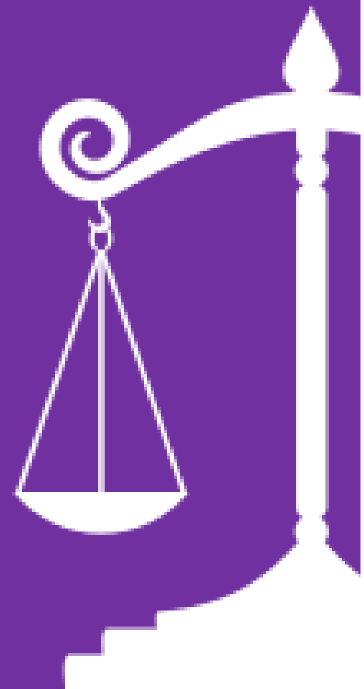
CUSPE 2018 Communications Special Issue:

Emerging Technology and Policy



Editor's Note

Erin Cullen, Head of Publications 2017/2018

An emerging technology is a technology that is in development, or that will be developed in the next decade. It is a technology that is capable of changing the status quo, and to disrupt the business or social environment in which it finds itself. But regulation for these technologies is proving to be a challenge, and it will be necessary to find a balance between protecting society and ensuring that innovation is not stifled.

The Cambridge Science and Policy Forum, held by CUSPE in 2018 was the first in the society's history. One of the important topics tackled by experts at the forum was opportunities for collaboration in regulating emerging technologies. Artificial intelligence and machine learning were discussed in detail as two of the new technologies that governments will soon need to consider. The impasse that can be reached between policy makers and developers was addressed, along with the perceived usefulness of regulation. The potential of 'reusing' existing regulation for new technologies was also discussed in great detail.

This special issue brings together articles published by CUSPE over the last year. They tackle the theme of emerging technologies and policy, starting with three articles that examine the emerging technologies of the digital age.

Aisha Sobey eloquently explains how Blockchain operates (elaborating on Distributed Ledger Technology, the technology behind virtual currencies such as Bitcoin), and examines the complexity surrounding legislation for this issue; does it stifle or promote innovation? Alex Koehler-Sidki then examines the advent of the quantum internet, and ponders whether the UK's science policy will keep up with new developments? An increasing amount of data is gathered on many aspects of individuals' lives. Emma Lawrence examines the potential of using genomic data in medical research and explains policy approaches to address these challenges.

CRISPR technology, a gene editing technology has many applications in research and in the wider context of gene therapy, manufacturing and agriculture. Here, Michele Sanguanini looks at the patenting contest surrounding CRISPR in the European context. Daniela Rodriguez-Rincon then examines the current infectious disease landscape and advocates a multi-sectorial approach to tackle infectious disease. Moving to the environment, Amanda Murphy dives into the divisive nature of fracking, and whether we should start fracking in the world's urban areas.

Finally, a dialogue between the developers of new technologies, governments and the public is essential both for the progress of technology and for society to benefit. Stephanie Bazley, Kasey Markel and Mrittunjoy Guha Majumdar examine this dialogue in their articles looking at the integration of science policy, environmental policy and science diplomacy respectively. All of these articles highlight the challenges for policy makers when legislating in a rapidly changing technological environment. I hope you enjoy reading these articles as much as we have enjoyed editing and working on the publications team this year.

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Erin is a PhD candidate in the Department of Plant Sciences, studying plant evolution and development. Erin is particularly interested in policy related to food security and the use of evidence-based policy in government. You can reach her at evc24@cam.ac.uk.

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Blockchain policy inertia: Where's the disruption?

Aisha Sobey, MPhil in IR and Politics, University of Cambridge

Blockchain has been framed as a technology that could alter the shape of the world dramatically in the coming decades, influencing how we act and govern ourselves as a society, as the decentralised nature of Blockchain means that these networks wouldn't be controlled by one person, group, corporation or government. Reuters [1] expects blockchain to be disruptive, to move from simple applications to displacing central market competitors, in many areas such as healthcare, tax and accounting, politics and entertainment. In healthcare for example, the nature of blockchain means it can be used in patient records, to increase consistency, remove duplication and aid in sharing information between relevant authorities.

However, the relationship between technology and governance is reciprocal, as technology may enable new forms of governance, but it is also defined and constrained by the regulation and actions of governments. In this article, the dynamic between the two will be explored to explain the lack of policy or uptake of Blockchain into government services, even though it is hailed as such a potentially significant advancement. The very interplay between policy and technology in this instance is because of the keen social and political implications Blockchain could have, meaning that the two areas have reached a stalemate, slowing the uptake and the current potential of the technology.

What is Blockchain?

Blockchain, also known as distributed ledger technology (DLT), is a decentralised networked database and way of recording transactions between the members of the network [2].

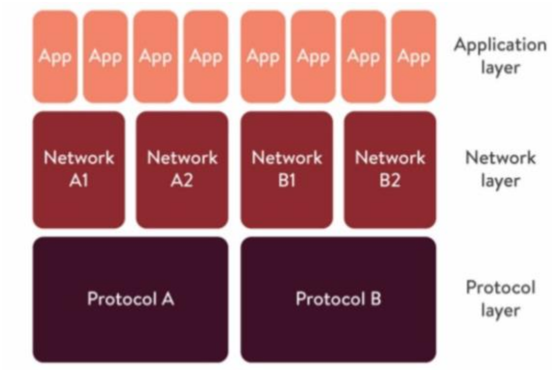

Figure 1. Source: [3] This shows the three layers of DLT, and the protocol layer is the significant base on which future layers are built. Each protocol layer sets out the expected behavior in the subsequent networks built on it.

There are three layers of DLT: the protocol layer, the network layer and the application layer [3]. The protocol comprises the main building blocks of the network, and developers of this layer are likely to influence further layers in the stack, as they are the foundation on which subsequent layers are built. The protocol layer differs from traditional internet protocol layers, such as HTTP/HTTPS. Traditional internet protocol layers allow computers to communicate effectively, but require a large amount of descriptive addition by applications such as Google or Facebook to enable the user to interact with the data. This setup means that centralised corporations own the data and require sensitive information, such as bank details, to be entered each time a purchase is made.

DLT uses cryptographically secure protocols to govern the rules, operations and communication on the networks, however, these protocols are much more specific and descriptive of the niche networks that can operate on them. For example, Etherium is an open-source protocol used in smart contracts [4], while R3's Corda is specialised for use to record financial agreements between regulated financial institutions. Other significant protocols include the Hyperledger, Bitcoin and Ripple Consensus network [5, 6, 7].

The network layer is made up of a custom blockchain network, or multiple networks, for users, built on existing protocols and governed by the network operator. Examples of these networks include the IMB Blockchain Platform [2, 5] (built using Hyperledger Fabric) and Mosaic [6]. The application layer comprises of all the custom applications built on the network. These applications can be built and run by the network operator or by third parties. Examples of DLT apps include cryptocurrencies and online contracts. One benefit of DLT at the application stage is that as the server is shared between all network participants, and built on this, anyone can create applications which share data, but if compromised do not affect others in the network. Traditional server architectures require every application to run on a separate server and code, which run in isolated streams. This not only makes sharing data difficult, but when a single application is compromised, this affects many other applications.

How does it work?

Blockchains organise the data into immutable blocks, or records of transactions, uniquely referenced to the block that came before it. The use of chronological sequences makes issues such as data changing or tampering near impossible as changes to block information have to be agreed upon by members of the network. How transactional information joins the chain is highlighted by the example below based on cryptocurrency.

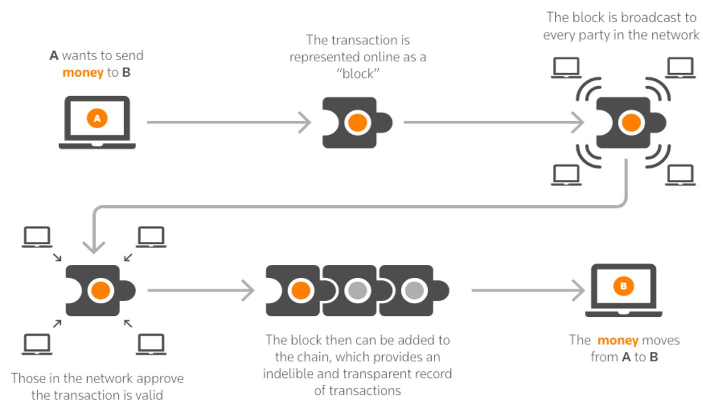

Figure 2. Source: [1] Using money as the example, this shows the steps required to add information to a blockchain. The decentralised authority is highlighted as the network highlights the vailidity of the transaction. Once verified, the information joins the sequence and is near impossible to tamper with.

Why does it matter?

Blockchain, in theory, removes trust issues during transactions and offers a way to accurately keep records free from unauthorised alteration or misinformation. The most common and well-known use of Blockchain is in cryptocurrency, following the whitepaper proposal of Bitcoin in 2008. The financial industry, including central banks, has the most interest in DLT technology, with the majority of start-ups using the DLT being based in this sector [3]. This industry has substantial process inefficiencies and a massive cost base issue. Legacy financial systems often have large premiums for transactions, as well as a complicated and poorly integrated matrix of operational infrastructure.

Additionally, the financial crisis highlighted the accountancy errors and difficulty in tracing the correct present owner of an asset, especially over a substantial chain of buyers within global financial transaction services. For example, when the US investment bank Bear Stearns was acquired by JP Morgan Chase in 2008, the number of shares offered was far larger than the shares recorded in the books of Bear Stearns. It was not possible to clarify the accounting errors and JP Morgan Chase had to bear the damage from excess (digital) shares [8]. This would be resolved using DLT, as each asset is verified and cannot be duplicated or altered.

Government and public sector services could benefit from DLT as its adoption could increase transparency and accountability, and allow e-governance and voting, increasing public participation. The Global Blockchain Benchmarking study found that 63% of Central Banks, as well as 69% of other public sector institutions, have been investigating the use of Blockchain in their operations [3]. Additionally, the use of DLT can be applied to physical assets or supply chain management, such as in internationally sold produce, which could be traced through all stages of transaction and the final customers identified, should a product be deemed defective or dangerous. With the potential advantages of use evident in almost all sectors, the question is posed as to why there has been very little or slow uptake of DLT technology?

Policy inertia

It has been 10 years since the whitepaper proposal for Bitcoin, which offered a new use of cryptographic techniques and consensus mechanisms as a new way of running a cryptocurrency. From this, DLT more generally has been recognized as a disruptive technology which has application potential in all sectors. However, the lack of significant disruption and movement in DLT use and in policy to regulate the technology is notable. The benefits and risks of using DLT are tied to the technological design, governance and regulation applied to it. Blockchain, essentially, is the "protocolisation" of computer software, providing much greater structure and rules to interactions between network nodes than the typical IP protocols. This makes the protocol layer, and setting standards therein, especially important as the first point in establishing internationally accepted standards for creating and regulating DLT technology, which would have comparative and political advantage. However, the risk of taking the first move is also amplified. This dynamic has created a standoff, in effect, between the regulators and developers. Without the oppositional force in place to indicate possibilities, both regulators and developers of the technology face potentially significant losses if the wrong protocol choice is made.

The advantages of implementation in, for example healthcare, even in supply chain management of medicines, could be significant. Through the nature of the technology, and the entering of each asset into the chain, would mean that if a single batch of a medicine is found to be contaminated, or out of date, then the individual boxes could be traced to the patients that have been supplied with them. Rather than a recall of all the medicine made on a day or dispensed from a pharmacy. The efficiency and specificity of DLT means much greater clarity in the supply chain. However, the system created would also need the right permissions for parties able to see the data, verification of data security as healthcare records are especially sensitive. Furthermore, for this to be efficient it would also need to be to scale, system wide, so the risk of implementing something

For regulators and policy initiatives, the decentralized nature of DLT means that the locus of power has been challenged. The data we share with companies could be controlled individually, rather than by a central entity such as Google, Facebook or governments. Additionally, cryptocurrencies, which are ungoverned and decentralised, have the latent possibility to undermine state-backed currency such as the US Dollar or Pound Sterling. Conversely, the use of DLT in government services could increase participation, reduce inefficiency, ensure security, as well as offer the potential for a government-backed cryptocurrency. As an example, the Estonian government is currently using DLT to support public services such as documenting health records [9]. Whilst cryptographic technology is foundational for this project, it hasn't yet set the standard or expectation of DLT use. There is still opportunity for developers and states to be part of the dominant protocol movement. This will determine the difference between founding the next Facebook or, conversely, Bebo (a social networking site that has lost all popularity).

Moving forward with Policy

The UK Government office for Science released a whitepaper on DLT [10] that suggested that effective regulation is key for implementation, but it is difficult to understand one without the other. Incremental development, therefore, is what has been seen surrounding DLT on both sides of the coin.

DLT may be disruptive, and change the way we in which we do business, governance and international transactions, however, the complexity of setting international standards and protocols that are innately linked with this technology has proven DLT to be different to other revolutionary technological advancements [11]. Rigorous regulation may still not be established within the next five, even ten, years and a likely scenario is that the emergence of this regulation will be such that Blockchain evolves by international agreement as trade develops, but that the pioneers of the protocols, and the authorities that govern them, have yet to be established. Estonia have made a strong start in using DLT for government services, working within the European Union and other international agreements. It is yet to be seen however, how this development will impact on state authority and the way in which international systems operate.

Acknowledgements

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Second editor: Erin Cullen

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About the Author

Aisha is an MPhil student in International Relations and Politics at the University of Cambridge. Her research focuses on the interaction of technological development and politics. Her MPhil dissertation is looking at the relationship between cyberspace and US power. She will be beginning a PhD focusing on smart city technology in Singapore and the reciprocal relationship this new mode of living has with inequality in October. In identifying the aspects of smart cities that interact negatively with inequality, she hopes to work towards inclusive use of technology.

Building a secure, quantum internet for the future: will the UK's science policy keep up?

Alex Koehler-Sidki, Department of Engineering, University of Cambridge

The digital world is changing fast; the computing power of today's smartphones outpaces that of supercomputers from just twenty-five years ago. We can video-call people on the opposite side of the globe, and we trust that our data are transmitted securely from one device to another. But, given this breathless speed of advancement, can we maintain our security in the coming decades? The use of quantum mechanics could be the answer. Is the UK's science policy up to it?

Ensuring our digital security has never been a more pressing issue. The WannaCry virus wreaked havoc on the NHS last year, Russia has been the subject of numerous hacking allegations, and, more broadly, businesses suffer losses of billions of pounds annually as a result of hacking. Yet, on the horizon, a more benign threat is appearing in the form of quantum computers. These computers promise to solve problems that are currently intractable by modern supercomputers, particularly when it comes to factorising very large numbers – a technique that serves as the foundation for much of modern-day encryption. This would mean that current encryption methods, which would take thousands of years to crack with a conventional computer, could be broken in just seconds by a hacker using a quantum computer.

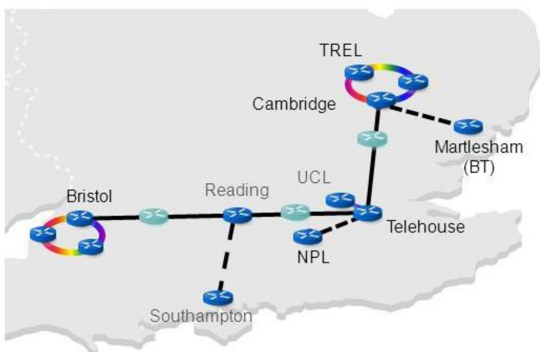
Much of contemporary internet security rests on a technique known as 'key encryption'. In general, key encryption provides security by encoding information that is shared between a receiver and transmitter using a key. The lynchpin of this security system stems from the mathematical complexity of determining the key. Keys are typically very large numbers, containing prime factors. Current computers struggle to extract these prime factors as they rely on a brute force approach that tests all possible combinations of factors, one after another. As these keys become larger and larger, the work required to crack them increases exponentially, quickly reaching the order of thousands of years.

The advent of quantum computers, a time that could be anywhere from ten to fifty years from now, would likely upend this entire encryption system. Quantum computers derive their computational power from quantum bits, or 'qubits'. While current computers use classical bits, which can only be in one of two states, a '0' or a '1', qubits can be in both states simultaneously due to something known as 'superposition'. This purely quantum phenomenon of existing in both states concurrently provides a huge advantage when it comes to factorisation: rather than trying thousands of combinations iteratively, quantum computer can try multiple combinations *simultaneously*.

Although several decades may separate us from quantum computers, quantum cryptography, which exploits a different quantum phenomenon, Heisenberg's Uncertainty Principle, is already commercially available in the form of a quantum key distribution (QKD). This cryptography technique encodes information on individual particles of light, known as photons. As an example, let us suppose that a sender, Alice, and a receiver, Bob, want to share a secure key. Alice prepares her photons and encodes information on them using their polarisation; she first chooses, at random, which basis, either horizontal-vertical (+) or diagonal (x). Then she chooses which bit, '1' or '0' to send, where horizontal (H) and anti-diagonal (A) correspond to '1' and vertical (V) and diagonal (D) correspond to '0'. She then sends these photons to Bob. Bob then chooses at random which basis to measure along. If he chooses correctly, he extracts the bit. If he chooses incorrectly, he has a 50/50 probability of getting either a '1' or '0'. After this, Bob announces publicly which basis he used for each measurement and Alice responds publicly whether he chose the correct basis. Bob then discards all the bits with incorrect measurements, after which Alice and Bob share a common string of '1s' and '0s'. They then publicly compare a small section of them to confirm that they do indeed have the same key. If an eavesdropper, Eve, would like to learn the key whilst going undetected, she can't for a number of reasons. Firstly, she doesn't know in advance which measurement to perform, so if she does an incorrect measurement, and then sends her own particle to Bob, this will introduce an error which can be detected by Alice and Bob when they compare their small selection of bits. Secondly, she cannot copy the photon, as this is physically impossible. In this way, Alice and Bob can share a key with perfect security. As such, since it is based on the laws of physics, quantum cryptography is theoretically unbreakable. Even an eavesdropper with an infinitely powerful computer, or even a quantum computer, could not break this means of communication. As other nations divert significant resources toward preparing for a quantum cryptography-era, one pressing question remains: has the UK kept up?

Well, actually, the answer is mostly 'yes'. In 2013, the UK invested in a £270 million Quantum Technology Hub [1], a nationwide initiative of universities and industrial partners who are dedicated to the development of quantum technology. Comprised of four hubs, the initiative has specialised teams responsible for sensing, metrology, computing and, most importantly, communication. Moreover, the Ministry of Defence (MoD) has committed £36m to the cause and the total investments from the public and private sector were estimated to exceed £350m this year. This hardly comes as a surprise since quantum technologies could be worth as much as the consumer electronics sector, which currently nets about £240bn a year globally [2].

The money invested so far has produced significant results. One ongoing project is the construction of a quantum communications network over fibre-optics. This would cover southern England, with nodes in, among others, Bristol, Reading, London, Martlesham in Suffolk (specifically at BT) and Cambridge, which also contains its own metropolitan network. However, the UK struggles with the commercial realisation of QKD. Currently, the Swiss firm IDQuantique have cornered the market, having sold their own systems for several years. American and Australian firms, such as MagiQ and Quintessence, claim to provide systems, but details are sparse at best. Toshiba look poised to announce their entrance into the market, having demonstrated numerous field trials over the years. The company also recently broke the record for the fastest transfer of secure keys over 50 km of fibre [3]. Although numerous British experts undoubtedly provide valuable services through consultancy, the only firm springing out of this is the Bristol-based KETS. Comprised of several researchers, KETS recently secured access to more than £125 million of venture capital funding at a recent start-up competition hosted by Facebook and BT [4]. Taken together, it seems the strength of British firms lies more in the provision of the components for these systems rather than developing the entire product themselves.



The UK is developing a quantum network, with nodes in several major cities and at R&D centres such as Toshiba Research Europe Ltd (TREL) and National Physical Laboratory (NPL).

Despite significant achievements, the UK should be hesitant to rest on its laurels, particularly when drawing comparisons to the achievements of other countries. China has easily led the way in terms of translating funding and resources into real, tangible results; the launch of their quantum satellite, Micius, catalysed their success, which began with the demonstration of QKD between Micius and a ground station, easily surpassing any previous distance records [5]. They then went even further by performing a quantum-secured intercontinental video conference between Beijing and Vienna, a world first [6]. This, coupled with their announcement of a 2000 km long metropolitan network [7], a brand new quantum centre [8] and a pledge to create a global, quantum-secured network by 2030 has placed the Chinese at the top of the sector. Indeed, these results have caused quite a stir, resulting in a number of countries announcing their own satellite projects, including Canada and Japan [9], as well as other more collaborative approaches. Despite significant progress in CubeSats – compact and comparatively cheap satellites suitable for space-based QKD experiments – thus far, there is no indication that the UK plans to follow suit. Undoubtedly, the uncertainty surrounding Brexit makes it highly unlikely that the enormous investment required will be appropriated in the near future. Indeed, the UK's involvement in the €1 billion EU Horizon project has already come under question.

The official position of the UK government is against implementing QKD. The National Cyber Security Centre, a branch of GCHQ, currently advises against the adoption of QKD due to uncertainty surrounding its practical security and feasibility [10]. However, this is not set in stone, and a leading science policy advisor has even indicated that revisions to this position are underway. Furthermore, significant work has been carried out by the European Telecommunications Standards Institute (ETSI) toward standardisation of QKD in anticipation of its widespread implementation, and the UK's National Physical Laboratory (NPL) has played a key role in this. Such a collaboration suggests that QKD is gaining momentum, and the focus has now shifted away from proving theoretical security to demonstrating real-world, practical security. This shift suggests QKD may be moving outside of the lab and into something that could soon be part of everyday life.

So, what are the next steps for UK science policy? This will hinge upon the outcome of Brexit; significant research funding currently stems from the EU (e.g., in the form of the Marie Curie Fellowship), which also sources many of the individuals currently involved in British QKD development. Next, as the initial funding phase for the four Quantum Hubs will end this year, policymakers must determine whether the funding will be extended or renewed. The Hubs have catalysed the development of several quantum technology clusters in York, Bristol and Cambridge, and, by continuing Hub funding, the UK government could not only grow the sector but also provide assurance to businesses that have yet to invest in quantum communication. Finally, Britain ranks within the top five in terms of spending, publications and patent applications in the area of quantum science [2], and continued collaborations between academia, business and government will ensure a strong global position for years to come. The age of quantum internet is imminent, and the UK must decide if it wants to continue as a leading player of the so-called 'quantum revolution,' or resign itself to a place on the sidelines.

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Alex Koehler-Sidki is a 3rd PhD student with the Engineering Department at the University of Cambridge. His current research is focused on the security of single photon detectors in quantum cryptography which is based at Toshiba Research Europe, just north of the city. Prior to this, Alex completed an MSci at the University of Nottingham, including a year at the Ludwig-Maximilians-Universität in Munich, before spending half a year working at a leading photonics company.

Data Governance in the Genomics Era

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In recent years, the volume of data generated from all aspects of our lives has been increasing, in parallel with the sophistication of analytical techniques used to process this data. This shift toward a 'data-driven' society has the potential to yield insights that can benefit many sectors of public life, but it has also prompted concerns related to privacy. A recent report by the Royal Society on data management and use [1] is a recognition that the fast pace of all areas of data growth requires careful consideration.

In the field of healthcare research, an area generating large amounts of highly unique data about individuals is that of genome sequencing and genomics. Sharing of genome sequence data has the potential to improve our understanding of diseases, which can, in turn, improve diagnostics, treatment and integration of personalised medicine into standard healthcare practices. However, the difficulties associated with maintaining privacy of this data are significant. These challenges demand a need for policies that will encourage innovation and scientific progress for the collective benefit of all whilst minimizing the level of risk to the individual.

This short article will explore the potential advantages and risks of using genomic data in medical research, and it will suggest policy approaches to address these challenges.

What is genomics and how can it be used for healthcare?

The DNA of all organisms is composed of a long sequence of DNA nucleotides – A, C, T and G – that together form a unique code. Through genome sequencing, scientists can determine the order of these letters in an individual organism. All humans have the same nucleotide letter for most positions in the genome, but they differ at a few positions which are termed 'variants'. While most variants in the genome do not impact our physiology, some can cause disease. Knowledge of these variants can be useful for informing treatment, as well as for providing timely diagnoses. Many of these disease-causing variants are rare, meaning that they are not observed at high rates in the general population. As such, genomic analysis requires large datasets comprised of many—typically thousands—of genome sequences, so researchers have enough statistical power to detect such variants. Luckily, the cost of sequencing a genome has plummeted in recent years, and therefore many individuals can be sequenced synchronously for minimal costs. Nonetheless, data sharing, which is simply the combining of different smaller datasets generated in different research centres, can help produce the large datasets required. It can also increase efficient interpretation of the same variants across different research centres, reduce the risk of misdiagnosis, and improve the reliability of diagnoses [2]. Taken together, data sharing can be of a direct benefit to patients living with rare diseases, and the UK has adopted several policies to encourage further data pooling [3]. Genomics England is leading a movement to adopt genomic testing as an integrated part of routine clinical care in the NHS, and the ongoing 100,000 Genomes Project aims to set up a genomic medicine service for the NHS in the coming decades [4].

Concerns and Risks

We have seen that the collection and sharing of genomic data has the potential to bring advances in scientific understanding and healthcare. However, there are some concerns associated with this.

First, guaranteeing the privacy of individual-level genomic data can be challenging. Data shared between research groups is typically 'de-identified', meaning that any personally identifiable information (PII) must be removed from the dataset before genomic data can be shared with other research groups. While PII most obviously includes information like name, date of birth and home address, other information, such as a post code, county or even ethnicity, could be combined with other PII to identify an individual, particularly those with rare diseases. In the case of patients with these diseases, there is a concern that a breach of confidentiality of this information could place them at risk of being subject to discrimination and/or stigmatisation. However, the de-identification of data could limit the ability of researchers to contact an individual in the future, for example if they are thought to have increased risk of a disease [2]. This can be circumvented by using 'coded data,' so individuals can still be linked to their genomic data and identification can occur if required, but the code is kept in a secure environment. However, it has been suggested that DNA can never be completely anonymised due to the inherent uniqueness of the genetic identity [5]. Current legislation does protect and regulate the sharing of personally identifiable data, but there is a lack of consensus over the appropriate level of safeguarding for genomic data to minimize privacy risks.

A concern for the collection of genome data is how to obtain consent for its usage. An individual may consent for their own personal genome being sequenced and the data released, but this can also give indirect information about family members, and to a lesser extent, members of the same ethnic group and population [1, 6]. Therefore, some question whether a genome sequence can be 'owned' and consequently whether one individual can consent to its use. It is also difficult to consent to all the possible future uses of the data. Both data analysis and genomics are rapidly advancing fields, and it may not be possible to foresee all future possibilities. A 'broad consent' model permits use of the data for an unspecified range of future research in recognition of these difficulties, but it is important that individuals understand what this consent means in practice.

Suggested policy approaches

Several different sources have argued for new regulatory bodies to address the challenges of a changing genomic medicine landscape. The Science and Technology Committee recently launched an inquiry into genomics and genome editing, where suggestions were made that a new body, similar to the Human Genetics Commission which existed up to 2012, should be formed [7]. In her 2016 annual report ‘Generation Genome’, Dame Sally Davies recommends that government public engagement with genomics should be increased with the creation of a new National Genomics Board [5]. This approach will help to ensure that progression will be monitored and investigation into any potential harm is carried out.

A consensus for how genomic data will be confidentially treated should be reached. If successful, lessons can be taken from the 100,000 Genomes Project and applied to other projects. They have created a secure data governance system for storage and access of sensitive patient data, where de-identified data is analysed in a monitored environment. Researchers need to apply to access the de-identified data which can only be approved if the purpose is deemed reasonable. In addition, the database of Genotypes and Phenotypes, which is a National Institutes sponsored repository of large-scale genetic and clinical datasets, has a rigorous application process for annonymised data and requires research institutes to provide secure data storage that aligns with their guidelines [8]. In agreement with this, a report by the Nuffield Council on Bioethics also makes the following recommendations; that privacy breaches must be reported to affected individuals, that criminal penalties should apply for misuse of data, and that access to data is restricted to researchers that are subject to institutional oversight [3].

Another consideration is the importance of cultivating public trust in any genome sequencing project. As in any area of human subjects research, the security of data storage must be made fully transparent to those involved in a study, and researchers should acknowledge that privacy cannot be completely guaranteed. An example of a healthcare data project that failed because it did not cultivate public trust was the NHS’s care.data program. The purpose was to extract data from GP practices and link it with that from hospitals, to improve treatments and patient care. However, it was stopped in 2016 after concerns over data privacy weren’t fully addressed or communicated to patients [9,10]. Despite extensive patient communication and public dialogue, there remains confusion over the concept of anonymised and pseudo-anonymised data in the 100,000 genomes project [11]. This highlights the importance of maintaining a clear dialogue with the public. Finally, new uses for genomic data emerge every year, and policymakers should consider how obtaining informed consent at each stage of these new developments could increase an individual’s knowledge and ownership over the use of their data.

Conclusions

It is expected that as genome sequencing and genomic testing becomes more commonplace in research and healthcare, a shift in the policy landscape will be required to manage the associated risks. It is important that scientific progress in this area can continue, but in a secure environment that people trust. Public participation is vital for the success of future genomic research projects, and their promise to deliver transformative genomic medicine.

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A Cutting-edge IP Litigation: the European Front of CRISPR Patent War

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CRISPR/Cas9 is a gene editing technology that is revolutionising the way that scientists design biomedical research. In addition to this, CRISPR/Cas9 is opening promising avenues for applications in gene therapy, manufacturing, and agriculture. The commercial and disruptive potential of this invention is so promising that it sparked a 'gold rush' towards patenting CRISPR/Cas technologies. Two principal players weighed in to define the CRISPR/Cas9 patent landscape in the US: the University of California Berkeley (UCB) and the Broad Institute, a joint MIT-Harvard research institute [1]. This ultimately led to a high-profile patent battle in front of the US Patent Trial and Appeal Board, where the Broad Institute prevailed in the first instance [2]. The dispute, however, continues worldwide. In this Communication, I will focus on the European front of this litigation; the problem being not only who owns this technology in Europe, but also what are the potential impacts of patent conflicts between academic institutions on European policy and law.

A song of CRISPR and Cas

Others have more extensively narrated how a niche field of research, an 'immune system' found in bacteria, became the next big thing in genome editing [3,4]. CRISPR stands for 'clustered regularly interspaced palindromic repeats' and describes a region in prokaryotic genomes where arrays of repeated near-palindromic sequences—nucleic acid sequences, e.g. GACGTC, where the complementary strand (CTGCAG) is the mirrored image of the primary one—are interlaced with short variable sequences. Scientists first acknowledged the existence of such genomic patterns in the bacterium *Escherichia coli* in 1987, and in many other prokaryotes (either archaea or eubacteria) over the next decade. In the mid-2000s, multiple authors suggested that CRISPR acts as a 'bacterial adaptive immune system' [3]. A few years later, multiple CRISPR-associated proteins (Cas) were described as effectors of this function in prokaryotes. Among Cas proteins, Cas9 has been characterised extensively from a biochemical and biological point of view.

At this point, one could use patents to tell the recent story of CRISPR/Cas9 systems. This approach might be less appealing than the (often controversial) 'heroic' narrative of CRISPR [3], but it also permits to avoid (cherry) picking which scientists provided major contributions towards understanding this system [4]. The players that are sectioning the patent landscape of CRISPR/Cas are also dividing a 'pie' worth tens of millions of USD [1], but are not the only people who contributed to the science behind this technology.

The first attempt at patenting CRISPR/Cas dates back to 2008 [5], when Luciano Marraffini and Erik J. Sontheimer from Northwestern University demonstrated that CRISPR/Cas could cut DNA – and could potentially be used to interrupt horizontal gene transfer from/to pathogens. The authors abandoned this patent due to a lack of sufficient experimental evidence; however, Marraffini would later become a key actor in the Broad/UCB patent battle in Europe. The first successful CRISPR patent application was filed by a Lithuanian researcher, Virginijus Šikšnys, in March 2012 [6]. This patent is, however, widely overlooked in most ensuing CRISPR patent battles as it contains claims on a CRISPR-RNA system created in vitro—not genetically encoded like the Broad/UCB one.

Another fundamental patent application was filed in May 2012 [7]. It came from Jennifer Doudna, a structural biologist at UCB, and Emmanuelle Charpentier, who was at the time a microbiologist at Umeå University in Sweden. The collaboration of the teams led by the two women made it possible to engineer a CRISPR/Cas9 system to induce a targeted double-stranded DNA cleavage in vitro [8]. Figure 1 shows the mechanism of this DNA editing technology. The plot twist in this story was a patent filed by Feng Zhang at the Broad Institute in December 2012, that contained claims on a protocol to apply CRISPR/Cas9 system for genome editing in eukaryotic cells [9]. Later on, his team published a study in Science, where they were able to edit the genome of murine and human cells [10]. With an expensive patent gamble, the Broad Institute collaboration fast-tracked its application to the US Patent and Trademark Office (USPTO) [1]; the patent was accepted in 2014, while the one from UCB is still pending.

CRISPR Total War

Both UCB and the Broad Institute claim an engineered CRISPR-Cas9 system for use in genome editing. Doudna and Charpentier's patent does not specify the cell types to which it might be applied, while Zhang's patent claims specific use on eukaryotic cells. If we represent the two patents as Venn diagrams, the claims of the latter patent might be a subset of the former. And to be patentable, an invention must be novel considering the information already available to the public (the 'prior art'), show non-obvious inventive step from already patented inventions, and it must be fully disclosed.

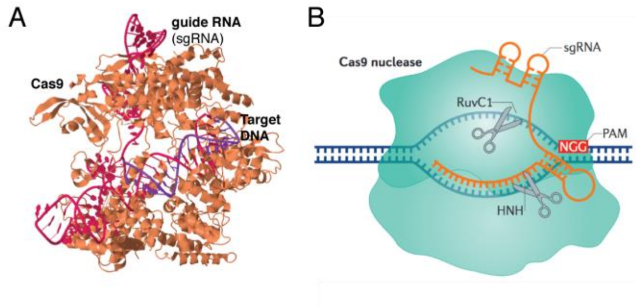

Figure 1 **CRISPR-Cas9 mechanism.** A) Cas9 (orange) is a Cas protein with multiple functions: in nature it complexes with targeting RNA derived from a CRISPR cluster (crRNA) and a second, structural RNA called tracer RNA (tracRNA). The group from Doudan and Chaprentier proved that these two RNAs can replaced with a single guide RNA (sgRNA, magenta) [8]. B) The RNA-protein complex then unwinds the double helix and scans the genome until it reaches a sequence which 1) is complementary to the spacer region of crRNA and 2) is adjacent to a sequence motif called a PAM site. After sequence recognition, Cas9 cleaves double-stranded DNA three bases upstream of

the PAM sequence from both sides leaving blunt-ends, which are hotspots for homologous recombination (fundamental to gene knock-ins) or small sequence deletions that might lead to gene knock-out. *Panel A from* Streptococcus pyogenes *Cas9 structure resolved with X-ray diffraction (PDB:4OO8). Panel B adapted by permission from Macmillan Publishers Ltd: Nat. Rev. Mol. Cell Biol, doi:10.1038/nrm.2015.2 © (2016).*

In 2016, UCB filed an interference to the USPTO stating that the Broad's patent is an 'obvious' derivation from their own. This action opened a high-level international patent war between Cambridge (MA) and Berkeley. The focal point being whether it would be trivial to use the system developed in vitro by Doudna and Charpentier in eukaryotic cells. The Broad Institute managed to convince the US Patent Trial and Appeal Board that its patent is a non-obvious application of the system patented by UCB [2]. The ruling opened a scenario in the US where both the UCB (when awarded) and Broad patents might be valid for commercial application in agriculture or human gene therapy. UCB has since filed an appeal to the decision of the USPTO, but their decision is still pending [2].

The war for CRISPR/Cas9 is not over yet, because each Regional/National Patent Office is a distinct battlefield. For example, in 2017 China took sides with Doudna and Charpentier, granting them a patent for the use of CRISPR/Cas9 in vitro and in all types of cells [2]. This came after the European Patent Office (EPO) also granted the two scientists a CRISPR/Cas9 patent with broad claims (EP2800811) in May of the same year.

CRISPR goes to Crete

When moving to the Old Continent, the dispute over CRISPR patents becomes labyrinthine, with no Ariadne's thread in sight. Multiple players are in the arena, along with Doudna and Charpentier, and Zhang. Some are to be expected—such as Vilnius University, the home institution of Virginijus Šikšnys, inventor of a non-genetically encoded CRISPR technology—others are not. Of note is Merck's subsidiary company MilliporeSigma, which was granted a patent for a CRISPR-based knock-in strategy specific for genome editing in eukaryotic cells (EP3138910). EPO's decision caused surprise among American commentators [11]. MilliporeSigma's patent—also granted in Australia, Singapore, and Canada—covers claims very similar to those presented by the Broad Institute [10], but was filed six days prior.

The EPO awarded the European equivalent of the patent at the centre of the American dispute to the Broad Institute back in 2015 (EP2771468) following an international patent application naming the Broad Institute, MIT and Harvard as applicants. The application was filed in December 2013 claiming a priority date of December 2012—i.e. the date the patent was first filed to the USPTO [12]. Claiming priority means that the novelty of the patent is to be established as if it were filed on the priority date (December 2012), and not on the filing date (December 2013) [13]. In this story, dates are as fundamental as reading.

Opponents of the Broad Institute's patent in Europe have found a winning argument, based on a technical difference between European and US patent law, which led to the revocation of the patent on 17th January 2018. One of the priority documents, dated 2012 (US application 61736527), named Luciano Marraffini, at the time at Rockefeller University in New York, as co-inventor with Zhang, while the application included only the latter as inventor. This mismatch is not coming out of the blue, but is the result of a non-conventional parallel patent dispute between Broad Institute and Rockefeller University, solved through arbitration in January 2018 [14]. According to European rules, the names of inventors listed on priority documents and on the filed application must be identical in order to claim priority (in the US, at least one of the inventors must be present in both documents). This technicality meant that the application could not claim priority date and its effective date became the filing date. The Broad application lacked novelty over the prior art in December 2013 (see for example [10]) and ultimately had to be revoked.

The Broad Institute is appealing the decision on the grounds that the EPO has rules contradicting international patent treaties. However, it is unlikely that the EPO is going to defy decades of patent case law to accommodate Broad's requests [13]. Nonetheless, this revocation does not directly affect the many follow-up CRISPR patents that the Institute still holds in Europe. Thus, at the moment multiple institutions are in possession of key patents with similar claims on CRISPR/Cas9 in Europe. This situation is probably not going to have a winner-take-all solution, and it is likely that multiple players will share rights to the technology [13].

CRISPR patents, academia, and policy making

The CRISPR patent war is not just a fascinating story for people interested in Intellectual Property law. At its core, there are fundamental issues related to the role of academic institutions in the commercialisation of their research, the consequences of 'academia becoming business' [1, 2, 15, 16], and the role of policy makers in addressing this issue (if need be).

Patents are a contract between inventors and society, where one side discloses their invention to the public, and the other grants them the negative right to protect the invention for a definite period of time. This, in turn, incentivises people to create new tools or processes that might benefit society as a whole; patents serve as a powerful tool to drive scientific innovation. The link between legal protection of inventions and innovation has been recognised for a long time, for example the United States Constitutional Convention introduced an 'Intellectual Property clause' in the U.S. Constitution (Article I, Section 8, Clause 8) as early as 1787.

However, advantages become less clear when academic institutions are pushed towards patenting—or rather, exclusive licensing—and commercialising their research. The CRISPR patent dispute is defining a quite unprecedented scenario where a plethora of (mostly academic) players, each with partially overlapping claims on a technology, are present in different regional/national markets. One aspect of this problem is that universities, the patent owners, transfer licensing rights to their private 'commercial arms' (a.k.a. spin-off companies) according to the practice of surrogate licensing [2, 15]. Compared with the past decades, this is a novel approach to the commercial exploitation of academic research [16] and it might be related to changes in the availability and distribution of research funding. Some scholars have warned that a convoluted licensing situation might end up hindering the development and commercial availability of CRISPR-derived biomedical technologies, since a handful of private companies would retain exclusive licensing rights to the technology [1, 15].

A second crucial point we need to focus on is the potentially detrimental effect that these litigations have on interinstitutional collaboration and on the way in which academic research is run. Again, the CRISPR example is paradigmatic, as it disclosed manual examples of toxic behaviours in academia: from downplaying the role of other groups in developing CRISPR/Cas9 [1], to using Prof. Doudna's critical analysis of her own work as a key argument against UCB patent claims [2]. In the long run, the fear of patent clashes might hold back institutions from collaborating—in particular when potentially profitable technologies are on the table. This would betray one of the main assets of scientific research: collegiality.

Funding bodies and policy makers might have a pivotal role in avoiding the emergence of a 'patent or perish' culture in applied research. For instance, they could respectively adopt or promote the adoption of evaluation criteria that would favour applicants providing forms of open licensing, such as patentleft (the patent analogue of copyleft), alongside standard ones. Another possibility is to encourage the use of patents to exert ways of 'private governance' [2] on their commercial derivations that would favour communities. For example, Monsanto's license from the Broad Institute for agricultural applications of CRISPR/Cas9 requires the multinational company to allow the practice of saving and resewing seeds from one season to the next [17]. A policy-driven push on academic institutions towards open and ethical licensing, if matched with policies that encourage a fairer distribution of funding, might discourage research institutions from pursuing time- and money-intensive patent wars and put the focus back on openness and scientific collaboration.

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Innovation in the Fight Against Infectious Diseases

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The discovery of antibiotics in 1928 led the world to believe that the fight against infectious diseases was one to be won within a few years. Nowadays, nearly 90 years following the discovery of penicillin, infectious diseases remain one of the main causes of mortality worldwide, with lower respiratory tract infections, diarrhoeal diseases, and tuberculosis ranking among the top 10 causes of death according to the World Health Organization (WHO) [1]. In recent years, the advent of antibiotic resistance, the anti-vaccination movement, and humanitarian crises have seen a rise in infectious diseases that were once thought to be nearly eradicated, such as polio, tuberculosis and measles.

Reducing the burden of infectious diseases by 2030 is one of the targets stated in the Sustainable Development Goals (SDGs), with SDG3 focusing on ending the epidemics of the Acquired Immune Deficiency Syndrome (AIDS), tuberculosis, malaria and neglected tropical diseases, as well as combating hepatitis, water-borne diseases and other communicable diseases [2]. Innovation in the field of Science and Technology has allowed for better surveillance, diagnosis, and treatment options, as well as contributing to the development and implementation of strategic policies.

Surveillance

Formal reports of suspected outbreaks are usually received by the WHO from ministries of health, national institutes of public health, WHO regional offices, and civil society. Traditional surveillance methods rely on routine reporting of pre-determined information by healthcare facilities. This often results in delayed notifications, making outbreak prediction difficult and leading to slow or less-than-adequate responses.

Technological advances, mainly in the field of digital transformation, have enabled the development of digital surveillance reporting systems and monitoring networks, providing a more rapid response to epidemic threats. These systems collect and analyse information obtained from diverse sources, including social media, news reports, and web-based searches, with the aim of detecting events with epidemic potential prior to official notifications [3].

As part of the Global Outbreak Alert and Response Network (GOARN), the Global Public Health Intelligence Network (GPHIN) was developed by Health Canada in collaboration with the WHO as a tool for event-based surveillance. This system is a secure internet-based multi-lingual early-warning system that continuously searches global media sources to identify information regarding disease outbreaks and other relevant events of potential international public health concern. Reports obtained in this way require verification to ensure cases meet a specific case definition. The importance of GPHIN was highlighted in 2003 during the Severe Acute Respiratory Syndrome (SARS) outbreak in China, issuing the first alert of unusual respiratory illness in Guangdong Province to WHO and GOARN.

Diagnosis

Advances in the field of genetics and biotechnology have enabled rapid diagnosis of infectious agents. New technologies allow the identification of unculturable bacteria thanks to DNA sequencing, and whole genome sequencing (WGS) can be used not only to diagnose an infectious agent but also to identify epidemic strains and transmission events. The most commonly used genetic tool in clinical microbiology is the real-time polymerase chain reaction (PCR), which amplifies genetic material for enhanced detection of pathogens, and is characterized by high sensitivity and specificity, low contamination risk, and high speed [4].

A notable example of the role of innovation in diagnostics, in the context of infectious diseases, is the case of tuberculosis (TB). The bacterium that causes TB takes approximately 21 days to grow in solid culture. Therefore, diagnosis using classical microbiology is typically slow, during which time the infected patient is contagious and can transmit the disease to anyone in close proximity, given the airborne nature of TB. In addition to genetic techniques as a method of identification, the invention of mycobacterial growth indicator tubes (MGIT) has been revolutionary, allowing identification of positive cultures as soon as 1 hour after inoculation. Rapid diagnosis leads to better treatment outcomes and reduces transmission — a key factor in eradication.

Moreover, innovation in the field of diagnostics has not been limited to speed, but also to comfort. Many infectious diseases can only be diagnosed through a blood sample, requiring patients to attend healthcare centres and have their blood drawn. Advances in the field of HIV/AIDS diagnostics have resulted in the invention of HIV home-tests, allowing people to test for HIV in the comfort and privacy of their homes.

Treatment

The treatment of infectious diseases consists of drugs aimed at killing or limiting the growth of the infectious agent, but, due to the intense regulatory pathways in drug development and the high increased risk of failure of clinical trials, pharmaceutical companies do not invest greatly in drug candidates for infectious diseases since the return on investment is generally quite low. However, antibiotic resistance is globally recognised as an emerging public health threat, and policy initiatives are underway to provide solutions for overcoming important obstacles in the fight against antibiotic resistance. These include strategies to incentivise the development of novel antibiotics, including the development of new economic models and policies for sustainable antibiotic use [5].

> *'The fight against infectious disease therefore requires a multi-sectorial approach; policy makers must consider all aspects leading to the spread of infection and the specific cultural traditions of the affected countries.'*

One of the main causes of antibiotic resistance is non-compliance with the prescribed treatment due to the length of treatment, the amount of daily pills taken, or the adverse side effects associated with the drug. These problems also arise in treating chronic non-bacterial infectious diseases, such as HIV. Research from the Massachusetts Institute of Technology, as well as the Brigham and Women's Hospital, into new delivery options for currently available drugs has led to the development of an ingestible capsule that can slowly release 1 week's worth of antiretroviral drugs [6]. Although its application is currently only being researched for HIV, this technology could be used in the delivery of a number of drugs.

Policy and its Role in Eradicating Infectious Diseases

Policies on infectious diseases are difficult to establish due to the range of competencies involved and the different socio-economic and cultural settings in which they are implemented. Scientific advances have played an important role in eradicating many infectious diseases in the developed world, however, many hard-to-reach areas in low- and middle-income countries may not reap the benefits of such advances due to high levels of poverty. Moreover, poverty creates conditions that favour the spread of infectious diseases and prevents affected populations from obtaining proper access to prevention and care. Therefore, policies to reduce poverty and inequalities play important roles in eradicating diseases.

The fight against infectious disease therefore requires a multi-sectorial approach; policy makers must consider all aspects leading to the spread of infection and the specific cultural traditions of the affected countries.

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Consider Fracking Your Backyard

Amanda Murphy, Department of Engineering, University of Cambridge

Fracking or hydraulic fracture stimulation is a very recognisable, very divisive topic. It is common to have a strong opinion about fracking, be it for or against. "Fracking. No. Not in my backyard." Indeed, for most, fracking is something for others to solve. But while we empathise with the impact of such industrial development, we seldom suggest fracking in our backyard.

The North Sea dominates the United Kingdom's (UK) energy supply. However, with North Sea oil and gas fields in decline, controversial fracking technology may be the best option to fill the gap in domestic energy demand. Exploration sites earmarked for hydraulic fracture stimulation are in relatively rural areas of the North West, Yorkshire and East Midlands, but shale oil and gas development should be considered in more urban areas. London and the South East overlie the prospective Weald and Wessex sedimentary basins and development here would be close to consumers in an area with a strong history of monitoring, industrial brownfields sites and existing road and power infrastructure. Perhaps it is time to consider fracking in our London backyard.

The UK remains the second largest producer of petroleum liquids in European OECD countries, with almost all the UK's oil and gas production from offshore fields in the North Sea. The declining production of these fields has led the UK to become a net importer of natural gas in 2004, crude oil in 2005 and all petroleum products by 2013. While the use of renewables increased to almost 20% of all electricity generated in 2016, petroleum and natural gas still make up 76% of total primary energy consumption, with natural gas providing 46% of electricity generation. The UK consumes approximately 2.5 trillion cubic feet (TCF) of natural gas a year and natural gas imports currently supply 40% of this domestic demand [1].

The UK principally imports crude oil from Norway with the balance from West Africa, the Middle East, Russia and North America. Crude oil can be transported in tankers or pipelines, however, while natural gas can also be transported in pipelines, tanker shipping requires conversion to liquefied natural gas (LNG) and then regasification at the destination. The UK gas grid is connected to mainland Europe through two major pipelines and via pipelines from the Norwegian sector of the North Sea. In 2016, 77% of imported gas came through these pipelines, principally from Norway [1]. However, Europe faces similar issues of production decline and Russian imports are increasingly part of the energy mix of continental Europe [2]. Imports of LNG ceased in the UK during the 1980s following development of the North Sea but resumed in 2005; the import amount now varies in response to global market conditions. For example, LNG imports significantly decreased following the 2011 Fukushima disaster as demand for LNG in Japan tightened the global market [1]. Companies such as Centrica are trying to secure gas supply through long term LNG import contracts [3], while National Grid and Ineos already import shale gas converted to LNG from North America [4,5].

The development of shale oil and gas in the UK could make a significant contribution to meeting the increasing domestic energy shortfall and help secure gas supplies as the North Sea declines. At present, the UK has no shale oil and gas developments and only limited shale oil and gas exploration has been attempted. Without significant exploration effort, the estimated volumes are very uncertain, however, suggested recoverable shale gas could be 5-40 TCF [6].

Exploration and development of shale oil and gas, and other unconventionals such as tight gas, coalbed methane, mine vent gas and gas storage come under the *Petroleum Act 1998* and onshore licensing in the form of a UK Petroleum Exploration and Development Licence (PEDL). The statutory regulations to allow drilling and well testing within a PEDL involves several government regulators. These regulators vary according to the jurisdictions of England, Scotland and Wales. Shale gas exploration came to a sudden halt in the UK following fracture stimulation of the Preece Hall site near Blackpool in 2011 [7]. Two minor earthquakes are thought to have been triggered during the operations [8]. Following this incident the UK government imposed a moratorium on hydraulic fracturing, but lifted it a year later following the review of scientific and engineering evidence by the Royal Society and Royal Academy of Engineering [9]. The review introduced new requirements and oversight for fracking operations [6] and additional regulation around hydraulic fracture stimulation was enacted in the *Infrastructure Act 2015*. These requirements mean fracture stimulation operations need to adhere to the traffic light seismic monitoring system. This system is designed to mitigate the risk of seismic activity and operators are required to monitor seismic activity in real time around the hydraulic fracture site using a Richter scale rating. Depending on the measured response they will continue (green), monitor (amber) or stop (red) [10].

In addition to induced seismicity, shale oil and gas development in the UK raises concerns around water contamination and handling. The Energy and Climate Change Select Committee's report on shale gas concluded that hydraulic fracturing itself does not pose a direct risk to water aquifers, provided that the well casing is intact [11]. Current regulation should ensure well integrity; however, there is criticism of how robustly this legislation can be enforced [6]. Baseline monitoring of air, land and water is critical and while the *Infrastructure Act 2015* requires 12 months of methane monitoring in groundwater prior to fracture stimulation and air quality monitoring following stimulation – a longer history of monitoring is desirable. A key recommendation of the Royal Society and Royal Academy of Engineering report was to carry out comprehensive baseline surveys [9]. Air quality can show seasonal variation, weekend variation due to road traffic and there can be episodes of winter or summer smog from Europe [12]. It will be important to distinguish these 'normal' levels from shale oil and gas activities and this will require a record of levels before stimulation. The British

Geological Survey (BGS) is currently undertaking a National Baseline Methane Survey in groundwaters across the UK. Findings from this survey show that where sites were sampled a number of times variations were generally minor but some areas show larger changes [13]. Without greater understanding of this variation, it is not clear if the mandatory 12 month monitoring will adequately capture longer term baseline variation in groundwater methane concentrations.

The surface disturbance and surface footprint of shale oil and gas is important, particularly as shale gas developments require the drilling of many wells. A major issue with regard to surface impacts is that areas of land and wildlife habitat can become fragmented. Land often needs to be cleared to allow access to the well site including construction of roads and pipelines [14]. This can change the look of the land and have implications for local wildlife populations which may need to be mitigated. The initial drilling and hydraulic fracturing process requires construction of a wellpad: a flat 2-3 hectare area. A drilling rig and equipment is then mobilised onsite to drill the well and carry out the hydraulic fracturing operation. During this stage there is often heavy vehicle traffic to the site and noise from the 24 hour operations. Following this stage, the site consists of a wellhead, perhaps with additional production equipment. The area of the wellpad may periodically be used again during workovers or restimulation. When the well is no longer economically viable, cement plugs are installed, and the land above can be reused [15, 16]. This plugging and abandonment of wells is commonplace in the UK for conventional oil and gas and is no different for shale oil and gas wells. However there are no precedents for large scale decommissioning of shale oil and gas fields. The technology behind shale oil and gas was only developed and implemented in the late 1990s and fields from this era are still producing [6]. While current regulations appear adequate, it will be important to follow the progress of these first shale oil and gas fields and regulation may need to be revisited based on their decommissioning experience.

No shale oil and gas fracture stimulation has been completed in the UK since the Preece Hall site in 2011. Now, in 2018, four companies are proposing to fracture stimulate wells in the North West, Yorkshire and East Midlands [17]. These proposed sites for future fracture stimulation are in rural areas; however, shale gas exploration and development can take place in urban areas. For example, shale gas wells have been drilled across the Dallas-Fort Worth-Arlington metropolitan area in North Texas, USA. Almost 2000 producing wells are located within the city limits of Fort Worth which is home to over 800,000 people [18]. Drilling in populated areas has also occurred in the UK; conventional oilfields underlie the villages of Gainsborough (the wells are on the golf course) and Wareham [7].

Urban exploration and development in London and the South East could investigate the shale oil and gas prospectivity of the Wessex and Weald Basins. These Basins already have a history of conventional (non-shale) oil and gas exploration and there are 13 producing fields within the Weald Basin alone. The source of the oil in these fields is from Jurassic aged shales; the Lias formation made famous by the Black Ven mudslides and fossils at Lyme Regis and the Kimmeridge Clay which seeps oil from the cliffs around Kimmeridge Bay. These formations would be the target for shale oil and gas exploration. It is not entirely clear how far these rocks extend beneath the surface but it is predicted that they go north as far as Croydon [7].

Shale oil and gas in London and the South East may be a better alternative than development in more rural areas. The energy is produced closer to the consumers, infrastructure is already present, and there is already a strong history of environmental monitoring within the city (for example, square mile air quality monitoring [12] and sampling and associated studies of methane in groundwater prior to the National Baseline Methane Survey [13]). The *Town and County Planning Register Act 2017* requires local authorities to prepare and maintain registers of brownfield (previously developed) land that is suitable for residential development. Croydon Borough lists 12 sites over 2 hectares and the 2012 National Land Use Database of Previously Developed Land also listed several locations south of London over 2 hectares including old brickworks. These and other similar sites might be suitable for activities such shale gas development particularly locations such as old gas works, sewage works or brickworks. Redevelopment of these sites is often complicated by possible contamination and costly clean-up may be needed before any sort of reuse. This could be an opportunity for developing government incentives to link shale oil and gas development with clean-up of these types of brownfields sites.

While regulation is critical in the development of shale oil and gas in the UK, the current major roadblock is public opinion [6]. It will be important to educate and consult the wider community on choices within the greater energy landscape. In the absence of more creative solutions, the UK has three main alternatives. We can look to Europe, and increasingly Russia, for our domestic gas supplies. Alternatively, we can secure LNG imports; which requires additional energy input for liquification, regasification and transport and almost certainly will include shale gas. Our third option would be to develop our own domestic shale oil and gas. While the UK has an informed regulatory framework, any development will involve significant construction of surface infrastructure and needs to have extensive baseline monitoring of the land. These concerns would be eased if developments were in the more urban areas of London and the South East. Developments would be close to consumers in an area with industrial brownfields sites, existing infrastructure and a history of monitoring.

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The Art of Science Diplomacy

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Richard Holbrooke once said '*Diplomacy is like jazz: endless variations on a theme*'. A fine-art as it seemingly is, diplomacy has recently had an added embellishment on its canvas: science. For the diplomats of the day, this new addition to the vanguard of diplomacy has come with a lot of additional resources and opportunities, over and above the traditional elements of 'soft power', which is an approach to international relations that involves persuasion using economic and/ or cultural influences.

Historically, science and technology were often used in diplomatic circles. Sometimes they were used to strike a sense of awe into emissaries from foreign lands. For example, the Byzantian Emperor had a special hydraulic system that elevated his throne to the ceiling of the Magnaura Palace, thereby making a lasting impression on visitors. At other times, science was an integral part of building international bonds. Jesuit missionaries played a major role in medieval international diplomatic circles, from helping in the signing of the Treaty of Nerchinsk to the Kangxi Emperor's favourite mapmaker-cum-diplomat Father Gerbillon. What they did do in the process of facilitating stronger international ties was to establish centres of learning and research that looked into scientific pursuits. This may well have been the first instance of science diplomacy between nations. Closer to Cambridge, Philip Zollman was made Foreign Secretary of the Royal Society in London in 1723 and his role was to maintain regular correspondence with scientists overseas to ensure that the Royal Society's fellows remained up-to-date with the latest ideas and research findings. Before World War II, news and information about scientific developments abroad were conveyed to London by commercial, military and even agricultural consignments.

However, it was only after the war that due to Joseph Needham, whose work in the area of promoting an 'International Science Co-operation Service' was widely-recognized, the natural sciences were recognised as subjects that could do with a bit of international cooperation in a regulated way. They were incorporated within the mandate of the United Nations Educational, Scientific and Cultural Organisation (UNESCO). This was done notwithstanding the international movement to address issues of global concern such as the threat posed by the introduction of nuclear weapons, which was written about in a manifesto by Bertrand Russell and Albert Einstein in 1955, that called on scientists of all political persuasions to address the issue. The famous *Pugwash Movement* on science and world affairs, which was recognized with a Nobel Prize in 1995, was also founded at around this time, in 1957, as what proved to be a major player in the world of science diplomacy: the science program by the North Atlantic Treaty Organisation (NATO).

After the Cold War, science diplomacy entered a stage of dormancy, which has only recently been broken through. Indeed science and diplomacy have recently entered into a new phase of symbiosis. As per the *Royal Society* and *American Association for the Advancement of Science (AAAS)*, the concept of "science diplomacy" refers to a number of parallel ideas under one conceptual umbrella. Not only can science inform and support foreign policy objectives (such as on climate change) and improve international relations (such as in international collaborations for scientific pursuits like the Large Hadron Collider), diplomacy can also facilitate international scientific cooperation. Famous American molecular biologist Dr Nina Federoff, while being the Science and Technology Adviser to US Secretary of State, once said '*Science diplomacy is the use of scientific interactions among nations to address the common problems facing humanity and to build constructive, knowledge based international partnerships*.'

Over the next century, foreign policy is poised to be increasingly shaped by certain linked challenges of sustainability on the global stage. This includes insufficient energy resources, climate change, food shortages and scarcity of water. Science and technology will be critical in addressing these hurdles and hence, the use of good scientific advice by policymakers should be prioritised. The global diplomatic world has increasingly moved towards a disaggregated model that not only involves governments, but also various non-state entities including nongovernmental organisations (NGOs), lawyers, the media and scientific bodies, amongst others. For instance, at the *United Nations Climate Change Conference in 2013 (COP19)*, there were more than 800 delegates from non-governmental organisations alone. However, after all is said and done, efforts to define and demarcate the role of scientists within this complex world order are still in a nascent stage. The United Nations Conference on Trade Development (UNCTAD) set up a science diplomacy initiative in 2001 to enhance 'the provision of science and technology advice to multilateral negotiations and the implementation of the results of such negotiations at the national level' [1]. The American Association for the Advancement of Science (AAAS) established its Centre for Science Diplomacy in 2008 to bring together people from the spheres of foreign policy, science and public policy to recognise areas where science cooperation can help build trust, leading to better intercultural understanding.

'Science diplomacy is the use of scientific interactions among nations to address the common problems facing humanity and to build constructive, knowledge based international partnerships.'

In the UK, the Royal Society has considered bridging science and diplomacy as one of its key objectives of its new Science Policy Centre. The UK government, too, has taken a number of measures to link science more directly to its foreign policy priorities. It set up a Science and Innovation Network (SIN) in 2001, which over the years has expanded to have bases (usually in High Commissions or Consulates and UK embassies) in 25 countries. The network does not provide any research funding itself, but rather facilitates collaboration between the United Kingdom and international research partners on a number of scientific and policy matters, such as climate change, energy and innovation.

Sir Peter Gluckman is widely recognized in the world of science diplomacy. He is currently the inaugural Chief Science Advisor to the New Zealand Prime Minister. He is a fellow of the Royal Society of London and has received the AAAS Award for Science Diplomacy, in 2016.

For effective science diplomacy, the scientific community must not only be up-to-date with information on the state of our planet's natural and socio-economic systems, but be capable and empowered to inform policymakers at the right time. It is also in the best interests of evidence-based policymaking and diplomacy for the scientists to know where uncertainties exist in these resources and where the evidence-base is inadequate for an informed decision or policy. Even on certain sensitive issues that may be of importance to national security, scientific collaboration can help to facilitate political cooperation and negotiations. In the 2009, the Geological Survey of Canada recently initiated a collaborative project that involved researchers from Norway, the United States of America, Sweden and Russia. They published the very first comprehensive survey of Arctic geology in a step that could have beneficial implications for contentious sovereignty claims between these countries. [2]

Establishing links between scientists and diplomats helps both: for the former by informing them about the realities of foreign policy and policymaking, and for the latter by highlighting the role and limitations of science in policy. Improving the scientific knowledge and understanding of delegations working on key world issues like climate change and health is crucial. In the United Kingdom, the Royal Society founded an interesting scheme in 2001 to pair an MP with a scientist to facilitate this in the domestic environment [3]. Diplomacy, in turn, can help to set up scientific collaborations that are the need of the hour for contemporary research that involve large upfront investments in infrastructure, which is beyond the budget of any one country. Scientists may require diplomatic assistance on a number of fronts, particularly in intellectual property agreements, contract negotiations, or even with visa regulations. Post-Brexit, this has been a major cause of concern for EU-UK scientific collaborations, since around 30,000 EU nationals occupy nearly 17% of University research and teaching posts in the United Kingdom. In a scenario where a “hard Brexit” could potentially impact more than 90,000 STEM (Science, Technology, Engineering and Mathematics) jobs as per a new analysis commissioned and published by London mayor Sadiq Khan [4], a pressing need at this time is to make Diplomacy for Science a priority. As for Science for Diplomacy, the much-needed positive feedback that is sought by diplomats from scientists and the world of science in the diplomatic processes can be established using science cooperation agreements to improve bilateral ties between nations, creation of new scientific institutions (such as CERN) and scholarships for network-building and partnerships. With new challenges such as environmental degradation, scarcity of resources and the danger of nuclear warfare, highlighting the scientific and environmental nuances of foreign-policy agreements has led to increased discussion and debate on science diplomacy.

Today, science diplomacy needs support from individuals and organisations placed at all levels of the science community. Young scientists should be made aware of opportunities and incentives to engage with policy and diplomacy very early on in their careers. Points, such as the consideration of how cooperation on scientific aspects of nuclear disarmament could support the wider diplomatic process, need to be addressed. Measures must be initiated with, and in, countries that have been struck by violence and war to see how science diplomacy can help, in all three ways: science for diplomacy, diplomacy for science and science in diplomacy. Last but not the least, international spaces that are beyond national jurisdictions such as Antarctica, the deep seas and outer space, need to be governed using an approach to international cooperation that is informed by scientific evidence and supported by scientific partnerships.

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Prospective and Retrospective Rigour: Scientific Evaluation of Environmental Policy

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The preservation of our environment is an ethical imperative and one of the greatest challenges of the twenty-first century. By necessity, much of the battle to protect the environment will be waged at the level of policy. However, the track record of environmental legislation shows much room for improvement, a development that will only be reliably achieved when it becomes common practice to rigorously evaluate the effects of all policies with scientifically rigorous studies, prospectively as part of the planning process and retrospectively after widespread implementation. Environmental scientists are uniquely positioned by virtue of their biological expertise, scientific training, and statistical skills to take an active role in this evaluation process.

On paper, science and engineering are completely distinct disciplines: the first attempts to understand the world, the second seeks to change it. This classification may be convenient for establishing academic departments, but it fails to capture the full scope of what many scientists and engineers really do. Engineers rely on scientific data, and frequently generate scientific data of their own. Scientists are often interested in engineering the subject of their study. Engineering and “pure” science are conceptually separate, but ultimately much research in both fields is a hybrid: applied or purpose-driven research.

Purpose-driven research is particularly common in conservation and environmental science, where mitigation and prevention of anthropogenic environmental disasters is usually the primary reason to document past and current disasters [1]. Law and policy are frequently the most powerful tools to achieve this goal, so environmental and conservation scientists find themselves with a closer association to policy than many other fields of science.

Every scientist must understand the branch of policy that governs their field, but those who wish to shape policy require a far greater degree of understanding. It is necessary to understand how a change in policy will impact the behaviour of nations, corporations, and people. If a natural system is in a given state as a result of human action and we wish to change it to another, we must understand not only how human action affects the environment, but also how specific policies affect human actions. One could imagine that it is the duty of scientists to provide reports on the state of the world and allow policymakers to devise schemes to improve it, but this scheme does not mirror the current course of events, nor is it the ideal solution to the problem. Conservation and environmental scientists frequently study anthropogenic ecological problems, and their work ideally culminates in policy changes that reduce the very environmental harm they study – a goal shared by engineers. The response to environmental catastrophes creates a feedback loop where human activity changes the environment, which attracts environmental scientists who lobby to develop policies that correct the human impacts that first caused the problem, as illustrated in Figure 1.

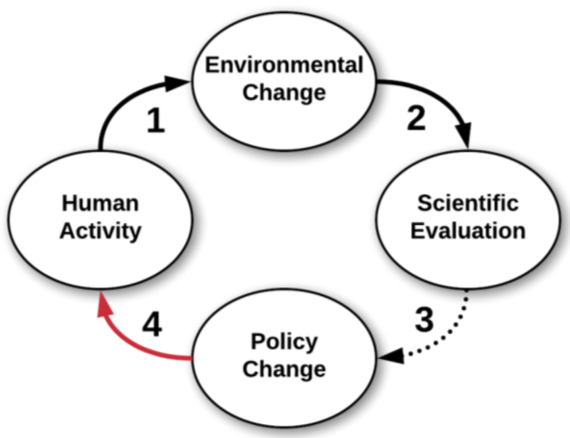

Figure 1: Feedback loop of human-environment interactions. Solid black lines denote pure environmental science, dotted black line denotes scientific input in policy, red line denotes the knowledge gap discussed here. To engineer the feedback loop, all four links must be understood.

Links 1 and 2 in this loop are firmly in the domain of environmental science, link 2 is simply the process of studying link 1. Environmental scientists often serve as advisors and advocates for policy change, and are therefore deeply influential in link 3. Link 4 in the feedback loop is how policy changes alter human behaviour, and the lack of evidence in this link is the limiting factor for understanding and controlling the whole loop. This critical final link traditionally falls into the domain of behavioural economics and behavioural sciences.

Richard Thaler won the Nobel prize in economics for his work surrounding "nudging", a branch of behavioural economics examining how subtle situational changes can alter human behaviour. The surprising truth is that small changes can radically alter behaviour, at costs often a tiny fraction of traditional "common sense" interventions. For example, assistance in filling out a financial aid form increased college enrollment 40 times more than a traditional program subsidising education [2], and another traditional program providing families with information about financial aid turned out to have no effect at all [3]. Unfortunately, these kind of experiments examining the effects of policy are the exception rather than the rule [4].

The scarcity of scientifically rigorous analysis of the effects of policy can result in mistakes like sex education that increases teen pregnancy [5] and criminal justice programs that increase delinquency [6]. Thankfully, these programs are being slowly phased out due to a slew of studies showing they fail to achieve their stated goals. This is a triumph of retrospective rigour, analysis of the outcome of a policy after deployment. However, policy mistakes were already widely implemented at substantial cost, and they remain difficult to eliminate for political and financial reasons. A cheaper and quicker way to discover the efficacy of a policy is prospective rigour, rigorously evaluating small-scale pilots before widespread implementation.

Though currently rare, using pilot studies to rigorously evaluate the impacts of policy before broad implementation is by no means a novel idea [7]. Prospective rigour has been widely adapted by international aid organisations such as the Abdul Latif Jameel Poverty Action Lab and the World Bank, which use small and controlled pilot studies to evaluate interventions before broad deployment. A surprising trend has emerged from these studies: many interventions completely fail to achieve their stated goals, while most others accomplish very little. Fortunately, some interventions work quite well, confirming that policy changes can indeed influence the world in the desired direction. These few highly successful interventions are frequently more than 50 times as effective as the average intervention, ignoring those that do nothing at all.

Given the urgency of problems such as environmental degradation or global poverty, it is tempting to skip this period of assessment and optimisation, but to do so would be a mistake of the highest order. Instead, the massive variation in efficacy between different interventions highlights the importance of using prospective rigour. As one example, the World Bank Disease Control Priorities in Developing Countries working group evaluated a variety of global health interventions targeted at reducing mortality and morbidity, as measured by disability adjusted life years (DALYs). They found that childhood immunisation saved over 180 times as many DALYs per unit cost as treating hypertension and nearly 700 times as many DALYs as antipsychotic medication, as shown in Figure 2.

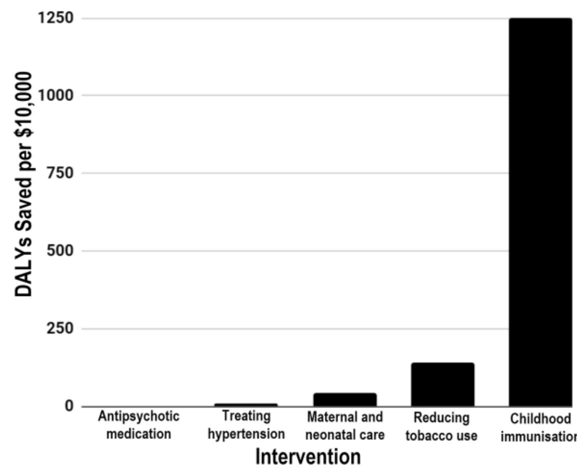

Figure 2: DALYs saved per $10,000 spent. Most interventions accomplish little or nothing, the best are orders of magnitude better. Adapted from [8].

All of these interventions are well-intentioned, and there was no way of knowing *a priori* that some would be so much less effective than others. Yet in study after study, the same pattern shows up: when different policy interventions are compared against each other, some achieve nothing, many achieve little, and a few are truly worthwhile. Given limited resources, the most effective interventions should be implemented first, until the law of diminishing returns reduces their cost efficiency down to the level of other options. Prospective rigour is the series of rigorous pilot studies required to know which interventions to prioritise.

The efficacy of environmental policy almost certainly varies over a similarly broad range, so it is critical we invest our time, energy, and money to ensure we are implementing the policies on the far right of this sort of graph – randomised pilot studies could go a long way towards achieving that goal. Environmental scientists have expertise to contribute for designing small-scale, blind, randomised controlled pilot studies appropriate for the initial evaluation of the effects of a given policy and a more systematic evaluation process after the selected policies are deployed. This approach is desperately needed because some widely-implemented environmental policies have been expensive and ineffectual.

In the United States and Europe, mandatory ethanol additives in petrol have increased the price of food, caused massive habitat loss, and increased agricultural pollution [9]. All these ills have been in hope of reducing greenhouse gas emissions, but the reduction is negligible - in the American case, less than a quarter of a percent of the greenhouse gas emissions from petrol, at a cost of over fourteen percent of the corn crop (the primary feedstock for fuel-additive ethanol) [10]. Diverting agricultural resources from food production to ethanol production increases corn prices by ~23% and increases the portion of land devoted to corn by 18%, according to the United States Department of Agriculture [11]. In attempting to solve any given problem, many well-intentioned ideas do not work in practice, and the best are orders of magnitude more cost-effective than the others. Retrospective rigour only tells us when a policy was wrong years after the fact, when changing course is difficult. Prospective rigour before the massive infrastructural and capital costs of the fuel ethanol policy program could have directed us down a wiser path from the beginning.

Of course, understanding how policy affects human action is not a simple challenge. Environmental scientists are used to studying complex and experimentally intractable phenomena, all while working with large and varied datasets. Their expertise in how the environment responds to human actions justifies a seat at the environmental policy-making table. This puts them in an excellent position to design and evaluate the rigorous pilot studies required for prospective rigour. At the minimum, this means sharing their unique skillset and expertise with policy makers and social scientists, collaborating to understand the fourth and final link of the feedback loop they study. It is a Herculean undertaking, but studying both the natural and the human systems involved in environmental catastrophes would massively increase environmental scientists' efficacy in protecting the environment.

Society relies on environmental and conservation scientists to prevent and mitigate anthropogenic environmental catastrophes. The primary tool for this has always been legislation and policy, and scientists have the skillset required to test which policies are most cost effective. The stakes are too large to not use the most effective policies available, and that calls for empirical analysis - for prospective and retrospective rigour.

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Ensuring Societal Advancement through Science and Technology: Pathways to Scientific Integration

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In an increasingly digitised world, those within STEM fields have a responsibility to communicate their research in an accessible manner to the funders and end-users of their innovation. Steps should be taken to incentivise improved scientific communication by scientists via social media, open source publishing and outreach programs. In this way, we can ensure equal access to research across society, and increased acceptance of innovation, whilst avoiding costly delays to their implementation.

The scientific field was built upon the basic core principles of collaboration and distribution. With the digital age came renewed opportunities for integration with the community. Now, the foundations of science and healthcare are once again changing, as paradigm-shifting technologies such as AI-powered healthcare solutions and genomic medicine become the norm. If our communities do not understand and accept these new services, any positive impact is significantly limited. In order to find a resolution to this problem, we need to focus on improved scientific communication and education, through re-examined frameworks for scientific impact and funding.

Current issues in science communication

In 2016, the UK Government promised yearly increases in research funding until 2020, and to spend £12.5 billion on R&D in 2021/2022[1].

This substantial public investment is made, not merely to support intellectual advances, but also with the belief that funded research will benefit the public. With Innovate UK chief executive, Dr. Ruth McKernan CBE, stating that '*Research and innovation has never been higher on the agenda*'[2], and the director of the Campaign for Science and Engineering, Dr. Sarah Main, claiming that '*Such sizeable public investment brings a responsibility to spend it effectively*'[3], one cannot deny the increasing expectation for STEM fields to deliver results. But what do we accept as responsible propagation and dissemination of our research in 2018? While advances in scientific research are published in scientific journals, only a selection of these findings ever reaches the general public.

Adler et al. previously outlined the impact of education, occupation and income on disparities in population health[4]. Research suggests that scientific literacy may also become a contributing factor. With reports suggesting that workers in STEM industries are currently earning approximately 29% more than their non-STEM counterparts, and projections for increased employment and job growth in STEM fields, policy makers must be proactive to minimise the practical inequities created by a shifting balance of power[5]. Due to current shortcomings in the dissemination of research to the wider community, those who have a formal scientific education, and access to scientific publications, may benefit from medical or healthcare research findings before they are translated into healthcare policy and practice. Without the non-technical, layperson communication of science, we could face demographic-based isolation from science and technology innovations, as they become more prevalent in future.

A major issue facing scientific communication and outreach is the distortion of scientific findings for mass media, both intentional and accidental. As journalists reporting research discoveries traditionally have little-to-no scientific research experience, their reporting of scientific research is often inaccurate[6]. Even with increased focus on the scientific education of journalists, and increased specialist journalists, inaccurate reporting of research continues, placing credible and robust scientific findings in serious danger of being labelled 'fake news'.

Given that tax contributions and charitable donations fund the majority of scientific research, it is the responsibility of scientists to improve the dissemination of their research in order to educate their communities and maximise the societal value of their work.

The potential benefit of direct science communication by researchers

Direct communication between scientists and the general public has the potential to reduce the reliance on easily accessible, low-quality sources of information. Questions that necessitate a sound scientific understanding are traditionally either left unanswered or answered poorly online by the ill-informed. Direct communication by scientists may also increase the validity and integrity of scientific communication as a whole, since fewer errors would be made in the translation and reporting of their work. This could, in turn, result in greater trust and acceptance of legitimate, but controversial research findings. In this way, scientists would be able to communicate their research in a manner that is impactful, and positive.

In order to create an environment and culture of outreach amongst the scientific community, it must be incentivised by government, and funding bodies. Most funding bodies already have established public engagement policies, such as the UK Research and Innovation's '*Pathways to Impact*' policy[8]. While these policies are designed to facilitate community involvement, and recognise the benefit and responsibility of such initiatives, more could be done to engage scientists in scientific outreach beyond their basic funding obligations.

Research policy solutions to increase community outreach

Research policy solutions to increase scientific communication may act to increase research impact. Current funding policies encourage publishing in open access journals[7], but publishing research in non-technical modes, and writing in clear language, would make publicly funded research more accessible to the general population. In the case of research that warrants education campaigns, such as those that influence lifestyle and health changes, government-verified social media engagement may provide opportunities to rely on free advertisement provided by the masses. Short easily digestible articles and 'viral' stories may provide avenues for mass distribution of scientific findings in simple, but accurate formats. In this way, government bodies could save money on education campaigns, health and lifestyle interventions, and even medical treatment. Saved revenue could be directed back into further scientific research.

Direct communication of science by researchers may also protect against low adoption rates of cost-saving innovations, due to public distrust of modernisation. Through increased societal integration of STEM researchers, governments may be able to adopt cost-saving modernisations and increase efficiency on much shorter timescales.

To this end, I propose the creation of an '**Office for Community Innovation**'. The remit of this office would be to connect researchers with members of the community who can facilitate their outreach initiatives, in order to promote social connectivity through the propagation of research and education. As well as researching opportunities for cross-communication, this office would provide three main services:

1) **Community contact** – community organisations would be able to contact the office to request scientists to come and speak to them on topics relevant to their field

2) **Researcher contact** – researchers would be able to contact the office to request community contacts for education initiatives

3) **Researcher-to-researcher connection** – the office would act as a conduit to connect with other researchers with complementary objectives that could be met through joint education initiatives

Imagine that elderly members of the community living in a retirement home would like to know more about how their medicines work. The administrator of the retirement home could contact the **Office for Community Innovation** to request a pharmacologist to speak about the basics of their work. Other examples may include medical researchers visiting hospitals, environmental scientists visiting companies interested in increasing their environmental awareness, or physicists speaking about the applications of their work to school children. By engaging scientists to assist in community education, they would also be given the opportunity to share their research to people who would otherwise not get that chance to learn about it. Moreover, through getting information first-hand, our citizens would be better informed on important issues, and more actively invested in the furtherance of science.

Researchers would be incentivised to attend these community engagements, on a basic level, as they would provide the opportunity to meet funding quotas for such outreach. The opportunities provided by the **Office for Community Innovation** would also allow researchers to build their communication and presentation skills, and to engage with the real-world applications of their work. Community members are likewise incentivised to attend these engagements to learn more about how research advances will affect their career, healthcare, and day-to-day lives in the future.

Increasingly, journals are printing a '*plain language summary*' of research papers along with standard abstracts. By adjusting existing policies to include explicit requirements to publish research findings in lay language on non-technical platforms, engage with outreach initiatives, and maintain social media presence, the real-world impact of scientific outreach will become apparent. Stricter funding guidelines and requirements, along with review processes set up to ensure these new criteria are met, will ensure rapid adoption of these new principles. Implementing a rating system for researcher engagement would also provide a clear, real incentive to comply.

By encouraging STEM outreach, governments and funding bodies may renew the spirit of collaboration (and competition) between laboratories and offices. There may also be more direct rewards. Increased research exposure would result in public consideration like never before. This unprecedented access to research may also increase collaboration between science and industry, ensuring rapid translation of research into beneficial outcomes. Optimised industry engagement may result in a higher diversity of channels in which research can progress to the point of benefiting those who are ultimately funding these discoveries.

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