New directions in innovation policy

Policy Exchange

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Foreword

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Economic history tells us that innovation lies at the very heart of improvements in living standards. It also tells us that the infrastructure supporting this innovation – from the setting of clear objectives to the creation of anchor institutions to the availability of long-term funding - shape this success. This innovation infrastructure turns basic science into the General Purpose Technologies (GPTs) – from fire to electricity to the internet – that unlock rises in productivity and living standards.

This fascinating and timely paper by Geoffrey Owen describes the evolution of the innovation infrastructure in the UK and internationally. Fascinating because of the repeated undulations in innovation policy, both its degree of activism and its orientation, over time. And timely because many governments around the world have recently sought to reshape and revamp their innovation strategies. That includes the UK government, where a White Paper on innovation is due soon.

Some clear common themes, or principles, emerge from historical experience of developing successful innovation strategies. The first, and most obvious, is the importance of having an innovation strategy in the first place – that has not always been the case in the UK. A second theme is the importance of focussing this strategy on a small number of long-lived, large-scale missions. This provides both focus and the prospect of operating at the scale necessary to affect change.

A third principle is the need to combine expertise and resource from across a variety of sectors – government departments, the private sector, universities and research institutes - in line with comparative advantages in know-how to deliver an effective innovation strategy. This typically requires a co-ordinating role for government acting in a project management capacity. Crucially, this project management role should operate independently of the political process.

Fourth and finally, meeting long-term challenges is not possible without long-term committed funding of these missions. Based on past experience, at least some of that is likely to need to come from the public sector given its long-term horizon, higher risk tolerance and, prospectively, deeper-pockets. De-risking high-risk, high-return projects, through public funding or procurement, can in turn crowd-in private funding in a public/private partnership.

International experience with innovation strategy – in the US since the Second World War and in countries such as Germany and Japan more recently – has broadly followed these principles, albeit to differing degrees. In each case, the latest vintage of innovation strategy has tended to put centre-stage an anchor institution responsible for innovation strategy and funding - an advanced research agency, in the spirit of the US Defence Advanced Research Agency (DARPA).

Innovation strategy in the UK has waxed and waned over the past half-century. Interestingly, one clear example of the innovation principles being followed in practice was the UK's vaccine programme over the past 18 months. This involved a clear mission, project management by Government drawing on the expertise of universities, the private sector, Government departments and civil society, all underpinned by large-scale public sector financing and procurement.

The questions facing innovation policy in the UK today include the following. First, can the successful approach to innovation around vaccines be replicated outside of crisis? How will the UK's new innovation strategy compare to international competitors? Will the new Advanced Research Innovation Agency (ARIA) in the UK provide the scale and scope necessary for success? What is the role for the UK's existing research funding agency – UK Research and Innovation (UKRI) - in this innovation eco-system, including supporting basic as well as applied research? And how will this innovation strategy support wider Government objectives, including net zero and levelling-up?

These are open questions. They will remains so, at least until the UK Government's new innovation strategy is published. Geoffrey Owen's paper provides a clear and coherent framework against which these questions can begin to be assessed and the likely success of the UK's innovation strategy thereby judged.

Executive Summary

Soon after entering office at the end of 2019, Boris Johnson's government committed itself to an unprecedented increase in spending on science. Although the Covid-19 crisis forced the government to change its priorities - most importantly the development and rapid rollout of an effective vaccine – the commitment to science was reaffirmed in the summer of 2021 as the crisis began to ease. Boris Johnson repeated his earlier pledge to increase government spending on research and development from £15bn a year to £22bn by 2024-25.

Referring to the success of the UK's vaccination programme, the Prime Minister said: "With the right direction, pace and backing, we can breathe life into many more scientific and technological breakthroughs that transform the lives of people across the UK and the world".

How can the government ensure that the additional funds for science will be well spent and generate the innovations that the Prime Minister wants? What changes need to be made in the organisation and management of publicly funded research?

Answers to these questions have to start from a clear understanding of the sources of innovation and what governments can do to promote it.

A central fact about the innovative process is the unpredictability of scientific research and hence the difficulty of planning it. History shows that many of the most important advances have sprung from basic or discovery research which was conducted with no clear practical or commercial objective in view.

Basic research has to be financed mainly by government because there is little incentive for private sector firms to invest in it. The role of government is all the more important in the light of the decline or disappearance of many of the large industrial companies, such as Bell Laboratories and Xerox in the US, or lCI in the UK, which in the earlier post-war years had the financial resources to invest in long-term speculative research. Most private-sector research today consists of projects which are expected to pay off in the short term.

This trend reinforces the importance of publicly funded research, which is mainly conducted in universities. The UK is one of several countries where governments have been rethinking their approach to the funding of research, as part of a broader review of science and innovation policy.

One of the motivations behind these reviews is the sense that the science funding system has become too conservative and risk-averse, and that opportunities for potentially transformative research are being missed. This has led to the creation of new funding agencies that draw on the DARPA model – a much admired technique for managing ambitious research and development programmes which was pioneered by America's Defence Advanced Research Projects Agency.

This agency, initially called ARPA (the D for Defence was added later) was set up in 1958 in response to the launch of Sputnik, the Soviet space satellite. Although the agency is part of the Department of Defence and its primary task is to protect national security, it has contributed to some transformative innovations which have had a profound impact in non-defence markets. The most famous example is the internet, where the crucial initial breakthrough, the development of interactive computing, was made by DARPA.

DARPA's achievements have been widely seen as showing how visionary scientists, if given the right support and the right incentives, can tackle high-risk, potentially high-return projects and produce innovations that change the world. One of the keys to the agency's success is thought to lie in its distinctive approach to the choice of programmes, and the high degree of autonomy given to its programme managers. Both the UK and Germany have created new agencies based on the DARPA model.

Another recent development, also partly influenced by US experience, is the shift towards mission-oriented innovation policies. In the earlier post-war decades such policies were generally associated with ambitious, government-directed projects in the defence, aerospace and nuclear fields. The Apollo moon landing project is the most famous example; Concorde, the Anglo-French supersonic airliner project, is one of the best-known failures.

Today's mission-oriented policies borrow some features from those earlier projects (including in some countries the use of the word "moonshot"), but they are generally focused on broader societal challenges which governments believe can best be tackled by a coordinated effort on the part of public agencies, academia and business. An example was the industrial strategy launched by the British government, then led by Theresa May, in 2017. The strategy was built around four "grand challenges": artificial intelligence and data, the ageing society, clean growth, and the future of mobility.[1]

These policy changes are too recent for their impact to be fully assessed, but neither missions nor DARPA-like agencies will in themselves transform a country's innovation performance. Missions can play a useful role, but they need to be few in number, carefully chosen, and given a clear objective and timeline. The new agencies represent a potentially valuable source of funding for high-risk, high-return projects, although there are dangers in giving them too wide a remit.

What matters most is the health of the science and innovation system as a whole, from basic research at one end to commercial development at the other. Governments must be careful to ensure that, in their eagerness to show that their spending on science is having an impact on people's welfare, they do not undervalue basic research, which remains the essential underpinning of a successful science policy. Within that area

1. Industrial strategy: the grand challenges, Department for Business, Energy and Industrial Strategy, November 2017.

there is room for improvement in the way applications for funding are assessed; for example, the peer review system is widely criticised for a bias against untried researchers with proposals that run counter to the scientific consensus.

In the British context a heavy responsibility for maintaining the excellence of the research base rests with UK Research and Innovation, which manages the bulk of the UK's publicly funded scientific research. This body was created in 2017 to bring together all the research councils, which fund academic research in particular disciplines such as biomedicine or engineering, as well as Innovate UK, a government agency that helps early-stage science-based firms bring their research closer to the market; UKRI also includes Research England, which provides block grants for university research.

UKRI has been criticised for excessive bureaucracy, but a large part of that problem stems from the tight control exerted by its sponsor ministry, the Department for Business, Energy and Industrial Strategy (BEIS), and the Treasury. That this needs to be urgently corrected is recognised by the Johnson government, and a review of how to reduce bureaucracy in research funding is now in progress. The recently announced plan to create a new Office for Science and Technology Strategy in the Cabinet Office, led by Sir Patrick Vallance, provides an opportunity for the government to sort out the relationship between UKRI, BEIS and the Treasury, so that UKRI can make a more effective contribution to the Prime Minister's plan to make the UK a science superpower.

Introduction

The UK government, like its counterparts in several other industrial countries, is committed to a large increase in spending on science. It is also making changes in the way government funding of scientific research is organised and managed. The objectives are: to make better use of science and technology in helping to solve the country's economic and societal problems; to gain a competitive advantage for British industry; and to foster the growth of world-leading science-based companies.

The purpose of this paper is to assess how far these objectives are likely to be realised, with a particular focus on the role of publicly funded scientific research, and to consider what other changes may need to be made in the science and innovation system.

The paper looks first at the general question of where innovations come from and what governments can do to encourage them (Section 1). It stresses the unpredictability of scientific research and the importance of serendipity. It notes the decline or disappearance of some of the big companies, such as Bell Laboratories in the US and ICI in the UK, which in the earlier post-war years were large spenders on research, including basic research. This has put greater weight on universities, where the bulk of basic research is undertaken. What is seen as an over-conservative, risk-averse bias on the part of established funders has prompted the creation of new agencies specifically charged with supporting transformative research.

Section 2 looks at three countries - the UK, Germany and Japan – which are in the throes of reorganising their science and innovation systems. It also considers President Biden's plans for reforming the science funding system in the US. The UK and Germany are setting up new funding agencies partly based on the DARPA model, an approach to the management of high-risk, high return research projects that has been pioneered by America's Defence Advanced Research Projects Agency. Those two countries, as well as Japan, have also adopted what are called mission-oriented innovation policies.[2] This involves the identification by government of ambitious objectives which are thought to be important for economic or strategic reasons, and the launch of research and development programmes designed to achieve those objectives.

Section 3 considers future directions in science and innovation policy, focusing mainly on the UK. It highlights some of the risks associated with the new policies that have been introduced, and points to other ways in which the science and innovation system could be improved. It also looks at the future of the body which manages the bulk of the UK's publicly funded research, UK Research and Innovation (UKRI) - its governance, management and its place in machinery of government. Reforms in these areas will be needed if UKRI is to make an effective contribution to the Prime Minister's aim to strengthen the UK's position as a science superpower.

2. The trend towards mission-oriented innovation policies is reviewed in Philippe Larrue, The design and implementation of mission-oriented innovation policies, OECD Science Technology and Industry Policy papers, No 100, February 2021. See also Marianna Mazzucato, Mission economy: a moonshot guide to changing capitalism, Allen Lane, 2021.

1. Sources of innovation

When Godfrey Hounsfield, an engineer, was working in the Central Research Laboratories of EMI, a British electronics company, in the late 1960s, his main interest was in computer storage techniques and in making the transmission of information from one medium to another more efficient. As part of this work, he explored the idea of detecting the information content of X-rays through crystals rather than film; this approach made it possible to obtain images of far greater contrast and clarity than could be achieved with conventional methods. [3]

Hounsfield (who later shared the Nobel prize for medicine) saw that the technique could have application in the diagnosis of disease. Although EMI had no previous involvement in medical technology, he persuaded his employer to let him continue this line of research, and in 1971 he produced the prototype of the CT Scanner, a diagnostic tool based on Computed Tomography, which uses a combination of X-rays, detectors and computers to produce cross-sectional pictures of internal organs of the body.

The CT scanner was a classic case of a transformational innovation; it was hailed as the most revolutionary radiological development since Röntgen's discovery of X-rays in 1895. It was also a typical example of serendipity.[4] Hounsfield was engaged in research which he thought would be useful in his company's existing businesses. The outcome turned out to be something entirely different.

Serendipity plays an important role in scientific research. As a well-known study pointed out some years ago, many inventions have had an element of the accidental about them, and the more revolutionary they were the less foreseeable they were.[5]

Moreover, when major advances take place, it is often hard to predict the uses to which they will be put. Thomas Watson, president of IBM, is said to have predicted in 1942 that there would be a world market for perhaps five computers. Policy makers are just as likely as scientists or businessmen to get things wrong. In 1912 the British Secretary of State for War expressed the view that the aeroplane would be of no possible use for war purposes.

If the outcome of scientific research is unpredictable, what can governments do to steer it in directions which will be of most value to society?

3. Ulf Berggren, CT scanning and ultrasonography: a comparison of two lines of development and dissemination, Research Policy 14 (1985) 213-223.
4. Manuel Trajtenberg, Economic analysis of product innovation: the case of CT Scanners, Harvard University Press, 1990.
5. John Jewkes, David Sawers and Richard Stillerman, The sources of invention, Macmillan 1958

The funding of scientific research

Scientific research can be divided into three categories: basic, applied and translational. Basic research, sometimes described as curiosity-driven or discovery research, is aimed at extending the frontiers of knowledge; it is mainly performed in universities and research institutes. Applied research is targeted at a specific problem or set of problems, which, if solved, could be the basis for practical application. Translational research is the bridge between the two; its purpose is "to expand the knowledge base in a certain area to a point where more directed development work becomes possible".[6] Applied research leads on to development, which generally takes place in industry.

The traditional view, accepted by most economists, is that basic research has to be supported by the taxpayer, since there is no incentive for profit-making private firms to invest in it.[7] If the outcome of the research is seen to have commercial potential, it is up to the private sector to exploit it. Whether the end result is an incremental improvement or a transformative innovation (or a commercial failure) is not something that government can directly influence.

In practice the boundary between basic and applied research, and between what is performed in the public and private sector, is blurred. Use-inspired research is a term now widely used for research which aims both to make scientific breakthroughs and to solve practical problems.[8]

Nor is there a clear linear progression from basic research through applied research to development. Many of the most successful inventors, such as the Wright Brothers or Thomas Edison, owed little to science. In some cases progress goes in the reverse direction; the development of a new product, by engineers rather than scientists, can open up new avenues for scientific research. Gordon Moore, co-founder of Intel and a leading figure in the semiconductor industry, has remarked: "The linear model is not the way this industry developed. It's not science becomes technology becomes products. It's the technology that gets the science to come along behind it".[9] Similarly, the use of lithium-ion batteries in consumer electronics, starting in the 1990s, gave a boost to academic research in electrochemistry.

Many government funding agencies support both basic and applied research, but the balance between them is a controversial issue. In the US, for example, the National Institutes of Health (NIH), the Federal agency responsible for biomedical research, has sometimes been criticised for putting too much emphasis on pure research and not enough on finding cures for disease. When President Nixon launched the War on Cancer in 1971, there was concern among some scientists that the programme would divert resources from what they saw as the most pressing task, which was to learn more about the causes of cancer, and that called for basic research across a broad front. Cancer research, they argued, benefited from the interplay with research into other diseases; some of the greatest advances in the understanding of cancer had resulted inadvertently from non-cancer research.[10]

6. Paul Nurse, Ensuring a successful UK research endeavour: a review of the UK research councils, Department for Business, Innovation and Skills, November 2015.
7. Richard R. Nelson, The simple economics of basic research, Journal of Political Economy, 67/3, June 1959.
8. Donald E. Stokes, Pasteur's quadrant: basic science and technological innovation, Brookings 1997.
9. Mcchael Riordan and Lillian Hoddeson, Crystal fire: the invention of the transistor and the birth of the information age, Norton 1997, p282.
10. Bhaven N. Sampat, Mission-oriented research at the NIH, Research Policy 41 (2012) 1720-1741

The NIH sees its primary role as support for basic research, and that accounts for the bulk of its spending. The same is true of its British counterpart, the Medical Research Council (MRC), although this does not imply a lack of interest in the outcome of research. The MRC works closely with the research arm of the National Health Service, the National Institute for Health Research (NIHR), which concentrates mainly on clinical research.[11] The MRC has also been active in promoting commercial spin-offs from the research that it funds.

In addition to supporting scientific research in universities, the MRC has its own laboratories, of which the most famous is the Laboratory of Molecular Biology (LMB) in Cambridge. The LMB, which has consistently prioritised basic research, has an impressive record of discovery; two notable examples are the discovery of monoclonal antibodies, now widely used in drug development, and its role in the Human Genome Project.

"Because science attempts to discover what is unknowable", a recent director of the NIH has said, "it is inherently unpredictable…History has repeatedly shown the benefit of allowing a significant proportion of our research activity to be governed by the imagination and productivity of individual scientists". [12]

The challenge for politicians, who are answerable to taxpayers for the way public money is used, is to demonstrate that their support for academic research serves not only to extend the frontiers of knowledge, but also to produce benefits for society.

This means, among other things, encouraging the private sector to make full use of the discoveries that come out of academic research. What can governments do to ensure that the private sector plays this role effectively?

The private sector

The business sector is by far the biggest spender on research and development in the UK, and most of it is financed from companies' own resources (Table 1). For countries like the UK which are trying to raise R & D expenditure as a proportion of GDP, an increase in business spending on research is essential.[13]

Table 1 Gross UK spending on research and development in 2018

By performing sector

Sector	Amount (£bn)	% of total
Business	25.0	68
Higher education	8.7	24
Government	2.5	7
Non-profit organisations	0.8	2
Total	37.1	100

11. A merger between the MRC and the NIHR has been considered, but rejected on the grounds that it would be too disruptive, Sir Davd Cooksey, A review of UK health research funding, HMSO December 2006.
12. Quoted in Sampat, Mission-oriented research.
13. In 2018 UK spending on R & D as a proportion of GDP was 1.7%, well below the OECD average. The current government's aim is to raise this figure to 2.4% by 2027.

By source of funding

Sector	Amount (£bn)	% of total
Business	20.3	55
Government/UKRI	7.1	19
Overseas	5.1	14
Higher education	2.7	7
Non-profit organisations	1.9	5
Total	37.1	100

Source: Office of National Statistics

Governments can influence innovative activity in the private sector in a variety of ways, most importantly by promoting competition, reducing barriers to new entrants and guarding against any tendency towards monopoly in newly emerging industries. Other instruments include tax credits for R & D, grants or loans to early-stage science-based companies, and an effective intellectual property regime.[14]

Companies generally steer clear of basic research, preferring to engage in near-market research that will benefit their business in the short term. Even the large pharmaceutical companies rely for much of their early-stage research on universities or on firms spun out of universities to exploit academic discoveries. Companies in other sectors have partially replaced their research divisions through investment in venture capital or by buying start-up firms.

This was less true in the earlier post-war decades. In the US and to some extent also in the UK there were several large companies during that period, such as General Electric, DuPont and Imperial Chemical Industries, which had the financial resources to invest on a large scale in scientific research, including basic research, in the quest for new products.

The most celebrated of these companies was Bell Laboratories in the US. As part of American Telephone and Telegraph (A T & T), which until its break-up in the 1980s was a regulated monopoly, it built up a large and extraordinarily productive research organisation, engaged in basic as well as applied research; thanks to the parent company's financial strength, it was willing to wait a decade or more for research to pay off. While the research was linked to the telecommunications business, it was responsible for several important inventions which had a much wider impact, the transistor being the most famous example; several scientists from Bell Laboratories won Nobel prizes.[15]

Another well-known case was Xerox, the copier manufacturer. Its research arm, the Palo Alto Research Center, known as Xerox PARC, set up in 1970, played a seminal role in several computer-related innovations, including the development of the first personal computer, the graphical user interface and the laser printer. Some of these innovations were later

14. For a review of instruments that governments can use to promote innovation see John Van Reenen, Nicholas Bloom, and Heidi Williams, A toolkit of policies to promote innovation, CEP Discussion Paper 1634, London School of Economics July 2019.
15. Jon Gertner, The idea factory: Bell labs and the great age of American innovation, Penguin, 2013.

exploited by Apple and Microsoft.[16]

The subsequent decline of Xerox is often attributed to mismanagement, but, like many of the older research-based companies, it was overtaken by a profound change in the business environment. From the 1980s onwards a combination of more demanding shareholders and more intense international competition forced companies "to direct their research away from fundamental science and pioneering technology toward activities that are more relevant to ongoing product and process development, more likely to produce results that can be kept proprietary, and more certain to produce a commercial payoff in the near future".[17]

In the case of Bell Laboratories, the precipitating event was the antitrust action against A T & T, which led to the breakup of the company in 1982. Although Bell Laboratories continued to exist for some years under different ownership, it never recovered its earlier pre-eminence in scientific research.

Many of the one-time leaders in research and innovation, in the UK as well as the US, have either disappeared or been substantially downsized; this has often involved the closure of central laboratories.[18] As the historian of Xerox PARC has written, "The utopian ideal of a corporate laboratory whose scientists are free to roam through Ideaspace (where the company's researchers worked) draws only ridicule today".[19]

In the US (but to a much lesser extent in Europe and Japan), the principal private-sector drivers of innovative activity in recent years have been new entrants that were quicker to exploit emerging technological opportunities than the incumbents. Google, for example, owes its success to a novel technology for information retrieval, which the two founders developed when they were students at Stanford University in the 1990s. The initial research on which the technology was based was funded by a government agency, the National Science Foundation, although there was no expectation on the funder's part that the research would lead to the creation of a world-leading company.[20]

Google is one of several American technology-based companies which have used the profits from their original business to expand into related areas. A major focus has been artificial intelligence, a technology which used to be the preserve of universities and research institutes but is now dominated by private sector companies. "These companies are investing huge sums in AI-related corporate science, building large AI research laboratories, and hiring leading researchers in the field. For example, in 2018 Google employed more than 1700 researchers, and universities reported a massive drain of their leading scientists to industry. Furthermore, these companies not only create basic knowledge but also share it through scientific publications and by releasing open-source code to the public".[21]

While firms such as Google, Apple and Microsoft are making a major contribution to America's innovative capacity, they are unlikely to offset the general trend towards a reliance on near market rather than basic or speculative research.[22] Transformative innovations such as the transistor

16. Michel A. Hiltzik, Dealers of lightning: Xerox PARC and the dawn of the computer age, Harper 2000. Xerox PARC was closely linked to ARPA through Robert Taylor, who was director of ARPA's Information Processing Techniques Office before moving to Xerox in 1970.
17. Richard R. Nelson, Richard S. Rosenbloom and William J. Spencer, Shaping a new era, in Richard S. Rosenbloom and William J. Spencer (eds), Engines of Innovation, Harvard 1996.
18. Ashish Arora, Sharon Belenzon, Andrea Patacconi and Jungkyu Suh, The changing structure of American innovation: some cautionary remarks for economic growth, NBER Working Paper 25893, May 2019.
19. Hiltzik, Dealers of lightning, p397.
20. Shane Greenstein, How the internet became commercial, Princeton 2015, pp365-391.
21. P. Hartmann and J. Henkel, The use of corporate science in AI: data as a strategic resource. Academy of Management Discovery, Vol 6/3, October 2020
22. These companies also face the possibility that, like A T & T, they will be broken up on antitrust grounds, or subjected to tighter scrutiny when they seek to enter new businesses.

from Bell or nylon from DuPont or polyethylene from ICI are less likely than in the past to emerge from the private sector.

A notable attempt to imitate Bell Laboratories' approach is being made in the US, not by a company, but by a non-profit foundation, the Howard Hughes Medical Institute (HHMI), which specialises in biomedical research. In 2007 HHMI set up a new research campus, known as Janelia Farm, in which outstanding scientists are given the same sort of freedom to pursue long-term programmes, and the same sort of financial support, as was enjoyed by scientists in Bell Laboratories and the UK's Laboratory of Molecular Biology. The internal organisation of Janelia Farm is based on a close study of those two organisations; an important difference is that HHMI, as an endowed charity, is not accountable either to shareholders or to the government for the way it spends its money.[23]

The retreat of the corporate sector from long-term speculative research has increased the importance, in national science and innovation systems, of university-based scientific research. It is in universities and independent research institutes – and in some countries, such as the US, national laboratories - that researchers are tackling unsolved scientific problems and creating new knowledge, some of which may, after further work, lead to useful innovations. This makes it all the more important that academic research is funded and organised in a way that makes such an outcome more likely.

Transformational research

Sydney Brenner, a Nobel prize-winning British scientist, once remarked that the "bureaucrats of science" did not wish to take any risks; they wanted to know from the start that the project would work. "This means that nobody will apply to do real research because they have to know the answer in advance." Fred Sanger, famous for his discovery of DNA sequencing methods, "would not survive in today's world of science", Brenner argued, because of his very limited publication record. "He would be labelled as unproductive, and his modest personal support would be denied. We no longer have a culture that allows individuals to embark on long-term – and what would be considered today extremely risky – projects".[24]

When this issue was examined some years earlier by the National Science Foundation in the US, the conclusion was, first, that only a small percentage of all research activity truly results in innovative insights, and second, that where genuine breakthroughs were made they were either completely serendipitous or were not part of the research being funded. According to this study, the best way to ensure innovative research was having a large and thriving scientific community, rather than attempting to identify and target proposals that might lead to breakthrough discoveries.[25] Transformative research is more easily identified after the research has been completed than before.

Despite these warnings concern over what is seen to be an over-cautious, over-conservative approach to research funding has persisted. It

23. Gerald M. Rubin, Janelia Farm, an experiment in scientific culture, Cell 125, April 21, 2006
24. Sydney Brenner, Tribute to Frederick Sanger (1918-2013), Science, Vol 343, Issue 6168, February 17, 2014.
25. Robert Frodeman and J. Britt Holbrook, The promise and perils of transformative research, Report on an NSF workshop, March 2012.

is one of the reasons why so much attention has been focused, in the US and elsewhere, on America's Defence Advanced Research Projects Agency (DARPA).[26] In the eyes of its many admirers this agency has shown how visionary scientists, if given the right backing and the right incentives, can generate transformative innovations that change the world.

DARPA was set up in 1958 in response to the launch of Sputnik, the Soviet Union's space satellite.[27] Its mission was to ensure that the US was never again overtaken by its enemies in advanced military technology.[28] Although it was part of the Department of Defence and its projects were linked to national security, it has been partly responsible, especially in its early years, for innovations which have proved hugely productive in non-military markets.[29] The best-known example is the internet, where the crucial initial breakthrough, the development of interactive computing, was made by DARPA-backed researchers.[30] The agency has also played a role in developing the Global Positioning System, unmanned aircraft and automated voice recognition techniques. Another notable contribution was to support research into mRNA technology, the basis for one of the most successful vaccines used to counter Covid-19. A guiding principle in these and other cases is DARPA's focus on transformational change, rather than incremental advances.

DARPA has benefited from the commitment of successive US governments, with bipartisan support, to investment in military-related technology on a scale which no other country could match. But the attraction of DARPA for other countries lies, not in its scale, but in its distinctive approach to organisation, management and accountability. Two key features are the absence of bureaucratic control and the freedom given to programme managers, once their project has been approved, to pursue the goal in whatever way they think fit, choosing for themselves which universities and firms to work with, and changing direction when necessary.

In an influential report published in 2007 by the National Academies of Sciences in the US, the authors called for funding agencies to emulate the DARPA model and to give a much higher priority to high-risk, high-payoff research.[31] One of the recommendations in the report was that the government should set up a clone of DARPA within the Department of Energy. The Advanced Research Projects Agency – Energy (ARPA-E) would provide an opportunity for "out of the box" transformational research in the energy field. Like DARPA, the new agency would identify research which was not mature enough to attract support from other funding agencies or from venture capital but had the potential to deliver radical change.

The proposal was controversial, with some critics arguing that, whereas DARPA had a clear customer in the Department of Defence, there would be no such customer for projects supported by ARPA-E; there was also a large number of vested interests in the energy field which would make it harder for novel technologies to be accepted. Despite these doubts the new agency was established in 2009, and, although it has not yet

26. See for example Robert Cook-Deegan, Does NIH need a DARPA? Issues in science and technology, 13/2, 1997.
27. The agency began life as ARPA; the D was added in 1972. It changed back to ARPA in 1993 before reverting to DARPA in 1996. For convenience the agency will be referred to in this paper as DARPA.
28. As stated on the DARPA website, the creation of the agency after Sputnik reflected "a commitment by the Unted States that from that time forward it would be the initiator and not the victim of strategic technological surprises".
29. "Directors and program managers explored promising technologies in their chosen areas and directed them to applications that appeared most auspicious, be they military or civilian. The agency never lost sight of its primary obligation to the armed services, but it did not let that distract it from other applications as well". Alex Roland, Strategic computing, MIT Press 2002, p45.
30. Other organisations, public and private, also played important parts in the development of the internet. Shane Greenstein, Inconvenient truths: interpreting the origins of the internet. Journal of Law and Innovation 3 (2020) 36-68.
31. Rising above the gathering storm: energising and employing America for a brighter economic future, National Academies of Sciences, Engineering and Medicine, 2007.

produced any spectacular breakthroughs, it has identified and supported some promising energy-related ventures which after some years under ARPA-E tutelage have come closer to commercialisation.[32]

ARPA-E is one of several DARPA clones that have been set up in the US, and two more have been proposed by President Biden (see below). Other countries are following in the same direction.

32. One example is Quantumscape, a developer of solid-state batteries which was spun out of Stanford University and backed by ARPA-E in 2010. It has recently gone public on the New York Stock Exchange.

2. Changes in government policy

Two trends in science and innovation policy outside the US in recent years have been imitation of the DARPA model, either through the creation of new agencies or by embedding DARPA-like methods in existing funding arrangements, and the adoption of mission-oriented innovation policies. This section discusses recent developments in the UK, Germany and Japan. It also reviews President Biden's plans for reforming the US science and innovation system.

In the earlier post-war decades mission-oriented innovation policies were associated with government-directed projects in the defence, aerospace and nuclear fields. The Apollo moon landing project is the most famous example; Concorde, the Anglo-French supersonic airliner project, is one of the best-known failures. Today's mission-oriented policies borrow some features from those earlier projects (including in some countries the use of the term "moonshot"), but they generally refer to government-directed programmes that address broader economic or societal challenges, such as global warming or the ageing population. Meeting these challenges may require, not only support for basic and applied research, but also other measures, including regulatory changes, tax incentives and the use of public procurement.

United Kingdom

The Conservative Party's manifesto for the 2019 general election included a promise to establish a DARPA-like funding agency to support high-risk, high-return research. After the Conservative victory the new Prime Minister, Boris Johnson, confirmed his support for the new agency, which would be part of an ambitious programme to increase government spending on scientific research. The formal announcement of the agency, to be known as the Advanced Research and Invention Agency (ARIA), was made in March 2021.

While many details about how ARIA will operate remain to be decided, it represents a potentially significant addition to the UK's research funding landscape.

For most of the post-war period government funding of scientific research in universities has been managed through the dual support system. One stream of funding, which supports research projects in particular disciplines, comes from the research councils, such as the Medical Research Council and the Engineering and Physical Sciences Research Council. The other consists of block grants from what used to be called the Higher Education Funding Council; that council has recently been replaced by separate agencies for each of the four nations of the UK.

The system has worked well in terms of enabling the leading British universities to establish a world-leading reputation for scientific excellence. But there has been a long-standing anxiety, shared by successive governments, about what is seen as the UK's inability to commercialise the results of scientific research.

The last few years have seen a considerable effort to correct this weakness, notably by the Conservative-Liberal coalition government which held office between 2010 and 2015. This included the creation of a network of Catapult Centres (loosely based on the Fraunhofer centres in Germany) to promote stronger links between academic research and industry.

Another change during that period was an expanded role for Innovate UK (formerly the Technology Strategy Board), an agency that had been created by the previous Labour government to help early-stage firms bring their research closer to the market. For example, Innovate UK joined forces with the Medical Research Council to create the Biomedical Catalyst, a fund designed to support young biotechnology firms. David Willetts, who had been Minister for Universities and Science in the coalition government, has argued that the government should be much more active in supporting applied research in non-university research establishments, building on what had been started with the Catapult centres.[33]

Strengthening the links between academic research and industry was part of the rationale for the creation in 2017 of UK Research and Innovation (UKRI), bringing together in a single organisation all the research councils, together with Innovate UK and Research England.[34] The inclusion of Innovate UK in this new body was designed to deliver, according to the government, "improved collaboration between the research base and the commercialisation of discoveries in the business community".[35]

UKRI became the principal source of public funding for scientific research. Its remit was extended when Theresa May, who had taken over from David Cameron as Prime Minister after the Brexit referendum in 2016, launched her industrial strategy.

In line with the trend towards mission-oriented innovation policies which was gaining ground in other countries, Mrs May's strategy was built around four "grand challenges": artificial intelligence and data; the ageing society; clean growth; and the future of mobility. As part of the strategy the government set in train a number of research and development programmes, also known as challenges, targeted at particular technological goals; most of them involved close cooperation between academic scientists and industry. One example was the Faraday Challenge, aimed at promoting the development of batteries for electric cars.

By early 2021 there were 24 approved challenges, supporting 1,613 projects, each of them linked to one of the four grand challenges. The funding for these projects was channelled through the newly established Industrial Strategy Challenge Fund, administered by UK Research and

33. David Willetts, The road to 2.4 per cent: transforming Britain's R & D performance, Policy Institute, Kings College London, December 2019.
34. The creation of UKRI followed a report by Sir Paul Nurse on the future of the research councils. Paul Nurse, Ensuring a successful research endeavour: review of the UK Research Councils, Department for Business, Innovation and Skills, November 2015.
35. Case for the creation of UK Research and Innovation, Department for Business, innovation and Skills, June 2016.

Innovation.

This new fund had some DARPA-like features. Substantial responsibility was vested in challenge directors, who coordinated the various entities – university science departments, government laboratories, and firms – that were participating in their programmes. However, the challenge directors in UKRI had much less freedom (and were much less well paid) than programme managers in DARPA.[36] They were also part of a large bureaucratic organisation (UKRI has some 8,000 employees) which was itself closely monitored by its sponsoring ministry, the Department for Business, Energy and Industrial Strategy (BEIS), and by the Treasury.

Mrs May's industrial strategy was well under way when Boris Johnson became Prime Minister after the 2019 election, but Johnson and his colleagues were not happy with it. After a long period of uncertainty the Johnson government announced in April, 2021, that the industrial strategy would be closed down and replaced by what was called the Plan for Growth.[37] How this change would affect the grand challenge concept on which Mrs May's industrial strategy was based, and the role of UKRI in administering it, was not clear at the time this paper was written.

What was clear was that the new research funding agency, ARIA, would go ahead, that it would be separate from UKRI, and that its management style and accountability would be radically different from that of other British funding agencies.

The principal architect of the new agency was Dominic Cummings, who had worked closely with Boris Johnson during the Brexit campaign, and became chief adviser to the Prime Minister after the election. Cummings had been arguing for several years, long before he joined the government, that science policy in the UK was dysfunctional. His view, set out in a series of papers and blogs, was that the funding of research had become enmeshed in bureaucracy, that the reliance on peer review was a recipe for conservatism in the way research proposals were assessed, and that scientists whose ideas ran counter to the prevailing consensus were unlikely to win support.

His model for how research should be organised was what he called old ARPA – that is, the ARPA of the 1960s and early 1970s, before it became, according to Cummings, "bureaucratised". The key to ARPA's success, as Cummings saw it, was its ability to recruit visionary scientists and give them the freedom to pursue their ideas with a minimum of bureaucratic interference. An outstanding example was J.C.R.Licklider, who as head of ARPA's Information Technologies Processing Office pioneered the concept of interactive computing, the starting-point for what ultimately became the internet.[38]

How this approach could be replicated in the UK has been the subject of much debate.[39] Some have argued that, just as DARPA was focused on national security and had a well-defined customer in the Department of Defence, the new British agency should concentrate on one or at most two areas such as energy or health.[40] However, the government decided that the head of ARIA should be free to establish his or her own priorities,

36. Evidence by Sir Mark Walport, former CEO of UKRI, to House of Commons Science and Technology Committee, October 7, 2020.
37. Build back better: our plan for growth, published by the government in March, 2021.
38. Cummings also referred in his papers to two other research-based organisations, Bell Laboratories in the US and the Laboratory of Molecular Biology in the UK, where scientists enjoyed a similar degree of freedom, but his main focus was on ARPA.
39. Iain Mansfield, Geoffrey Owen, William Schneider Jr, Visions of ARPA: embracing risk, transforming technology, Policy Exchange, January 2020.
40. This was one of the recommendations in a report on the new agency published by the House of Commons Science and Technology Committee in February 2021.

without direction from Ministers, and would not be restricted to particular sectors or technologies.

ARIA would be run on the programme manager model which had proved successful in the US. As the government explained, the programme manager "is a highly unique role requiring visionary technical expertise, leadership, and project management skills". He or she would be given "significant autonomy" to make investments. Whether the process of selecting and managing projects would involve peer review "would be a decision of the incoming ARIA leadership."[41]

Among the issues left unresolved by the government's March announcement was the relationship between ARIA and UKRI. The government had previously announced that ARIA would be allocated £800m of funding over a four-year period; this compares with UKRI's budget of £7.9bn for 2021-22[42]. However, the government clearly hopes that ARIA will be more than a marginal addition to the research funding system. When Dominic Cummings gave evidence to a House of Commons Committee in April 2021 (after he had left the government), he said that if ARIA was created in the right way it would have a very positive effect on British science in general.[43] The pressing need, in his view, was to de-bureaucratise the system and make it more open to original ideas.

On this and other aspects of science policy a new and potentially important player in UK science policy will be the Office of Science and Technology Strategy, announced in June 2021. Based in the Cabinet Office and led by Sir Patrick Vallance, who as chief scientific adviser has been a leading figure in the government's response to the Covid-19 crisis, it "will drive forward the strategy of Whitehall's science and technology priorities from the centre".[44] The future of UKRI, and its relationship with BEIS and the Treasury, is likely to be high on Sir Patrick's agenda over the next few months.

Germany

In the early post-war decades Germany adopted what Henry Ergas, an OECD economist, defined as a diffusion-oriented innovation policy, designed to provide "a broadly based capacity for adjusting to technological change throughout the industrial structure"[45]. Ergas contrasted Germany with countries such as France, which followed mission-oriented policies, using government funds to promote national champions in industries such as aerospace, computers and nuclear power.

During that period Germany made only a few forays into selective industrial policy, supporting technologies which were thought to be strategically important but too large or too complex to be taken on by the private sector. One such foray was the Airbus, which can be regarded as a success (albeit at considerable cost to the taxpayer). Most of the others, such as the fast breeder reactor and the Transrapid magnetic levitation train, were failures. Reviewing the record in the early 2000s, two economists concluded that the mission-oriented elements of German technology policy had done more harm than good.[46]

41. Advanced Research and Invention Agency (ARIA): policy statement, Department for Business, Energy and Industrial Strategy, March 19, 2021.
42. UKRI's budget allocation for 2020-2021 was 5% lower than in the previous year, mainly because of the government's decision to cut back on Official Development Assistance, some of which was channelled through UKRI.
43. Evidence to House of Commons Science and Technology Committee, available on the committee's website.
44. Press release from the Prime Minister's Office, June 21, 2021. In addition to his new role as National Technology Adviser, Sir Patrick Vallance will continue as chief scientific adviser and head of a separate body, the Government Office for Science.
45. Henry Ergas, The importance of technology policy, in Partha Dasgupta and Paul Stoneman (eds), Economic policy and technological performance, Cambridge 1987.
46. Horst Siebert and Michael Stolpe, Technology and economic performance in the German economy. Kiel working paper 1035, April 2001.

Germany's economic success was built on a group of industries – principally cars, mechanical and electrical engineering, and chemicals - in which technical change was incremental rather than radical. Companies operating in these sectors benefited from a set of institutions, including supportive banks with strong local connections, a well-organised apprenticeship system and an array of technical universities, which allowed them to invest in continuously upgrading the quality of their products and the skills of their employees. They also drew on publicly funded scientific research carried out in universities and in public research organisations such as the Fraunhofer Society[47].

Yet diffusion-oriented policies had some disadvantages, as Ergas pointed out. "The system as it has evolved is geared to the existing industries, which basically set the technology agenda; that is, they determine the direction of research, dominate the process of standardisation and have a large role in training and education policies. Entirely new industries and technologies may find it difficult to capture the attention they deserve."

The first challenge to the German model came in the 1970s as German firms lost ground to Japanese competitors, especially in electronics-based industries such as TV sets. But a bigger threat came later, with the emergence of new industries such as biotechnology, semiconductors and personal computers. Many of the American front-runners, such as Intel, Microsoft and Apple in information technology, and Genentech and Amgen in biotechnology, were new entrants. They were supported by a financial system which included a large and sophisticated venture capital industry as well as a stock market that was highly receptive to early-stage science-based firms. Such support was lacking in Germany, and innovative, high-growth start-ups were rare.

By the 1990s there was a growing recognition in Germany that the financial system needed to become more entrepreneur-friendly, but the first attempts to change the system were unsuccessful. There was a flurry of start-ups at the end of the of that decade, partly linked to the dot-com boom, and several early-stage biotechnology firms listed their shares on the Neuer Markt, a new stock market set up by the Deutsche Börse to attract young, high-growth firms. The hope was that the new market might emulate NASDAQ in the US, but it collapsed in 2002 amid a welter of scandals arising from over-optimistic and in some cases fraudulent profit projections.

Over the next few years the government introduced a series of measures aimed at improving access to finance for early-stage firms. These included the High-tech Gründerfonds (High-tech start-up fund), the EXIST programme, the GO-Bio Gründungsoffensive Biotechnologie (Start-up offensive in biotechnology) and more recently the $10bn Future Fund.

The effect has been to stimulate the growth of the German venture capital industry, although it remains much smaller than its British counterpart. One of the successes in the worldwide search for vaccines to counter Covid-19 was a small German company, BioNtech, which was one of the first to develop, in collaboration with Pfizer of the US, a vaccine

47. The Fraunhofer Society is one of the four main Public Research Organisations, the others being the Max Planck Society, the Helmholtz Association and the Leibniz Association. They are funded jointly by the Federal Government and the Laender, but they also derive part of their income from contracts with industry.

based on mRNA technology. The Research Minister, Anja Karliczec, was able to point to the support which BioNtech had received from the GO-Bio programme and later from the Leading-Edge Cluster Competition.

Improving conditions for starting new firms with high growth potential was one part of what was necessary to correct the weaknesses in Germany's industrial structure. The other part was to reform the research funding system.

The launch in 2006 of the High-Tech Strategy marked a partial shift towards the new-style mission-oriented approach to innovation policy. Instead of using public funds to support basic and applied research across the board, the new policy sought to adopt a more selective approach. The Commission of Experts for Research and Innovation (EFI) described the High-Tech Strategy as marking "a completely new orientation for research and innovation policies".[48]

The new policy did not involve any major institutional change in the research funding system. The principal actors at the Federal level remained the BMBF (Ministry for Research and Education) and the BMWi (Economic Affairs), together with the four Public Research Organisations.[49] The purpose of the strategy was to promote greater coordination among these agencies, and with the universities, in supporting scientific research in five "priority areas": climate/energy; health/nutrition; mobility; security; and communications.

In the years following the launch in 2006 the High-Tech Strategy has been refined, with a tighter focus on specific targets. The fourth and current phase, given the title of HTS2025, is built around twelve missions (Table 2). This approach was strongly supported by the government's advisory body, the High-Tech Forum; this body is co-chaired by the state secretary at the BMBF and the head of Fraunhofer, and is made up of senior figures from government, academia and industry.

48. EFI Report 2017. The EFI was established in 2007 to provide advice to the Federal government on research and innovation.
49. The division of responsibility for research between two separate Federal ministries is widely seen as a weakness in the German system.

Table 2: The twelve missions of the German high-tech strategy

1.	Ensuring good living and working conditions throughout the country
2.	Building up battery cell production in Germany
3.	Preserving biological diversity
4.	Putting artificial intelligence into practical applications
5.	Creating sustainable circular economies
6.	Combating cancer
7.	Digitally networking research and healthcare for intelligent medicine
8.	Achieving substantial greenhouse gas neutrality in industry
9.	Substantially reducing plastic discharge into the environment
10.	Developing safe, networked and clean mobility
11.	Shaping technology for the people
12.	New sources for new knowledge

Source: BMBF High-tech strategy 2025: progress report.

In its most recent report the Forum stressed that missions should not be too ambitious or too broad, but should be based on achievable and measurable goals. The Forum also said that Germany was "too hesitant with regard to scaling up and commercialising the results of cutting-edge research. Stakeholders in Germany too rarely exploit scientific breakthroughs and develop them on a global scale".

To correct this weakness the government has created what it calls an agency for disruptive innovation; it is known as SPRIN-D, an acronym from its official German name[50]. The case for the new agency was the need to create room for high-risk and potentially high-return projects which were too speculative to win support from the established funding agencies. SPRIN-D's projects, like those of ARIA in the UK, would be transformative and aimed at a goal that had significant economic or social benefits. In its 2019 report the Commission of Experts emphasised that crucial factors in SPRIN-D's success would be its independence from political and bureaucratic interference and its ability to attract entrepreneurially minded figures to serve in leading roles.

The new agency is based in Leipzig and is co-sponsored by the BMBF and the BMWi. In 2019 the government appointed as founding director Rafael Laguna, a serial entrepreneur whose biggest success had been in creating and running a software company, Open Exchange. However, he appears to have rather less autonomy than is proposed for the chief executive of ARIA in the UK.

Project proposals come in via two mechanisms: bottom-up via a rolling open call for submissions, and top-down via innovation challenges. The selection of topics for the challenges is not subject to interference from Ministers, but every funding decision over 500,000 Euros has to be approved by the Board, which includes representatives from three

50. Agentur zur Forderung von Sprunginnovationen

government departments, BMBF, BMWi and BMF (finance).

SPRIN-D's first projects were approved in 2020. Among them was a plan, put forward by an academic from the technical university in Dresden, for an AI-based computer, known as SpiNNaker 2, which can generate a simulation model of the human brain. Another is a proposal for a high-altitude wind turbine for low-wind onshore use. The agency's most recent projects include a new drug mechanism for treating Alzheimer's and other neurodegenerative diseases; a new way of filtering microplastic from water by means of microbubbles; and an attempt to downsize analogue computer capabilities to the level of a chip.[51]

The creation of SPRIN-D marks a novel departure in German innovation policy. Given its modest size it is open to question whether it can do much to correct the continuing weakness in Germany's innovation performance – its lag behind the US and increasingly also China in emerging technologies. According to one recent report, "there is a sense of malaise among German business leaders that a new industrial era based on software and data is passing them by".[52] At the time that report was written, the market value of Apple was more than that of the entire Dax index of Germany's thirty leading companies. While the number of new science-based firms with growth potential is increasing, there are not enough of them as yet to reduce the country's dependence on older industries.

Japan's moonshot programme

In Japan, the creation of a new instrument to promote disruptive innovation formed part of the "revitalisation strategy" launched by Shinzo Abe when he became Prime Minister in 2013. The strategy was designed to breathe new life into an economy that had suffered a long period of stagnation and to re-establish Japan as a world leader in innovation.

A novel element in an extensive reorganisation of Japan's science and innovation system was the ImPACT programme[53]. ImPACT was a successor to an earlier programme, known as FIRST, which had been focused on high-risk, high-reward R & D projects[54]. It was built around five themes, and within each theme a key role was played by DARPA-type programme managers, who were given the freedom to design and manage the projects under their control.

The five themes were: release from constraints on resources and innovation in manufacturing capabilities; realisation of an ecologically sound society and innovative energy conservation that changes lifestyles; realisation of a society of highly advanced functionality that surpasses the information networked society; provide the world's most comfortable living environment in a society with a declining birth rate and an ageing population; control the impact and minimise the damage from hazards and natural disasters that are beyond human knowing.

ImPACT, which ran from 2014 to 2018, supported sixteen projects, which were chosen because of their potential to contribute to one of the five themes. One project, led by Professor Kozo Ito from Tokyo University, aimed to develop ultra thin and flexible tough polymers. This project,

51. https://www.sprind.org/en/projects/
52. Patrick McGee and Guy Chazan, The Apple effect: Germany fears being left behind by Big Tech, Financial Times, January 29, 2020.
53. The full title was the Impulsing Paradigm Change through Disruptive Technologies programme.
54. The full title was Funding programme for world-leading Innovative R & D on Science and Technology

which drew on Japan's long-established strength in polymer technology, was part of the drive towards a more energy-efficient, safe and sustainable society. A prototype car which was built as part of this project weighed 850kg, compared with about 1300kg or 1400kg for a similar-sized car made with conventional materials.[55]

ImPACT was regarded as a partial success, but it was thought to be not aspirational enough. There was insufficient emphasis on risk taking, and a reluctance to accept that failing projects must be closed down. What followed was the Moonshot programme, launched in 2020. Designed to run for ten years rather than five, it was built around seven overarching goals. (Table 3).

Within each goal a programme director was chosen and his or her task was to select between three and thirteen projects, some of which were given a target date of 2030. For example, within Goal 4, dealing with the environment, the projects include: technologies to recover greenhouse gases and convert them into valuable materials; technologies to recover nitrogen compounds and convert them into harmless or useful materials; and technologies to develop marine biodegradable plastics with a controllable rate of decay.

A key feature of the Moonshot programme was that projects in each goal would be managed on a portfolio basis, with the expectation that some of them would fail. A clearer differentiation had to be made between projects funded by existing funding agencies, where the outcome was generally an incremental scientific advance, and Moonshot projects, where the risks were higher and success could not be guaranteed.

Table 3 Japan's seven Moonshot goals

1. Realisation of a society in which human beings can be free from limitation of body, brain, space and time by 2050[56]
2. Realisation of ultra-early disease prediction and intervention by 2050
3. Realisation of an AI robot that autonomously learns, adapts to their environment, evolves in intelligence and acts alongside human beings, by 2050
4. Realisation of sustainable resource circulation to recover the global environment by 2050
5. Creation of the industry that enables global food supply by exploiting unused biological resources by 2050
6. Realisation of a fault-tolerant universal quantum computer that will revolutionise economy, industry and security by 2050
7. Realisation of sustainable care systems to overcome major diseases by 2040 for enjoying one's life with relief and release from health concerns until 100 years old.

55. This project was described in Robin Harding, Strings, rings and automobiles: Kozo Ito's revolutionary polymers, Financial Times, August 9, 2019 . The technology has been taken on by several Japanese companies, including Toray, which are seeking to move it towards commercial application.
56. R & D under this goal will develop "core technologies related to cyborgs and avatars", known as cybernetic avatars, which will expand human physical and cognitive capacities. The aim is to overcome the challenge of a declining birth rate, ageing population and associated labour shortage, and to allow people with various backgrounds – such as the elderly and those responsible for nursing and childcare – to actively participate in society.

The Moonshot programme has been described as the most significant step in the Japanese government's effort to implement better targeted and more effective science and innovation policies.[57] It aims to promote disruptive innovations and to tackle societal challenges, using "inspiring, imaginative and credible" missions. However, the programme is unlikely in itself to lift Japan onto a higher growth path or to narrow the gap with the US in the commercialisation of new technologies.

Apart from support for basic, curiosity-driven research, which remains an essential component of the system, there are other programmes in operation, or recently announced, which address different parts of the country's science and innovation system. This year the government announced the creation of a $95bn University Fund, which will strengthen the science departments of leading universities; the aim is to halt the decline in Japan's international university rankings. Another new programme, called Forest (Fusion Oriented Research of disruptive Science and Technology), is aimed at funding young scientists who wish to pursue challenging projects that are outside the remit of established funders.

Kazuto Ataka, a neuroscientist who is chief strategist at Yahoo Japan and a critic of past government policies, has strongly argued for the new university fund which he hopes will foster a less constrained approach to scientific risk-taking. An innovative society, he says, needs a permanent pool of people who are not only different from everyone else but actively cherished for their desire to disrupt everything.[58]

Science policy in the US

One of the early announcements by President Biden, soon after he had taken office, was to promise a big increase in Federal spending on science and technology, together with a reorganisation of the research funding system. The measures were presented in the Endless Frontier Act, a deliberate echo of the famous report – Science, the endless frontier – which President Roosevelt had commissioned from Vannevar Bush at the end of the second world war.[59]

As head of the Office of Scientific Research and Development during the war, Bush had overseen a massive programme of military R & D which contributed in no small way to the Allied victory. In his report to the president in 1945 he set out an ambitious vision of how science and technology could solve peacetime problems, generating innovations which would strengthen the economy and raise living standards. A central theme was the importance of Federal support for basic, undirected research, which Bush regarded as an essential element in a successful innovation system.

Out of these proposals, after some delay, came the National Science Foundation (NSF), which was created in 1950 as the principal funder of basic research in universities. In contrast to UKRI is the UK, the NSF is only one of a number of agencies that support scientific research in the US. They include the National Institutes of Health for biomedical research,

57. Philippe Larrue, Mission-oriented innovation policy in Japan, OECD Science Technology and Industry Policy Papers, No 106, April 2021.
58. Leo Lewis, Japan's innovators seek their lost mojo, Financial Times, March 7, 2021.
59. Vannevar Bush, Science, the endless frontier, A report to the President, US Government Printing Office, 1945

as well as several entities within the Department of Energy and the Department of Defence, the latter including DARPA. (There are also several sizeable philanthropic foundations which support research, especially in the biomedical field.) One of the strengths of the American system is the existence of numerous, largely independent sources of funding, which have different missions and different criteria for evaluating research proposals.[60]

President Biden wants to give the same sort of boost to scientific research as Vannevar Bush proposed in 1945, but his motivation is different. The focus is on technology rather than basic research, reflecting widespread anxiety that the US is losing ground to China in new technologies such as artificial intelligence. A separate legislative proposal, The Meeting the China Challenge Act, was combined with the President's Endless Frontier Act to form what is called The US Innovation and Competition Act.

The reaction in the scientific community to Biden's proposals has been mixed. Although the increase in funding was welcomed, there was concern among some scientists about whether the money would be spent in the right way. Much of the anxiety centred on Biden's plan for the National Science Foundation (NSF).

Biden's proposal was that the NSF should be given a new responsibility for technology; it would set in train programmes "to facilitate and accelerate the transfer of new technologies from the lab to the marketplace, including expanding access to investment capital". Research would be funded in ten "technology focus areas"; these include artificial intelligence and machine learning, robotics, automation and advanced manufacturing, and advanced energy technology.

In commenting on this proposal, a group of distinguished scientists pointed out that it would change the character of the NSF. "By proposing very large sums for the new Technology Directorate the bill is likely to raise concerns that a realigned NSF will have objectives that are at odds with its traditional strengths in fundamental science and that the new directorate will overwhelm existing ones, siphoning funds away from their activities."[61] The scientists urged that the NSF should retain its existing name and not be renamed, as Biden proposed, the National Science and Technology Foundation.

Another part of the bill proposes the creation of two new DARPA-like agencies. One, to be called ARPA-C, would be established within the Department of Energy and focus on climate change. It would work alongside ARPA-E, the energy agency, and focus on areas such as batteries for grid-scale electricity storage, small modular nuclear reactors, and carbon capture and sequestration for power station exhausts. The other new agency, ARPA-H, would be part of the National Institutes of Health and would "drive transformational innovations in health research and speed application and implementation of health breakthroughs"; the initial focus would be on cancer and other diseases such as diabetes and Alzheimer's.

The case for the new health-related agency was strongly supported by

60. Diverse sources of government support were especially important in computing. See Funding a revolution, government support for computing research, National Academy Press, 1999.

61. David Baltimore and others, Should the endless frontier of Federal science be expanded, published by the American Association for the Advancement of Science, February 28, 2021.

Eric Lander, director of the President's Office of Science and Technology Policy, and Francis Collins, director of the National Institutes of Health.[62] They argued that, while good progress in medicine was being made through basic research in the NIH and commercial development in the biotechnology sector, some of the most innovative ideas did not always fit existing support mechanisms. This was because: the risk is too high; the cost is too large; the time frame is too long; the focus is too applied for academia; the near-term market opportunity is too small to justify commercial investment; or the scope is so broad that no company can realise the full economic benefit. ARPA-H's mission will be to fill that gap in the funding system.

These proposals, which were approved by the Senate in early June, show how far the DARPA model has penetrated the US research funding system. The first of the DARPA clones was the Homeland Security Advanced Research Projects Agency (HSARPA), established in 2002. It was followed by IARPA, the Intelligence Advanced Research Projects Activity, established within the Office of the Director of National Intelligence in 2006, and then by ARPA-E. Now two more are to be set up, reflecting a wide though not universal consensus in the scientific community, and even in Congress, that the DARPA model can speed up the development of transformational and innovative ideas.

62. Francis S. Collins, Tara A. Schwetz, Lawrence A. Tabak, Eric S. Lander, ARPA-H: accelerating medical breakthroughs, Science, June 22, 2021.

3. Conclusion

All the four countries discussed in this paper are reorganising their science and innovation systems. The motivation in each case is somewhat different, but a common objective is to generate a higher return from the investment their governments are making in scientific research. In the UK, as noted in the last section, government policy is as yet incomplete. While ARIA is going ahead, its strategic direction will remain unclear until a chief executive is appointed. The UK no longer has an industrial strategy, but the government has not spelt out in detail what will replace it. There are other aspects of the science and innovation system which will need attention if the government's ambitions for science and technology are to be fulfilled.

Missions

Most of the broadly-based mission-oriented innovation policies that have been discussed in this paper are too recent for their impact to be fully assessed. It is clear, as Philippe Larrue, the OECD economist who has studied these policies in detail, has observed, that they should not be regarded as a "silver bullet" that will solve economic and social problems. They are relevant in specific conditions and for certain missions, he wrote, and they are not meant to substitute for more traditional policies aimed at providing generic scientific knowledge and raising the general level of business R & D.[63]

Whether the Johnson government will stick with the "grand challenge" framework on which Mrs May's industrial strategy was based is not yet known, but it seems certain that missions in some form will continue. The government has said that one of the first tasks of the new Office for Science and Technology Strategy will be to review the "big bets" that the UK should back and prioritise for strategic advantage.

What are the principles that should guide the choice of missions and the way they are managed?

The first requirement is clarity of objective. To take an example from the UK, one of the grand challenges set out by Theresa May's government in 2017 was the future of mobility. One of the objectives was to "put the UK at the forefront of the design and manufacturing of zero emission vehicles, with all new cars and vans effectively zero emission by 2040".[64] It is not clear what "forefront" means in this context. Does it mean that the UK's position in the league table of world car manufacturers should be at least as high in 2040 as it is today, or is the goal more ambitious than that? How will the progress of the mission be measured in the intervening

63. Philippe Larrue, Mission-oriented innovation policy in Norway, OECD Science Technology and Industry Papers No 104, April 2021.

64. Press release from the Department for Business, Energy and Industrial Strategy, January 26, 2021.

period?

It is true that in this case the success of the mission depends, not just on research, but also on government intervention in other areas, including the provision of charging points for electric cars and financial incentives for buyers. But the need for clear and measurable indicators of progress remains essential.

Missions can be useful as a means of drawing attention to a challenge which the sponsor regards as important and feasible, and of attracting wide support, including financial support. But there is a danger of vaguely defined objectives which may or may not be achievable at some future date. More promising are missions that target an emerging technology which, given additional resources, can be brought to maturity in a clear timeframe; the Human Genome Project, launched in 1990 and completed in 2003, is an outstanding example.

Missions are unlikely to be successful when they depend on scientific advances that are yet to be made. One of the contributory factors in the speed with which the AstraZeneca/Oxford vaccine was brought to the market, as noted in a report by the Industrial Strategy Council, was that scientists were able to leverage technologies that had been developed before the pandemic.[65]

The UK's vaccine programme has been rightly praised as a highly successful operation, but it was a crisis-induced mission with a very specific objective, different in character from policies aimed at solving broader economic or societal problems. Nevertheless, the study by the Industrial Strategy Council was able to draw some general lessons which are relevant to science and innovation policy.

One of those lessons was: "Choose a small number of clear, measurable missions and make them a priority at the highest level of government". Missions should be deployed sparingly, the report said. "Many policy challenges do not lend themselves to a mission-based approach, because the potential benefits are not large enough to justify the resources required. Missions should be terminated when the goal is reached, or when it becomes clear that the goal is not reachable.

The DARPA model

When the UK government announced the creation of the Advanced Research and Invention Agency, it said that the new agency "will focus on projects with potential to produce transformative technological change or a paradigm-shift in an area of science. While it is anticipated that most programmes will fail in achieving their ambitious goals, those which succeed will have a profound and positive impact on society".

In one respect – the search for a paradigm shift in an area of science – ARIA's remit appears to differ from the DARPA model. According to an American study of how far the model is applicable to sectors outside defence, DARPA-type projects generally fall between basic and applied research.[66] The primary aim is not to make advances in science, although some scientific problems may have to be overcome, but to do much

65. Filip Balawejder, Skye Sampson and Tom Stratton, Lessons for industrial policy from the development of the Oxford/AstraZeneca Covid-19 vaccine, Industrial Strategy Council, Research Paper, March 2021.

66. Pierre Azoulay, Erica Fuchs, Anna Goldstein and Mchael Kearney, Funding breakthrough research: promises and challenges of the "ARPA model", NBER Working Paper 24674, June 2018.

more than search for improvements in existing technologies. The focus, these authors argue, should be on areas where the technology exists, is relatively unexplored, has little attraction for private firms, and has great potential for improvement. Most important of all, the end-result must be clearly defined. "The mission must be associated with quantifiable goals and subgoals with trackable progress metrics".

This last requirement is an essential part of the DARPA model. So too is the role of the programme manager. This is a function which is under-developed in the UK. Individuals with deep understanding of the relevant technology and the ability to lead a team of researchers in a variety of institutions – like DARPA, ARIA is not expected to have its own laboratories – will be hard to find. Some recruitment from the US may be necessary.

The choice of ARIA's early projects will be crucial, not least because their outcome will determine how far the agency can retain political support. In DARPA's case a few spectacular successes in its early years were skilfully used by its sponsors to burnish the agency's reputation, and to hide its failures. ARIA will have political as well as technological challenges to overcome, this will determine how much additional funding it will be able to attract. (One possibility might be to look for partnerships with City institutions, some of which are showing a greater appetite for advanced technology; ARIA will have the power to take equity stakes in start-up ventures.)

ARIA has been welcomed by some UK-based scientists because it is a new source of funding which will use different selection criteria from other funders. But there is also concern about the small amount of funding that has so far been allocated to ARIA and about the open-ended remit that the agency has been given.

One group of economists, after a close study of the DARPA clones in the US, concluded that such agencies need to have a clear mission (as is the case with the new agencies proposed by President Biden). "There is no evidence to suggest the model would work well as a fund for general science and technology".[67] This group has recommended that ARIA's focus should be on meeting the UK's net zero carbon targets. Others have suggested that the initial focus should be on health. These options should be revisited by the chief executive of ARIA, when he or she is appointed.

The importance of basic research

Neither missions nor the creation of DARPA-like agencies will in themselves transform a country's innovative performance. Much more important is the health of the science and innovation system as a whole. Within that system funding for basic or discovery research is an essential building block, and governments must make sure that it is not downgraded in favour of applied research that is aimed at short-term results. If governments want more transformative discoveries, they should not forget that most such discoveries arise from curiosity-driven research.

When Emmanuelle Charpentier, a French biochemist, was working in Vienna in 2008, her research was of little interest in the scientific

67. Laura Diaz Anadon and others, evidence to House of Commons Science and Technology Committee, September 10, 2020.

community. As a fellow scientist, Brooke Morriswood, has recently written, "Would you have paid attention to the role of small RNAs in bacteria? Would the question of how bacteria defend themselves against viruses sound like a potentially world-changing topic for research? Not only was this work of limited health benefit, it was also far from being fashionable".[68] Yet out of this work, after a decade of further research in several different institutions, came CRISPR, a gene editing tool which is widely regarded as a revolutionary advance in biomedical science. Charpentier and her American collaborator, Jennifer Doudna, shared the Nobel Prize for chemistry in 2020.

In Morriswood's view, the current incentive structure in science does not reward the kind of work that led to the CRISPR discoveries. "To get funded these days you maximise your chances if you're doing something fashionable, and that usually means doing something well-established. The pioneer work needs to have been done in advance".

Most public sector funders require applicants to show evidence of impact, in terms of practical consequences which will improve people's lives. The effect is to encourage scientists and their departments to put forward short-term, near-market projects.

The issue is relevant to the UK at the present time, not only because the government is planning a big increase in public funding for science, but also because it sees that investment in largely instrumental terms – to "end the chasm between invention and application" and "to make the most of UK breakthroughs so that British ideas produce new British industries and British jobs".[69] In pursuing these aims the government must ensure that basic research – which is the starting-point for many spin-off companies – is adequately supported.

A focus on basic science does not imply that scientists who work at that level rely solely on serendipity or have no interest in where their research might lead. As an executive in a major medical charity has remarked, "We fund outstanding research because it adds to our scientific understanding and because we know that at some point it will, in aggregate, improve human health".

Scientists in the Laboratory of Molecular Biology are mostly engaged in basic research, but they work in close proximity to Addenbrooke's Hospital in Cambridge and have regular contact with clinicians. Part of the purpose of the establishment of the Francis Crick Institute in 2015 was to bring the Medical Research Council's discovery scientists closer to the medical schools and teaching hospitals in central London.[70] Both the LMB and the Crick interact with scientists from the pharmaceutical industry, both large companies and small.

Peer review

Most public-sector research funding agencies rely partly on peer review in assessing grant applications. This is a long-established system which is generally effective in weeding out poor applications, but it has some disadvantages. It may tend to favour proposals which build on existing

68. Brooke Morriswood, The CRISPR Nobel: back to basics, Total Internal Reflection, October 25, 2020.
69. Boris Johnson, speech at Dudley, June 30, 2020.
70. The creation of the Crick Institute involved the relocation of the MRC's National Institute for Medical Research from Mill Hill in north London to a new site in Central London. In addition to the MRC, the other sponsors of the institute are Wellcome Trust, Cancer Research UK, Imperial College, Kings College London and University College London.

knowledge and to reject ideas which involve greater risks of failure.

Applicants are often asked to comment on the feasibility of their proposal. The consequence is that ambitious and highly innovative proposals are likely to score poorly unless the applicant can convince the reviewers of his or her ability. As one senior scientist has suggested, funders need to be clearer that they want to support innovation, perhaps by replacing the question "is it feasible?" with "does the potential advance justify the risks in supporting the proposal?"

Non-government funders also use peer review, but they can be more flexible in their requirements. The Wellcome Trust, for example, a big funder of discovery research, requests that applicants provide their research vision rather than experimental detail, and that reviewers should judge the boldness of the proposed research and the candidate's ability to do what they propose based on their prior outputs.

In the US a recent study has pointed to the differences between the Howard Hughes Medical Institute (HHMI), a leading medical charity, and the National Institutes of Health, in the way they handle applications.[71] Whereas NIH reviewers are notoriously risk averse and often insist on a great deal of evidence before deciding to fund a project, the HHMI encourages researchers "to take risks, to explore unproven avenues, to embrace the unknown - even if it means uncertainty or the chance of failure".

The HHMI is much smaller than the NIH and can afford to be highly selective in choosing the researchers it is willing to support. It is also an endowed charity (like Wellcome in the UK) and does not have to rely on raising funds from donors - nor is it accountable to shareholders or politicians. Funders of this sort can afford to take more risks than public sector agencies. But that does not prevent such agencies from operating a range of funding mechanisms which avoid the straitjacket of peer review. Some of the best public sector laboratories, such as the LMB, have had directors who were free to use their own judgement in assessing the quality of research proposals, without over-reliance on peer review or on citations.

Politicians and scientists: who is in charge?

How to reconcile autonomy and accountability has long been a contentious issue in science policy. In the US the creation of what was to become the National Science Foundation, as proposed by Vannevar Bush in 1945, was delayed for several years, partly because of President Truman's insistence that the head of the agency and its directors should be presidential appointments. That argument was settled in 1950, and since then the NSF has operated as an independent federal agency, subject to Congressional oversight but largely free to set its own priorities - although Congress has sought from time to time to push it in particular directions.

There has been much less stability in the UK. Control over science policy has gone through numerous changes in recent decades. For a short period in the 1990s science was represented by a single minister

71. Pierre Azoulay, Joshua S. Graff Zivin and Gustavo Manso, Incentives and creativity: evidence from the academic life sciences, Rand Journal of Economics, 42/3, Fall 2011.

in the Cabinet – the Chancellor of the Duchy of Lancaster – who was responsible for the Office of Science and Technology. In 1995 that office, and responsibility for science policy, was transferred to the Department of Trade and Industry. That remains the situation today, with science policy, including supervision of UK Research and Innovation, handled by what is now called the Department for Business, Energy and Industrial Strategy (BEIS).

UKRI has been criticised for excessive bureaucracy, but a large part of that problem stems from the control exerted by BEIS and the Treasury. This has involved, among other things, long delays on senior appointments and on securing Ministerial approval for major capital projects or new ventures.[72]

This interference does not flout the Haldane principle, which bars politicians from intervening in how research funds are allocated, but it complicates the management of UKRI and slows down decision-making.[73]

One possibility would be to detach UKRI (and ARIA) from BEIS, making both agencies responsible to a Cabinet-level Minister of Science.[74] The Johnson government has not pursued this idea, but it has made a potentially important change in the management of science policy through the creation of the Office for Science and Technology Strategy, based in the Cabinet Office.

The new office, which will be led by Sir Patrick Vallance, the government's chief scientific adviser, and will work closely with a new National Science and Technology Council, will take an independent view of science policy across all Whitehall, including BEIS. Although UKRI handles more than half of the government's R & D spending, other large spenders, mainly on applied research and development, are the Ministry of Defence and the NHS, through the National Institute of Health Research.

The creation of the new office (which has some similarity to the Office of Science and Technology Policy in the US[75]) does not directly affect the position of UK Research and Innovation, which remains within the Department for Business Energy and Industrial Strategy. An urgent task for Sir Patrick Vallance over the next few months, working with Kwasi Kwarteng, the Business Secretary, and the new leadership of UKRI[76], will be to review the relationship between UKRI, BEIS and the Treasury, so that the UK's principal research funding agency can make a more effective contribution to the Prime Minister's plan to make the UK a science superpower.

72. According to a report on the Industrial Strategy Challenge Fund by the House of Commons Public Accounts Committee, published on April 22, 2021, the long time taken by BEIS and UKRI to provide funding for successful bidders risks putting off businesses from applying for the programme. "It took UKRI, the Department and HM Treasury 72 weeks to select and approve the challenges that were given funding in 2019-2020. It took UKRI on average a further 31 weeks to assess applications for project funding and approve individual projects".
73. In March 2021 the government launched a review, led by Professor Adam Tickell, to make recommendations to remove unnecessary red tape in the UK research system. It will be completed in early 2022, with interim findings to be published in autumn 2021.
74. A proposal along these lines was contained in Paul Nurse's 2015 review of the research councils but was not taken up by the government.
75. The OSTP acts as the President's agent, "asserting the President's vision of the nation's interests against the more parochial interests of the scientific and technological community and the federal bureaucracy", David M. Hart, An agent, not a mole: assessing the White House Office of Science and Technology Policy, Science and Public Policy, 41, 2014.
76. The new part-time chair of UKRI, who is expected to be confirmed shortly, is Sir Andrew Mackenzie; he succeeds Sir John Kingman, a former civil servant. Sir Andrew is a scientist by background but has spent most of his career in business; he is currently chair of Shell. UKRI's chief executive is Dame Ottoline Leyser, a plant biologist who was appointed to the post in 2020.

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