science
- Regenerative medicine
- Big data
- Synthetic biology

These have received a combined £600 million of public investment. Using additional evidence gathered during TIF2, the Government has also invested a combined £305 million since 2012 in two further broad areas: quantum technologies and the internet of things; these, too, are developing at pace.[4]

TIF3 has not unearthed new technological domains. But since TIF2, these technologies have moved towards or already delivering economic gains and other practical benefits. The Government is sponsoring work on the use of remotely piloted drones in a variety of real-world settings. The roads of Coventry, Greenwich, Bristol and Milton Keynes are set to become trial sites for connected and autonomous vehicles. There is a broader constellation of satellites available for weather forecasting and many other types of Earth-based monitoring, with increasing deployment of "CubeSats" set to expand capacity and significantly bring down costs. CRISPR gene editing, which can precisely change the DNA of nearly any organism, is now available – with the ultimate prospect of curing such debilitating conditions as sickle cell anaemia.[5]

3 www.gov.uk/government/publications/forensic-science-and-beyond; www.gov.uk/government/publications/distributed-ledger-technology-blackett-review; www.gov.uk/government/publications/artificial-intelligence-an-overview-for-policy-makers; www.gov.uk/government/publications/quantum-technologies-blackett-review.

4 www.gov.uk/government/publications/technology-and-innovation-futures-uk-growth-opportunities-for-the-2020s.

5 CRISPR stands for clustered regularly-interspaced short palindromic repeats.

Role of government

CRISPR reminds us, however – as have distributed ledgers – that we often cannot predict which application of any given underlying technology is going to have a defining impact. There are a number of competing gene-editing techniques in development, but CRISPR's low cost and accuracy have made it stand out for specific uses. Indeed, cost-effectiveness, reliability and ease of use are essential features of all disruptive applications – whether one thinks of taxi or holiday accommodation services, or crowd-sourced funding models for business. Similarly, the internet of things, on which GO-Science issued a report in 2014, is dependent in part on the falling price and increasing availability of semiconductors, which have enabled the proliferation of sensors, transmitters and controllers.[6]

> "We often cannot predict which application of any given underlying technology is going to have a defining impact"

Attempts to identify and support particular "killer apps", therefore, should not be within the remit of government; that is the preserve of the private sector. Government's attention should be on articulating a clear vision for UK innovation as a whole: on creating an environment in which underlying technologies can be developed, and helping business, where it can, to overcome the challenges specific to each of them.

Approach in TIF3

TIF3 is the first iteration of the report to explore emerging technologies through a public sector lens as well as a private one. It has also included a wider range of inputs than its predecessors. It received more than 1,000 responses from academic and industrial technologists to an online survey covering the emerging technology landscape. These views were then evaluated alongside a comparative analysis of international patent activity at a series of expert roundtables, to build a picture of the UK's technological strengths and to explore some examples of plausible applications.

Evidence base

- Over 1,000 crowd-sourced responses from academic and industrial technologists
- Data analysis of Intellectual Property Office's 20,000 patents and Innovate UK and Research Councils' research grants
- Literature review of around 100 articles published since 2012
- Seven roundtables involving more than 80 experts from industry, academia and the investment community
- Market potential analysis of over 50 technologies

6 www.gov.uk/government/publications/internet-of-things-blackett-review.

Convergence and interaction

As noted above, the most interesting conclusions to emerge from TIF3 did not involve the identification of wholly new technologies or domains. Rather, the expert contributors argued that the greatest future opportunities – in both productivity gains and public service delivery – lie in enabling existing and emerging technologies to interact with each other, and from making the resulting applications readily available to the public. These applications could disrupt and displace existing markets for goods and services. The potential for disruption also lies in acting upon the fresh insights gained from consumer data, as well as from datasets mined in unison for the first time, once compatibility and barriers to safe sharing have been tackled satisfactorily. Doing both would also provide a more detailed evidence base for government to develop more directed policies and to allocate finite resources more efficiently.

Convergence and interaction are not new ideas. The latest mobile telephony depends on a raft of technologies: transmitters, sensors, data storage, battery and power management, and user interfaces, among others. Some homes are already powered by solar cells and batteries, controlled by smart meters and appliances. The internet of things, however, has signalled the potential for technological interaction of a different order and scale – offering the prospect of literally billions of everyday objects communicating with each other to transform transport, home life and energy efficiency.

> "The greatest future opportunities lie in enabling existing and emerging technologies to interact with each other"

Impact

Such convergence will yield applications benefitting, among other things, our cities and public health. In the field of forensics, we concluded that genomic science, information technology, machine intelligence, the internet of things and quantum technologies are coalescing to power major advances in analytical power.

The value of technologies interacting to offer practical solutions can be further illustrated by considering the challenge of our ageing society. Already, we can realistically envisage the prospect of blended systems where humans, robots, sensors and software operate together: enabling older people to be economically productive for longer, thanks to technological assistance at work; and to live independently for longer, thanks to assistance at home and on the move. Both types of assistance ultimately promise productivity and cost benefits – in addition to improving quality of life for a growing proportion of our population.

Farming is another area where the combination of synthetic biology, sensors and accurate geo-location could mean more efficient pest control, food production and, in turn, more effective land allocation. Disease-resistant, nutrient-rich and high-yield crops could be planted in optimal environments, using big data insights to match them to soil types. Farmers would then be able to monitor crop growth remotely and in real-time to understand drivers of productivity variance and refine their business plans.

Implications

This exercise has generated findings consistent with other horizon scanning by government into such areas as the future of work and decision making. It highlights the need, for example, to anticipate and debate the long-term ramifications of artificial intelligence and autonomous systems: more robots working alongside humans; drones sparing humans from performing dangerous inspection functions; artificial intelligence helping citizens to navigate their way through public services.

But one key recommendation from those consulted through TIF3 is that government should act more systematically in supporting the advancement of emerging technologies. It should ensure greater coordination among departments to help bring technologies to market. The feedback from the expert roundtables was that government has long been adept at working with established technologies and sectors. Where they want to see a more proactive approach from government is in formulating a concerted response to the opportunities presented by emerging technology platforms – whose salience cuts across policy areas and requires collaboration between different government departments. This accords with a number of recommendations in Paul Nurse's review of the Research Councils.[7]

Levers

We have has also given thought through TIF, therefore, to the main activities government can undertake to support technologies, address market failures and tackle roadblocks to innovation. These are summarised in the table on page 9.

Government, of course, already deploys these levers to support technologies and move them closer to market, though the sense from contributors was that it sometimes does so in an ad hoc manner. It takes steps – among other things – to maintain a pro-innovation regulatory environment, address high-level skills needs in the longer term and to stimulate demand through public procurement.

Indeed, there are several examples of the UK boosting its comparative advantage: implementing judicious regulation of stem cell research; enabling a future for autonomous vehicles; focusing investment in graphene; and establishing the Alan Turing Institute for Data Science. The BEIS-led Challenger Business Programme, for example, has looked at unmanned aerial vehicles (UAVs), education technologies, and the satellite and commercial space sector to help innovative firms enter and grow in their target markets. More recently, GO-Science has collaborated with other departments on value chain analyses of the UAV and connected and autonomous vehicle markets – to understand which segments present the best long-term opportunities for UK business and R&D.

7 www.gov.uk/government/publications/nurse-review-of-research-councils-recommendations.

Government policy levers for supporting emerging technologies

Early intervention	Market framing	Adoption & integration
Catalyser Analyse value chains to identify which technologies present opportunities and long-term value to the UK	**Regulator** Ensure regulation is sufficiently agile and permissive to enable technology interactions and innovative applications	**Intelligent customer** Develop a procurement environment that encourages big businesses to engage with SMEs in public contracts – allowing them to demonstrate capability and build commercial links
Innovation facilitator Create test beds for developers to try out applications in real-world settings, assess scalability and engage with the public	**Standard setter** Use insights from "living labs" to develop UK standards – setting the global agenda by "showing, not telling"	**Platform provider** Scale up deployment of proven technologies in national infrastructure, the NHS and other public services
Skills planner Prepare for growing demand for workers with multi-disciplinary technical skills, and mitigate the impact of robots and machine learning replacing unskilled and graduate-level roles	**Fiscal incentiviser** Deploy financial and other mechanisms to stimulate innovation and market growth	

Other countries are similarly engaged, such as Singapore, which has gained a leading international position in information technology through ensuring a pipeline of highly skilled workers, investing in infrastructure and being willing to experiment at scale. Japan, meanwhile, is a frontrunner in robotics, and is seeking to maintain its lead by establishing the Robot Revolution Initiative Council. In the UK, there are opportunities to be more systematic in the use of levers at government's disposal, to achieve similar ends. To improve public services, in particular, we should ensure active consideration of available policy options in future work on emerging technologies.

Real-world testing

Demonstrator facilities speed up the emergence of early-stage disruptive technologies. Contributors stressed the importance of establishing further "test beds" to experiment with emerging technologies in carefully supervised real-world systems, like cities, as opposed to laboratories. Test beds enable innovation by being open to a wide range of users from the outset – with a culture both unafraid of failure and alert to solutions which could be deliverable at scale. There are some UK facilities which fulfil this remit in various ways. For example, the NHS test bed programme is responding to priority challenges such as dementia, diabetes and the management of long-term conditions. The programme has matched businesses, large and small, with trusts and hospitals to trial combinations of technologies together with innovations in how services might be delivered.[8]

"Test beds enable innovation by being open to a range of users at the outset – with a culture unafraid of failure and alert to scaleable solutions"

Another example is the regulatory sandbox launched by the Financial Conduct Authority (FCA), following a recommendation contained in GO-Science's report on financial technologies.[9] The sandbox provides a safe space where companies can test innovative products, services, business models and delivery mechanisms without immediately incurring the normal regulatory consequences of engaging in such activity. As well as reducing risk for business, it allows the FCA to work with innovators to ensure that appropriate consumer safeguards are built in to new offerings.

But the message was that we could do more to create test beds in complex environments. Some organisations already have capability to test their intellectual property (IP) in complex systems like urban environments through self-selecting partnerships or closed contractual agreements. Test beds would create equivalent opportunities for any business or entrepreneur with a relevant technology-based application to try out. With more businesses competing and collaborating simultaneously, there is increasing room for creative interactions that can bring about promising solutions appropriate to those systems – solutions which government itself might procure to improve public services. GO-Science will work with the Cabinet Office, BEIS and other government

8 www.england.nhs.uk/ourwork/innovation/test-beds.
9 www.gov.uk/government/uploads/system/uploads/attachment_data/file/413095/gs-15-3-fintech-futures.pdf.

departments and agencies to identify opportunities for new test beds or for repurposing existing facilities – and to gather evidence of best practice and economic impact.

In addition, test beds offer existing or aspiring high-tech clusters the chance to advance their innovation credentials. City councils and local authorities in the UK are already recognising the leverage to be gained from co-locating demonstrator facilities alongside university researchers and technology firms. With the right ambition and focus, UK cities and regions can keep pace with agile countries like Singapore that also see these benefits.

Standards

A third theme strongly emerging from TIF3 was the need to develop workable standards for technological interaction. Test beds themselves highlight the fundamental importance of standards to enable different items of hardware, software and data to interact to yield new applications – and to then scale and export those applications. When this is done well, it can yield substantial benefits both domestically as well as internationally. When mobile telephony was in its infancy 30 years ago, for example, the UK was influential in the development and promotion of the European GSM technical standard. While eventually dealing a hammer blow to applications such as pagers and cordless phones, GSM was instrumental in hastening the ongoing mobile revolution. More recently, the BSI has created and shared open standards for Building Information Modelling (BIM) and for smart cities, with both subsequently taken forward for international adoption by the International Organisation for Standardisation (ISO). In the case of smart cities, some 60 countries have now begun to use standards developed first in the UK.

> “Government would benefit from a clearer understanding of the value of standards”

Where appropriate, this open approach should continue: catalysing further innovation and seeking to gain first mover advantage for the UK, while continuing to influence international standards bodies so that all parties ultimately benefit. Government as a whole would also benefit from a clearer understanding of the value of standards.

Conclusion

The findings from TIF3 imply a fresh set of challenges for the UK around catalysing collaboration.

In the case of government, which has focused to date primarily on supporting the advancement of specific areas of technology, a balance needs to be struck between continuing that agenda and also supporting technological interaction to generate additional economic and social benefits. Both, though, should be part of our expressed ambition for UK innovation and the strategic thinking we devote to this sphere of policy and activity.

Clearly, this cannot be a matter for government alone. Achieving technological interaction requires input and collaboration from the research base and UK business as well – not least to engage the public on sensitive issues around digital privacy and data sharing to gain informed buy-in for transformative applications.

The applications envisaged in this report will, I hope, persuade readers – whether policy makers, scientists, business leaders, or simply those with a lay interest – that a collaborative national effort to reap the full benefits of emerging technologies is worthwhile. We already have many of the key ingredients required to succeed, especially a world-class research base, the expertise of Innovate UK and growing high-tech business clusters focused around disciplines including life sciences, quantum, artificial intelligence, robotics and e-commerce. Together, we should seek to capture more value for the UK economically and to deliver the effective and accessible public services enabled by the best uses of emerging technologies.

Sir Mark Walport
Government Chief Scientific Adviser

Convergence and disruption

The key conclusion from this report is that technologies are converging to create important applications for businesses and consumers, and for governments and citizens, in multiple contexts. They promise significant productivity gains as well as improvements to the delivery and individual experience of public services. A major feature of this trend will be the influence and application of data-derived insights – some of them generated by machine intelligence – in designing and improving both goods and services.

This section considers technologies at two levels.

First, it looks at the basic elements underpinning a convergent digital world: sensors, data, means of transmission and connectivity, algorithms to analyse and automate, and user interfaces to monitor and control. A similar (but less developed) trend is underway in biology, where vast amounts of data, the manufacture of synthetic parts, gene editing and bio-computers to manipulate our bodies are giving rise to disease-resistant crops, new medical treatments and the ability to regenerate tissue.

Second, it explores the consequences of convergence in important domains like healthcare, energy, transport, food, and work and leisure. In essence, the interaction and interoperability of technologies could transform the world around us and create opportunities to improve our own physical condition, our environment and help to address many of the challenges we face now and in future.

Included in this narrative is additional detail about certain categories of disruptive technology, including robotics and autonomous systems and quantum technologies. Their importance extends beyond the trend of convergence itself, not least as technologies relevant to the twin aims of boosting national economic productivity and improving public service delivery.

TIF is neither a blueprint nor a strategy, but aims to assist policymakers in ensuring that the UK remains technologically agile and alive to both the opportunities and risks posed by a range of possible futures. It is also necessarily speculative, a synthesis of the views of the contributors. Some scenarios will be achieved by means similar to those outlined here. Others will be realised using quite different methods or not at all – dependent upon the development of as yet unknown technologies, or changing social challenges and priorities.

Technologies in TIF3

The 53 areas of technology surveyed during the second TIF exercise in 2012 were the starting point for this refresh.[10] An online survey sought the views of tech-based businesses, academics and industry analysts regarding the continued salience of these technologies (and asked participants to identify any new ones which might have subsequently emerged). The survey responses were reviewed by the Government Office for Science and the chief insights – together with summaries of technology-related patent analysis and research grants – were then tested at six expert roundtables.

These roundtables covered broad areas of technological activity, including domains where they might be most disruptive: quantum; energy and materials; data, computing and sensors; synthetic biology and regenerative medicine; agri-tech; and robotics and autonomous systems. They were chaired by departmental chief scientists and by members of the Council for Science and Technology. A seventh round table brought together the chairs of each of these discussions to synthesise findings and consider the appropriate role for government in support of emerging – and converging – technologies.

What follows is a distillation of the findings generated by this process.

The drivers of interaction

Our lives are being increasingly influenced by several closely related classes of technologies that

- allow us to sense, detect and measure what it happening around – and within – us
- connect and collect the data that are being sensed or gathered from other sources
- combine and mine this data to produce fresh understanding, and
- make this understanding accessible to inform both our individual and social activities.

This is a new age of sensing and measurement: multi-arrays of sensors on satellites enabling observation of our planet; quantum positioning technology for navigation systems, directing our movements above and below ground; and wrist bands recording our heart rate and how we sleep. The precision of these measurements is continually improving, while new types of sensor are generating fresh data for analysis – from underwater locations, remote corners of the Earth and out in space.

Many more sensors are being deployed as components become cheaper and smaller, as new quantum-based devices reach the market, and as batteries too become smaller while also gaining in capacity. The real value of these increasingly ubiquitous sensor technologies lies in the data they collect and then transmit.

10 www.gov.uk/government/publications/technology-and-innovation-futures-uk-growth-opportunities-for-the-2020s.

Batteries

As we carry more technology than ever before – with new kinds of wearable devices joining mobile phones, laptops and tablets – advances in battery technology are crucial to maintaining this trend. The same is necessary for electric vehicles, for various kinds of remote sensors requiring off-grid power – such as those carried by drones – and for robots operating untethered.

Big gains look set to come from new battery chemistry, fuel cells, and materials such as natural crystals. Tesla, for example, is building a factory that could reduce the cost of lithium ion batteries by more than 30 per cent. General Motors estimates that the battery in the forthcoming Chevy Bolt electric car will cost around $145 per kilowatt hour. Some forecasters predict that once the cost falls to around $100 per kilowatt hour, electric vehicles will become mainstream – able to compete with petrol cars without resort to subsidies. Other companies, meanwhile are pinning their hopes on scaled up, but affordable, solid state lithium batteries. Such cells could double energy density. Dyson recently purchased Sakti3, one of the proponents of this technology.[11]

There are a number of ways in which sensor systems gather and distribute information, whether using radio or light waves (photons). Bluetooth enables connections within line of sight using very short-range radio waves. Wi-Fi and mobile broadband bring internet connections to hand-held devices. There are over 20,000 kilometres of fibre optic cable running between Western Europe and South-East Asia.[12] At the extreme, x-band radio waves cover the 400 million kilometres between Earth and the Curiosity rover currently surveying the surface of Mars.

Today, there are around 14 billion objects connected to the Internet. Analysts estimate the number of connected devices could reach between 20 and 100 billion by 2020.[13] The data being transmitted and shared by this vast number of sensors must be protected in transit from the point of collection to the point where it is stored and analysed. Countries in Europe and beyond are beginning to deploy new Low-Power Wide Area Networks dedicated to connecting internet of things devices that consumer less energy than existing wireless technologies.

Quantum security for the Internet

Next generation photonics could offer greater online security for digital networks by exploiting quantum effects. In the simplest terms, quantum-based technologies would reveal whether transmitted data had been intercepted or viewed by unintended parties. However, quantum computational advances – with the potential to be exponentially faster than existing technologies – also threaten existing encryption used to secure the internet, possibly within 15 years. First mover advantage is critical for UK security and leadership.

Quantum effects create opportunities for other new technological capabilities and applications. More precise time measurement will enhance accurate geo-location and enable greater independence from GPS – on which the UK and all developed economies heavily rely. It will work below ground and other areas of poor satellite coverage.

11 www.teslamotors.com/en_GB/gigafactory; www.cleantechnica.com/2015/10/05/chevy-bolt-battery-cells-145kwh-new-chevy-volt-with-autonomous-driving; www.insideevs.com/at-100kwh-it-is-all-over-for-the-internal-combustion-engine-energy-expert; www.cleantechnica.com/2015/10/28/dyson-buys-sakti3.

12 www.submarinenetworks.com/systems/asia-europe-africa/smw5.

13 www.gov.uk/government/publications/internet-of-things-blackett-review.

Super-accurate, chip-sized atomic clocks and time stamping will support increased innovation in financial services, for example, by aiding monitoring of high frequency trading and reducing the risk of flash crashes or impropriety. The National Physical Laboratory is developing the most accurate clocks in the world, making the UK well-placed to set global standards.[14]

More and more data are being collected in unstructured databases that do not require manual input, rules for data entry or descriptions of what they are. Here, data can be combined for novel or clearer insights – to identify predictors of heart failure, for example. They can also be mined in near real time, accelerating feedback and making systems more responsive. Computing power is crucial to the speed at which analysis can be done – as is the sophistication of the algorithms used to make sense of voluminous data.

Algorithms and machine learning

Search and decision-making algorithms are the most disruptive technologies in making use of data. Google has been investing in companies like the UK's Deep Mind to bolster its algorithms and serve the most relevant internet content. Some algorithm-driven applications, such as predictive text, are established features of daily life – becoming almost pre-cognisant and influencing how we write; Microsoft has purchased UK firm Swiftkey to raise its game in this area. Meanwhile, smartphones can remind us to take an umbrella, depending on the weather forecast, or track our daily physical activity.

Algorithms are becoming ever more sophisticated, underpinning digital distributed ledgers, for example, which offer a vast array of practical applications as well as the dual promise of security and transparency. Algorithms are also getting smarter, as they develop learning techniques that attempt to mimic human brain processes, evolving through trial and error, or making inferences. Artificial intelligence has already designed a working radio from transistors, invented new recipes and flavour combinations, drafted news reports and learned the product preferences of online shoppers. Deep Mind has defeated the world's top players at one of the most complex games: Go. In the field of drug development, Baylor College of Medicine teamed up with IBM Watson – which uses natural language processing and machine learning to pull insights from unstructured data – to search for new cancer treatments.

In the UK, the Alan Turing Institute – the result of one of several recommendations made to the Prime Minister on algorithms by the Council for Science and Technology[15] **– will be investigating a range of applications, among them data security, data intensive healthcare, and distributed and deep learning. The Institute places a priority on how the research community can address the complex ethical issues involved in this area.**

Humans are no longer required to take every decision. Increasingly, algorithms are automating decisions by operating within specified tolerances – as in the case of self-driving cars. Automated decision making in this and other contexts must be continually monitored, of course, to maintain the public trust which is a pre-requisite of ongoing innovation. In particular, there needs to be openness in and human accountability for how personal data is used and interpreted, and careful thought given to how a level playing field can be maintained between those applying machine intelligence and the individuals it may affect.[16]

14 www.npl.co.uk/news/npls-atomic-clock-revealed-to-be-the-worlds-most-accurate. On quantum, see www.gov.uk/government/publications/quantum-technologies-blackett-review.

15 www.gov.uk/government/uploads/system/uploads/attachment_data/file/224953/13-923-age-of-algorithms-letter-to-prime-minister__1_.pdf.

16 See www.gov.uk/government/publications/artificial-intelligence-an-overview-for-policy-makers.

Achieving meaningful and productive interaction between ourselves and the information gleaned from algorithms is challenging. Much of this data is digital and is subjected to logical processes, whereas we are analogue and emotional. Hence the efforts of designers – of hardware, operating systems and "apps" – to create the most direct and intuitive interfaces with our own senses. This final interface is essential to unlocking the potential of the sensors and the wealth of data they are producing – whether from inside us, from the world around us or indeed other worlds.

In practical terms, this means designing interfaces to command autonomous or semi-autonomous vehicles that can convey us to work through busy city streets; for programming aerial drones to inspect farm land or hard-to-reach infrastructure; for directing robots to seek out mineral reserves or help us perform routine domestic tasks.

Robotics and autonomous systems

Robotics and autonomous systems are enablers for virtually all sectors and industries. Plenty of dangerous, dirty or unpopular work is ripe for automation: in defence, nuclear decommissioning or infrastructure maintenance.

Emerging applications of remotely piloted aerial systems, for example, include crop spraying, delivery of emergency medicines and crowd monitoring, while the Swiss postal service and Amazon are trialling drones for logistical purposes. Spill over benefits include image stabilisation, sense and avoid, and secure data transmission technologies. Rapid adoption of such technologies also carries risks. The US federal government now requires hobbyists to register small unmanned aircrafts, prompted in part by an estimated 1 million recreational drones placed under American Christmas trees in 2015.[17]

Next-generation RAS could automate a very wide spectrum of jobs, as machines develop causal reasoning, predictive reasoning and conceptualising abilities. As with previous advances in automation, this has wide-ranging ramifications, not just within the labour market, but for education, welfare and considerations of social equity – requiring both public dialogue and attention across government.

17 www.independent.co.uk/news/world/americas/us-aviation-authorities-to-register-estimated-1-million-civilian-drones-to-be-sold-during-christmas-a6781776.html.

Convergence in context

These technological advances – in combination – are having widespread effects.

Mobile access to the internet, coupled with the rapid growth of the smartphone market, has begun to create consumer demand for applications that exploit the internet of things. Businesses are already grappling for market value, with offerings including connected appliances and smart heating and lighting systems.

Business models are changing too. Companies' relationships with their customers are increasingly intimate, with social media opening more direct channels. Customer feedback is shaping the evolution of products and services, once the preserve of traditional business development teams. New manufacturing processes such as 3D printing not only allow for greater personalisation of goods but will change the traditional factory model. At the same time, data flowing along supply chains can deliver just-in-time efficiencies and new kinds of flexibilities. Some commentators have described these developments as a fourth industrial revolution.

> "Companies' relationships with their customers are increasingly intimate"

More radically, some businesses could face a situation where it is no longer their products which represent the greatest source of value but the data these products can send back about their customers' usage patterns, giving rise to commercial opportunities. White goods and other products could soon be treated as part of a service, rather than simply consumer items, as manufacturers are alerted by sensors to unmet needs and faulty parts, or can remotely install upgrades to improve performance. This follows local car hire schemes, cloud-stored digital music and video streaming, all chipping away at established modes of ownership and economic models that make a clear distinction between goods and services.

Nascent disruption is all around us. Uber is redefining taxi services. Airbnb is doing the same for holiday accommodation, creating value from private assets. TIF3 has focussed on domains that the experts we consulted believe would be most disrupted by emerging technology – and on those domains where the UK can achieve the greatest gains in increasing economic productivity and improving delivery of public services.

The implications for five such domains are set out below.

Health

Spending on the National Health Service has reached £120 billion in 2016-17.[18] The costs of social and private care are also rising. With a growing as well as ageing population, with poor diet and physical inactivity stressing the system, disruptive technologies offer partial solutions in combination with efficiency programmes and behavioural insights.

Synthetic biology seeks to treat biology as a world of standardised parts – offering reliable and reproducible materials for the first time to create novel devices and systems as well as to redesign existing, natural systems. The related discipline of regenerative medicine may one day revolutionise the treatment of heart disease and neurodegenerative disorders, solve the shortage of organ donors and completely restore damaged tissues. These areas of research hold out the prospect of helping us to stay healthy and of treating disease more effectively. Moreover, new opportunities are coming from the convergence of synthetic materials, automation and manipulation of genetic data.

Regenerating organs

As far back as 1999, bladders have been successfully regenerated for patients in a laboratory, using their own cells. In 2008, surgeons successfully transplanted an engineered trachea. Stem cells are key to many current regenerative techniques, as well as novel materials – bringing together biology and engineering. Scientists are also beginning to explore whether the key to regeneration may be found in understanding the electrical signals that are transmitted among our cells.

Round-the-clock labs

Automated labs can run 24/7. Robots can free humans from handling dangerous substances and reduce the risk of human contamination. There is potential to significantly speed up high throughput screening (a key process in drug discovery), clinical testing and combinational chemistry – delivering breakthroughs in such areas as cancer immunotherapy and economic gains from the optimal marriage of human and machine intelligence.

Gene editing

Genomics has not only given us the tools to map our entire genome but has opened up the possibility of editing individual genes. For example, clustered regularly-interspaced short palindromic repeats – better known as CRISPR – are found in the DNA of single-celled organisms. When combined with particular proteins and with ribonucleic acid (RNA), they can be used to identify a specific piece in a DNA sequence and allow it to be replaced or removed: the mutated gene that causes sickle cell anaemia, for example, which could be replaced with the healthy version. Clearly, gene editing raises profound ethical questions, which must be debated openly.

18 www.gov.uk/government/news/department-of-healths-settlement-at-the-spending-review-2015.

Food

The UK food industry is worth over £100 billion annually. Animals and produce farmed here account for almost three quarters of land use. Imports make up about 40% of domestic food consumption – a figure forecast to reach 50% within a generation.[19] Convergent technologies have clear potential to improve productivity of UK farming and its contribution to the economy – with the attendant benefits of greater food security by making us less reliant upon imports and even allowing for land reallocation.

"Convergent technologies have clear potential to improve productivity of UK farming and its contribution to the economy"

Unmanned aerial vehicles, for example, are already helping farmers to monitor what they grow more effectively and work more efficiently – with on-board sensors detecting pests or dehydrated crops. Local weather sensors mean farmers can adjust watering or pasturing regimes. Autonomous weeding keeps pests at bay and avoids overuse of pesticides. Data is shareable with neighbours, helping to manage disease outbreaks or pass on successful husbandry methods. Such data can also increasingly be analysed in the field without the costly delays of waiting for sample results from the lab.

Stopping disease outbreaks

Pathogenomics, recently pioneered in the UK, will allow farmers to analyse the DNA of pathogens from field samples without requiring slow, expensive lab work. The scope of detectable diseases is expanding. Accurate, near real-time diagnostics will make farms more productive and cut down on the use of pesticides and other agri-chemicals.

Freeing up land

Genetic and technological advances which hold the prospect of effective nitrogen fixation, more efficient photosynthesis and synthetic animal feeds – as well as using big data to better match crops to soil types – could lead to a fundamental reallocation of land. More efficient food and feed production delivering greater yields could shift land usage towards delivering benefits like biodiversity, clean water and recreation.

Offshoring aquaculture

Another way to resolve the lack of land and a growing population is move food production offshore. Moving fish pens out to sea would reduce the pollution and parasites that are problematic for inland and coastal waters. Sensors, data and automation would enable remote management, increase productivity and cut costs. The UK's oil and gas experience of the harsh North Sea environment offers a competitive edge.

19 www.gov.uk/government/news/industry-kick-starts-work-on-great-british-food-and-farming-plan; www.foodsecurity.ac.uk/news-events/news/2013/130710-n-cost-of-farming-uk-economy.html; www.theguardian.com/environment/2015/feb/24/uk-will-need-to-import-over-half-of-its-food-within-a-generation-farmers-warn.

Living

Converging technologies could well transform our homes and places of work, as well as blurring those two domains. According to a Gallup report in 2015, 37% of US employees said they had worked remotely at one point in their career, compared to just 9% in 1995.[20] In both settings, the likes of Apple, Google, Philips and Samsung are designing ecosystems in which heating, lighting and security can be automated or operated through a single control. Such systems will change our behaviour, anticipate our needs and save us money. Other systems will support us more directly in carrying out daily tasks or free us from certain mundane chores entirely.

Assisted living and work

Body sensors will enable remote, real-time health monitoring and provide cognitive assistance to dementia sufferers. Robotic hoists, exoskeletons and posture sensors could improve independence of older people or anyone who requires such equipment – complementing more basic adaptations such as improved non-slip surfaces based on new materials. Both categories of technology offer improved care and reduced costs – and signal the expected evolution of blended systems in which humans, robots and software collaborate. This could lead to workplaces in which robots enable older people to work for longer, while for others, robots could help to expand their responsibilities or allow them to enter the workforce for the first time.

Smarter buildings

In new builds and retrofits, where Building Information Modelling (BIM) techniques are already starting to yield long-term efficiency gains, a wide range of convenient and money-saving applications are set to become available. Access could be managed – whether to the building itself or a zone within – by mobile phone, allied to an electronic token; alternatively, this could rely on face recognition. Sensors dependent on sound, temperature or movement – or a combination – could activate pre-defined heat and light levels, and reduce them when rooms become unoccupied. Water can be efficiently heated by the grid at the lowest available price or from micro renewable sources, and made available according to patterns of use. Entertainment systems can be shared, controlled and monitored according to preference.

20 www.gallup.com/poll/184649/telecommuting-work-climbs.aspx.

Transport

Better sensors and faster, more reliable connectivity are converging on cars, trains, planes and ferries to keeps us safe, get us from A to B quicker and integrate more smoothly within the fabric of our lives. Not only is the open sharing of scheduling data helping us to plan journeys and be aware of congestion and delays, but autonomy is spreading from the flight cockpit and systems like the Docklands Light Railway to individual travel. Car ownership will become less necessary as personal transport is increasingly viewed as a service. The UK has held self-driving car trials in London, Bristol, Coventry and Milton Keynes. Transport infrastructure will become smarter – with new materials and embedded sensors providing safer travel and more data on both use and performance.

"Autonomy is spreading from the flight cockpit to individual travel"

Smarter roads

Some countries are beginning to introduce smarter roads. In the Netherlands there are road markings that capture sunlight and then glow in the dark. South Korea has tested a stretch of road containing a dynamic system that recharges electric buses on the move. Other opportunities being explored include harvesting energy from the road network itself.[21]

Remote monitoring and self-repair

Smart coatings allow remote monitoring of the materials they protect, transforming maintenance and safety assurance. Self-healing materials in roads could take this one step further – using polymers containing micro-capsules that rupture in order to repair damage.

Self-driving pods

Automated (self-driving) vehicles are seen by many as the future of personal transport, with the eventual promise of fully-automated vehicles expected to bring significant societal benefits. Road safety is perhaps the most important of these (human error is estimated to be partly responsible for more than 90% of road fatalities).[22] It is also anticipated that automated vehicle systems will allow for more efficient movement of people and goods – potentially leading to a marked reduction in congestion and associated environmental benefits. If vehicles can be made to run entirely without human drivers, automation could also offer new freedoms for those currently unable to drive on account of age or disability.

21 www.bbc.co.uk/news/technology-27021291; www.wired.com/2013/08/induction-charged-buses.
22 www.economist.com/node/21560989.

Energy

On average, UK households spend over 5% of income on energy bills. For energy intensive businesses like chemicals, it can be as much as 50%.[23] Converging technologies could disrupt the current incremental gains being achieved by bringing down the cost of storage of renewables to resolve intermittency; introducing new materials to dramatically improve the efficiency of photovoltaic cells and the safety of nuclear fuel cells; rolling out a smarter grid that supports distribution and a variety of different generation technologies; and by simplifying the task and associated safety risks of infrastructure maintenance.

"Digital technologies allow for two-way communication between utilities and customers"

Solar fuel

The ability to capture light energy and immediately store it as a chemical fuel will solve the problem of intermittent availability, while materials such as perovskite crystals herald major advances in performance. Adding perovskite – one of a new generation of materials exploiting crystalline structures from substances like ammonia, iodine, and lead – on top of a silicon solar cell can boost overall power output by half.

Accident-resistant cladding

Long-life, accident-resistant cladding for nuclear fuel cells could transform regulation and safety – addressing public concerns and creating a new export market. Hope lies in the development of new materials like silicon carbide to replace zirconium cladding. The risk of producing hydrogen is massively reduced. The importance of this is illustrated by the hydrogen gas explosions that obstructed the containment effort at Fukushima.

Smart grids

Upgrading the UK network to a smart grid will improve reliability, availability and efficiency in our energy supply. Digital technologies allow for two-way communication between utilities and customers, making the system dynamic and far more responsive to demand. The £11 billion smart meters programme, for example, is the biggest government investment to date in internet of things technologies. By 2020, up to 53 million smart electricity and gas meters in homes and small businesses could be connected to our energy infrastructure.[24]

23 www.ons.gov.uk/ons/rel/household-income/expenditure-on-household-fuels/2002---2012/full-report--household-energy-spending-in-the-uk--2002--2012.html; www.carbontrust.com/resources/guides/sector-based-advice/chemicals.

24 www.ofgem.gov.uk/gas/retail-market/metering/transition-smart-meters.

Government
Office for Science

The Government Office for Science ensures that government policies and decisions are informed by the best scientific evidence and strategic long-term thinking. The Government Chief Scientific Adviser is head of the Government Office for Science and head of the Government's science and engineering profession. He is responsible for:

- Providing scientific advice to the Prime Minister and members of Cabinet
- Advising the Government on aspects of policy on science and technology, and
- Ensuring and improving the quality and use of scientific evidence and advice in government.

We have three areas of focus:

- Science for resilience
- Science, engineering and technology for the economy, and
- Evidence and analysis for policy.

Our key functions involve:

- Acting as a transmission mechanism between leading scientists, engineers and technologists and government policy makers
- Working across government on complex issues that go beyond the domain of individual departments
- Providing high-quality futures capability though Foresight projects and the Horizon Scanning Programme (jointly with the Cabinet Office)
- Identifying gaps and opportunities for the UK, particularly in emerging technologies, to drive economic growth
- Providing the best scientific advice in the case of emergencies, through the Scientific Advisory Group for Emergencies, and
- Helping the independent Council for Science and Technology provide high level advice to the Prime Minister.

This publication available from www.gov.uk/go-science

Contact us if you have any enquiries about this publication, including requests for alternative formats, at:

Government Office for Science
1 Victoria Street
London SW1H 0ET
Tel: 020 7215 5000
Email: contact@go-science.gsi.gov.uk