Science and innovation policy for hard times: an overview of the UK's Research and Development landscape

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Abstract

The UK is the mid-term of a government that has placed a lot of emphasis on science and innovation for the future of the country. There has been a lot of rhetorical ambition, and some snappy slogans ("science superpower", "innovation nation"). There has also been a lot of change in the way the nation's science system is wired up, and much of that change is yet to work through.

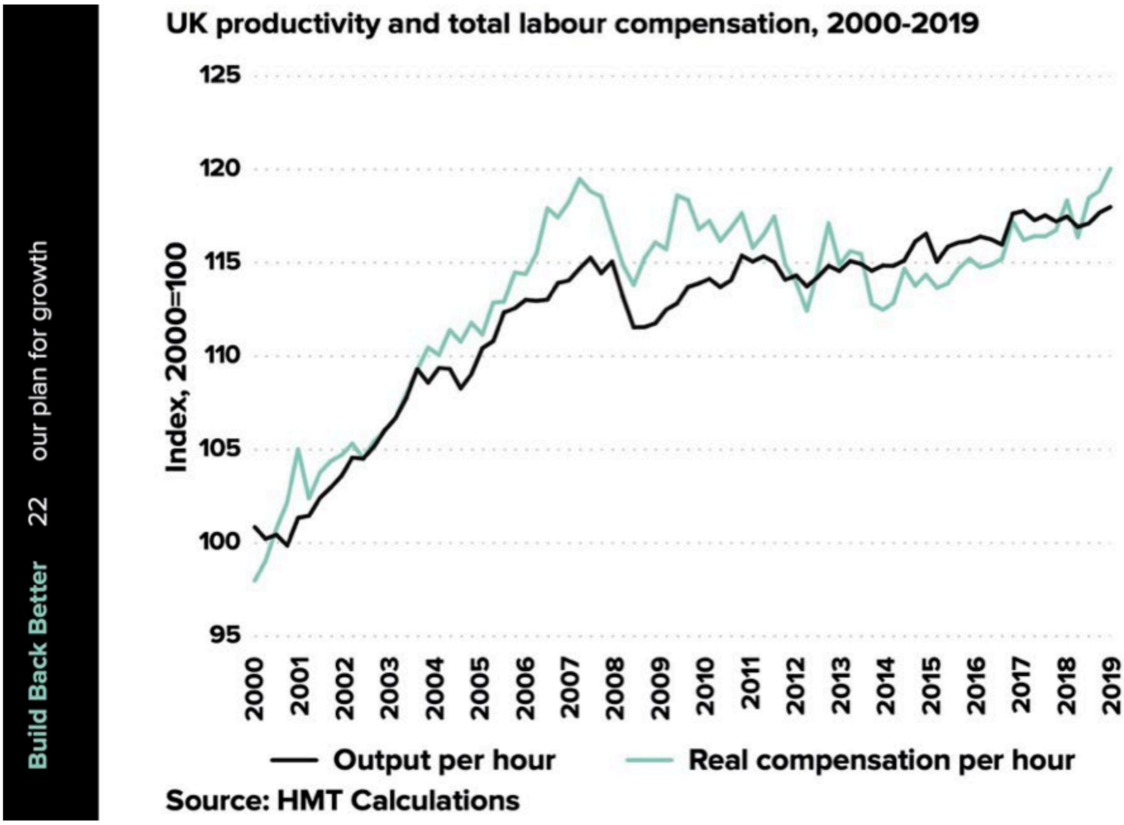
This paper is an overview of where this process of change has got to, and what is yet to evolve. It is in nine parts, covering:

1. The wider challenges the UK government faces, asking what problems need science and innovation system to contribute to solving.
2. How the UK's science and innovation system works.
3. The history and future of the UK's Research and Development (R&D) system.
4. Realistic aspirations for the UK's science and innovation system.
5. Government support for Business R&D through the tax system
6. UK Research and Innovation and the agencies that allocate R&D money on behalf of the government
7. The other UK R&D investment channel: Government and Departmental Research
8. The UK's future in the Horizon Europe research programme, and the potential of the new agency, ARIA.
9. Science and innovation policy for hard times: understanding the UK's place in the world

Part 1: The strategic context

1.1 Getting the UK economy growing again

The UK's most serious economic problem now is its lack of productivity growth. After many decades in which productivity grew at a steady rate, a little more than 2% a year, this growth was arrested after the global financial crisis in 2008; since then, productivity has been more or less stagnant. This translates directly into a stagnation in average wages, as the first plot shows – this is the painful backdrop to the current "cost of living crisis".



Productivity and average wages since 2000. From Build Back Better: our plan for growth, HMT, March 2021.[1]

This stagnation almost certainly has more than one cause. There may be some general factors affecting all developed economies. Progress in some areas of technology may be slowing; the exponential growth in computer power that came from the combination of Moore's law and Dennard scaling came to an end in the mid-2000s, for example. But, while productivity growth in all developed countries has slowed, the stagnation has been more pronounced in the UK than any other advanced economy except Italy.

Structural effects specific to the UK include the rapid fall-off of North Sea oil and gas production since the early 2000s, and the unwinding of the bubble in financial services that burst in the global financial crisis. The combination of North Sea oil and the financial services boom may have led to a touch of "Dutch disease", squeezing other sectors such as manufacturing. There have been difficulties in specific sectors that the UK has been specialised in – notably pharmaceuticals[2].

There is an effect of some policy choices over the last decade; macroeconomists focus on the role of demand in driving productivity growth, so the effects of the fiscal consolidation of the early 2010s may themselves have contributed. Other economists highlight the beneficial role of international trade in driving productivity growth, so the choice to impose additional frictions on international trade will give an additional headwind over coming years.

But the fundamental driver of productivity growth is innovation, which finds ways of reducing the inputs needed to produced existing goods and services, and develops entirely new, highly valued goods and services. Not all innovation arises from formal research and development, but it is striking that the UK's decline in productivity growth follows a period in which the overall R&D intensity of the UK economy declined substantially, and that the UK's weak performance in productivity growth compared to international comparator countries is correlated with comparatively low R&D intensity.

In terms of productivity, the UK is a highly divided country. The Greater South East – London, the South East, parts of East Anglia – has an economy with a comparable level of productivity to other high performing Northern European economies, but most of the rest of the country more closely resembles Southern Italy, Spain or Portugal. Moreover, the UK's large second tier cities – Birmingham, Manchester, Glasgow etc – instead of being drivers of the national economy, actually have levels of productivity below the national average[3].

Without a recovery of productivity growth, wages will continue to stagnate, living standards will fall, and it will be impossible for governments to provide public services of a quality that people have come to expect. It will not be possible for one corner of the nation to carry the economy of the whole country, so it should be a priority to raise the productivity of those parts that are currently lagging behind their potential – particularly the UK's large, second tier cities. This is the pre-eminent economic driver that the development of science and innovation policy needs to focus on.

1.2. Managing the energy transition to Net Zero

All western economies and lifestyles depend on the availability of cheap, abundant energy – and this has been supplied by fossil fuels, which still account for around 80% of energy supplies. But dependence on fossil fuels has driven accelerating and potentially disruptive climate change. There's widespread agreement about the need for the UK's energy system to make a transition to one that stabilises the output of greenhouse gases, and in the UK a commitment to producing Net Zero greenhouse gases by 2050 is rightly enshrined in legislation. But it is not clear that policy makers and politicians fully understand the scale of this challenge.

The UK has made some good progress in decarbonising its energy economy, but naturally has done the easy bits first. Much heavy industry has been off-shored, there has been a shift from electricity generation from coal to gas, and roughly half of electricity generation is from a combination of burning biomass, offshore wind and the continuing operation of legacy nuclear power stations.

What remains will be much more difficult. The majority of UK energy use still comes from directly burning oil and gas, for transport and domestic and industrial heat. There is a need to reduce demand by much more focus on energy efficiency, especially in heating. This will need a major drive to retrofit existing commercial and residential buildings, and a large-scale programme building out new, zero-carbon social housing, with the remaining heating needs being met by electric heat pumps.

The transition to electric vehicles needs to accelerate; heavy goods vehicles and shipping may need to transition to hydrogen or ammonia, and its likely long-haul aviation will only be viable powered by synthetic, zero carbon hydrocarbons (e-fuels)[4]. These new fuels themselves need to be synthesised in a zero-carbon way – hydrogen by electrolysis using renewable energy and/or high temperature process heat from high temperature nuclear reactors, synthetic hydrocarbons from green hydrogen and carbon dioxide captured directly from the atmosphere.

In addition to totally decarbonising the UK's electricity supply, it will need to be substantially expanded to accommodate the transition from directly burnt oil and gas to electricity. The heavy lifting in the UK will likely be done by offshore wind, including floating offshore wind.

In addition to intermittent renewables, both more storage capacity, and sources of zero carbon firm power will be needed.

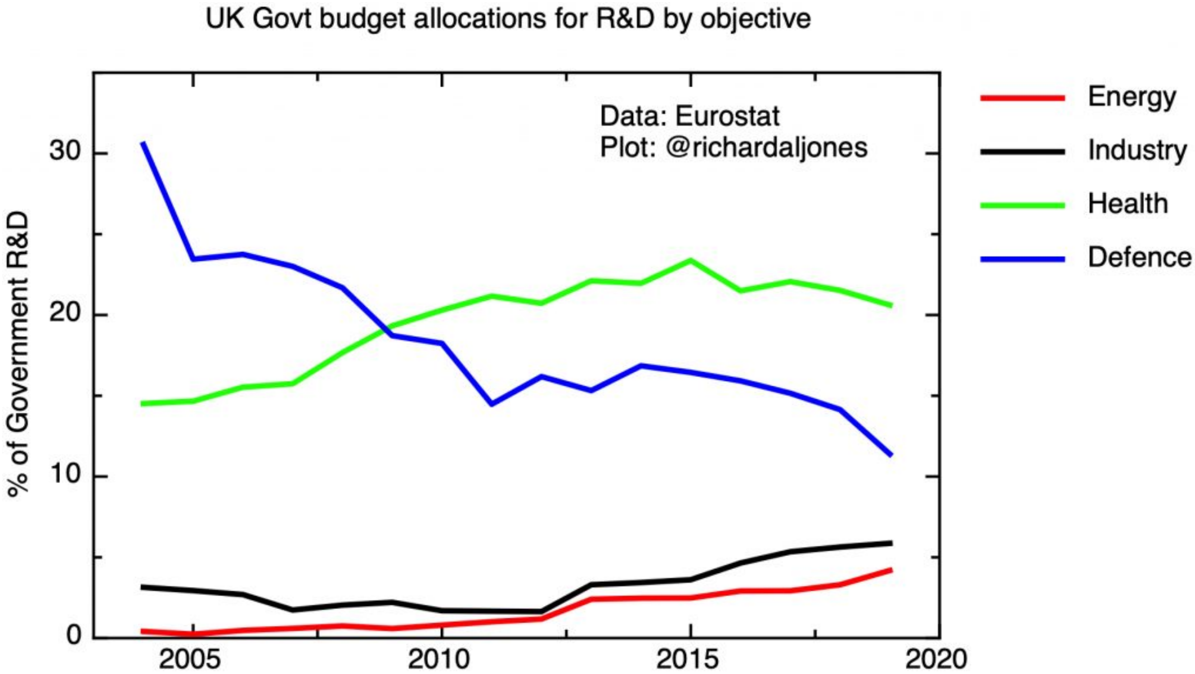
For the latter, the choice is between continuing to burn gas, but with carbon capture and storage, and a bigger programme of nuclear new build[5]. Fusion R&D (where the UK has a genuine comparative advantage) in case it works should be supported, though it is not likely to make a substantial contribution to the 2050 Net Zero target.

This is a daunting list, combining some established technologies, some that exist but are not yet cheap or deployable at scale enough, some that exist only in principle. The scale of the transition is wrenching, and like all big changes, it will produce winners and losers, both at a national level and geopolitically. Innovation is needed to drive down the cost of the new, cleaner technologies to the point at which economic forces drive the transition more than political ones.

1.3. Keeping the nation secure in a more dangerous world

The war in Ukraine involving a nuclear-armed adversary is a forceful reminder that one of the primary duties of a state is to keep its people secure. The 2021 Integrated Review of Security, Defence, Development and Foreign Policy[6] reasserted the importance of science and technology as a source of strategic advantage and as a central part of national security. Although the war in Ukraine has called into question some of the assumptions of the Integrated Review, with a painful reminder that the security of the UK's European neighbourhood cannot be taken for granted, this emphasis on security as a key motivation for the state's involvement in science and technology will surely only strengthen.

The Ukraine war is also a reminder that the geopolitics of energy never went away, and that the resilience of the material base of the economy and lives cannot be taken for granted. Since the end of the Cold War and the subsequent deepening of globalisation, the UK has become complacent about the degree of its dependence, as a small country, on imports for energy, food, materials, and finished goods. Of course, the UK's prosperity depends greatly on its international trade, so a North Korea-style Juche-UK policy would be ridiculous – but the pandemic was a reminder of a dependence on other countries for some essential items like PPE (personal protection equipment) and pharmaceutical precursors, as well as teaching how sensitive the UK's complex global supply chains have become, with the effects of disruptions in obscure corners rippling out worldwide.

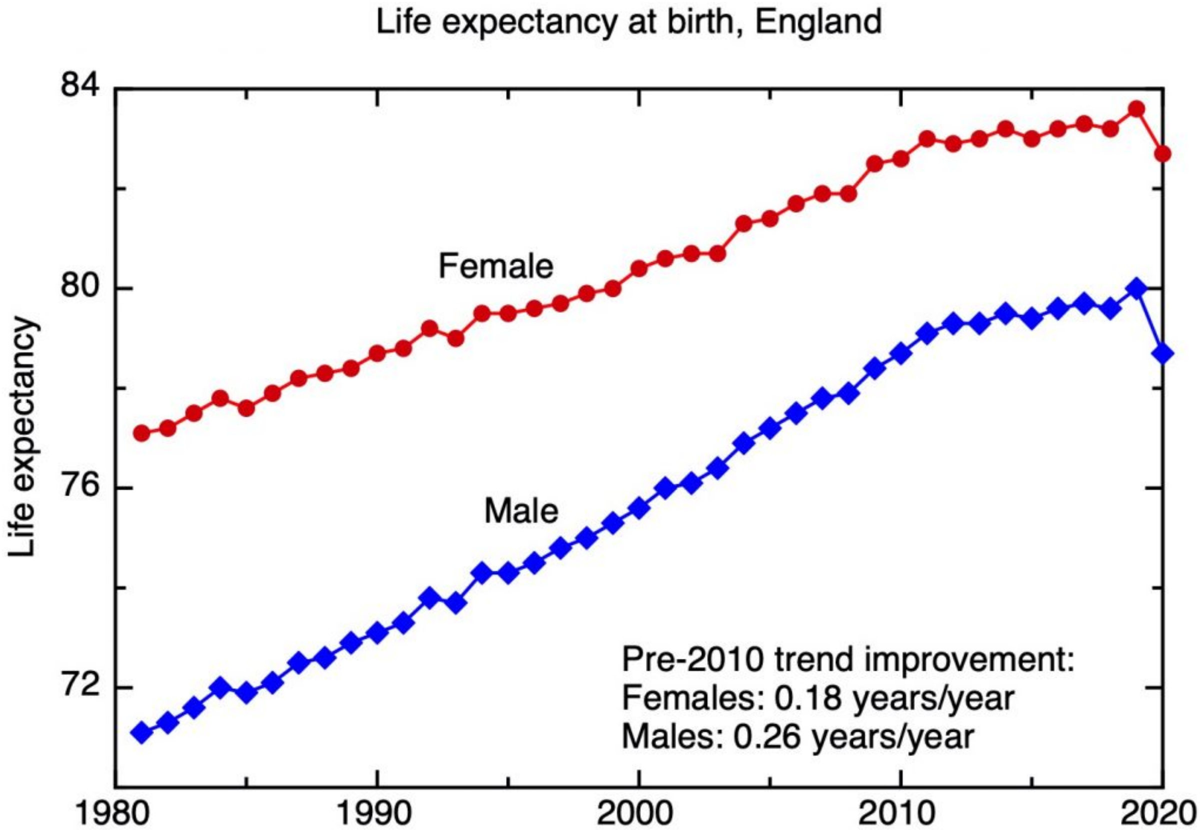


UK government research and development spending by socio-economic objective, for selected sectors. Data: Eurostat (GBARD)

After the end of the Cold War, one of the ways in which the UK cashed in the "peace dividend" was by reducing the amount of R&D devoted to defence. In 2022, the priorities for the government's R&D spending will inevitably and rightly be different, with more emphasis on food and energy security, rebuilding sovereign capabilities in some areas of manufacturing; as well as a return to higher spending directly on defence R&D, including new threats to cybersecurity.

1.4. Keeping an ageing population healthy

The pandemic has been a traumatic experience for the nation, with more than 175,000 deaths. As the UK went into the pandemic, there was some optimism that its strong position in life sciences would place it in a better position to weather the pandemic than other countries. As it turned out, its record was mixed. On the one hand, there was a successful rapid vaccination programme; on the other, the pandemic was unforgiving in the way it revealed and exacerbated widespread health inequalities.



Life expectancies at birth for males and females in 2020 for England. These are not predictions of how long a baby born in 2020 will live; instead they represent an estimate of the average number of years a baby born in 2020 would live if they experienced the age-specific mortality rates for 2020 throughout their life. Data from Public Health England[7]*.*

A more complete reckoning of the strengths and weaknesses of the UK's pandemic response awaits a full inquiry. The plot shows the impact of the pandemic on life expectancies. What is interesting, though concerning, is that even before the pandemic the rate of increase in life expectancies seen in 1980s, 90s and 2000s had already, after 2010, begun to stall.

The paradox here is that this slow-down in the rate of improvement of life expectancy follows soon after the substantial increase in R&D devoted to health. As always, there are probably many factors at play here. But there is a conceptual muddle about the way the UK thinks about its *"Life Sciences Strategy"*. The problem is that this strategy has two, largely separate, goals, which are sometimes in tension[8].

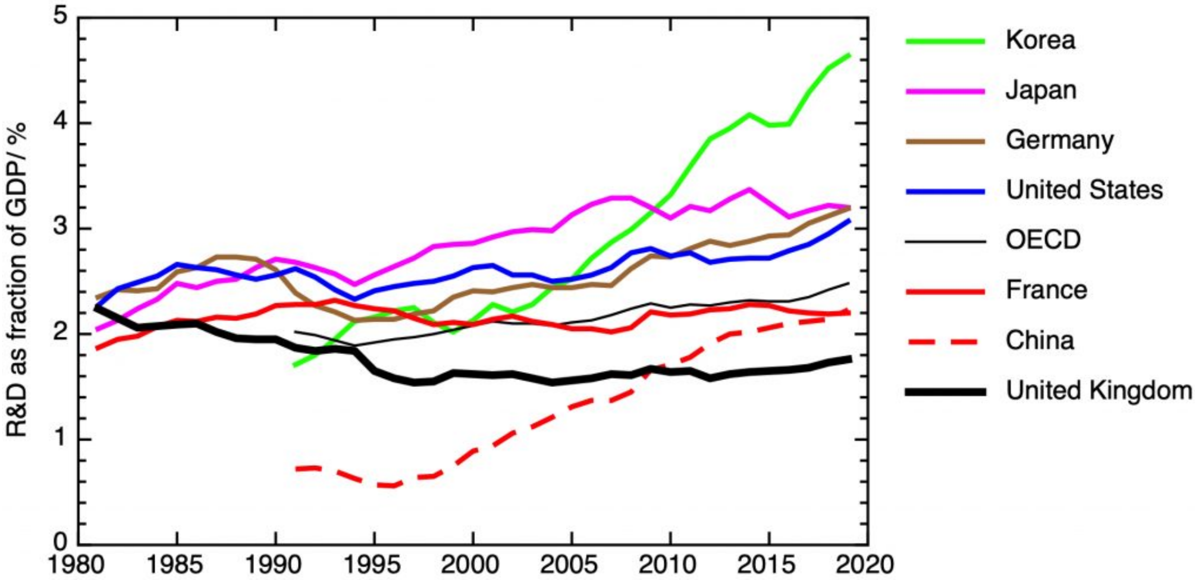
One objective of a life sciences strategy is to do the research needed to improve the way healthcare is delivered to the UK's population, and to address the broader determinants of the health of the public. The other is to support the UK's pharmaceutical and biotechnology industries. These are important areas of comparative advantage for the UK economy, strong exporting sectors. But in recent years, productivity growth in the pharmaceutical sector has markedly slowed down, and given the UK's specialisation in pharma, this underperformance has made a material contribution to the UK's overall productivity problem, as demonstrated by recent from The Productivity Institute's Diane Coyle's recent research[2].

So, while it is an entirely appropriate piece of industrial strategy to support the pharmaceutical and biotechnology sectors, it is important also to think about the wider innovation needs of the health and social care system. Nor should it be expected that COVID-19 will be the last pandemic, so attention should be paid to being better prepared for the next one.

As other priorities for R&D – like national security and Net Zero – become more pressing, it is going to be more important than ever to be clear about how the UK sets its strategic priorities.

Part 2: Overarching issues and questions

2.1. How research intensive should the UK economy be?



Total R&D intensity of selected countries, and OECD average (General expenditure on R&D as fraction of GDP). OECD Main Science and Technology Indicators.

The research intensity of the UK's economy, according to previous years' estimates, is low, both by the standards of other comparable countries, and by comparison to its position at the beginning of the 1980s as one of the world's most R&D intensive economies. In 2019, the UK's R&D intensity – as measured by the fraction of total GDP spent on R&D, both public and private – stood at a little less than 1.8% (as we shall see in section 5.1, the ONS now regards this as an underestimate, and in future years will produce new figures with a revised methodology). The current average for OECD countries is nearly 2.5%. The government has a stated policy of increasing R&D intensity to 2.4% of GDP by 2027, while the Labour opposition campaigned for a more ambitious goal, of 3% by 2030. So, there is consensus on the need to increase R&D intensity. But why the focus on a single number, and how should one choose such a target?

The reason 2.4% was chosen was because it corresponded to the OECD average (which itself, as the plot makes clear is itself slowly increasing, presenting a moving target). Measuring R&D as a fraction of GDP is simply a measure of the proportion of total economic effort devoted to the systematic development and application of new knowledge; economists currently think of it as being a subset of investment in intangible assets, itself part of the wider picture of investment in the capital stock.

The wider picture here is that the UK has a history of low investment of all kinds – over the 20-year period to 2017, the UK had the lowest level of private sector investment for any G7 nation, and the second lowest government investment[9].

So, one way of interpreting the UK's low R&D intensity is as part of a wider reluctance, both from the private sector and HM Treasury, to forgo consumption now in the hope of rewards in the future. In other words, there is a kind of national failure to pass the marshmallow test.

Of course, this is not a question of some national moral failing, if true it's likely to reflect institutional factors.

R&D is carried out (and paid for) both by private sector firms and by the government and its agents – in economies like the UK, there is a rule of thumb that the private sector carries out about twice the value of R&D than the government. So, there is a need to look for such institutional factors both in the private sector, for example in the demands placed on companies from the financial markets, as well as in the accounting conventions and wider assumptions used in government. It is likely there are issues here, the necessary institutional changes will be difficult and take time to have an effect

Another argument is that the low R&D intensity of the UK is an inevitable consequence of the sectoral make-up of its economy, reflecting the transition from R&D-heavy manufacturing to the less research-intensive world of services. In such an economy, intangible assets are central. Although R&D itself produces such intangible assets, in the form of patents and know-how, there are other forms of intangibles. Defining intellectual property products (IPP) slightly more broadly than patents and R&D, to include, for example, entertainment products such as film, TV, or radio, one finds that among G7 nations, UK invests more in IPP than Italy and Canada, less than USA, Japan and France, and (interestingly) about the same as Germany.

"Services" is not a single sector, however. The parts referred to as "knowledge intensive business services" – including design, technical consultancy, and professional services – are a significant area of comparative advantage for the UK, and they do undertake a significant amount of R&D. Other kinds of service industry – such as social care – measure relatively low in terms of apparent economic value but are of vital social importance. More attention should be given to innovation in areas like these. Ultimately, though, what matters is not whether a sector can be classified as manufacturing or services, but whether it can deliver productivity growth.

Although there is a case to be made that, even given the UK economy's existing sectoral structure, R&D spending is too low, it probably is true that targeting an increase of R&D intensity to 2.4% (or higher) does represent an implicit commitment to reshape the economy's sectoral structure.

An R&D target should be thought of not as an end in itself, but as a means to an end. What kind of economy is needed if the UK is to meet big strategic goals? With a clearer view comes a better understanding of the necessary fraction of national resources that should be devoted to research and development. It is unclear if this would produce the exact figure of 2.4% or be significantly higher.

2.2. The UK – good at research, no good at innovation?

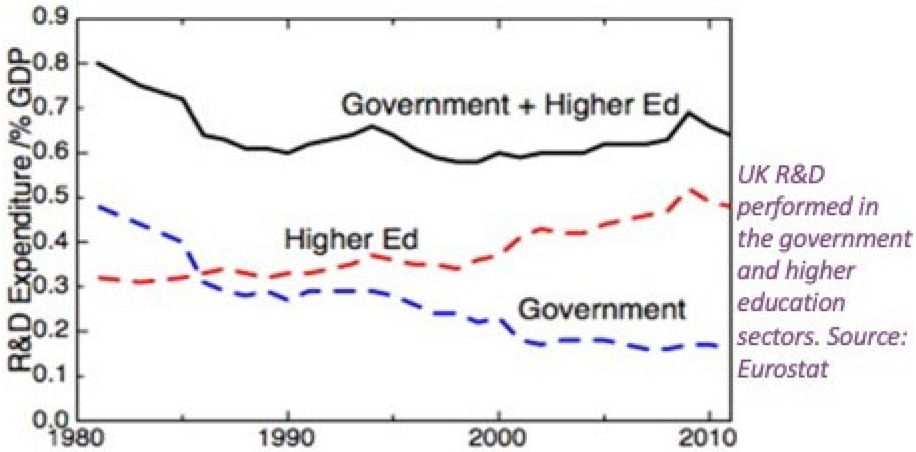
There is a long tradition – amounting to cliché – of arguing that the UK is very good at basic research, but systematically fails to commercialise it. Instead of the rather mystical cultural explanations sometimes advanced for this; another reason is more obvious – it is because the UK does not put in the resources that are needed to turn science into money. This is not a result of some trait in the national character; it is the outcome of deliberate policy choices to de-emphasise the more applied R&D needed to convert ideas into products, in favour of more basic science.

Innovation is about matching new technical opportunities with unmet demands, and for that reason it needs to be done (at least strongly steered) by those agents who are in a position to recognise those unmet demands. In the UK economy, with the notable and important exceptions of the health service and the armed forces, that puts the emphasis on the private sector. Yet, as economists know well, the fact that firms are not able to capture all the benefits of the innovations they make means that, in the absence of some form of government intervention, the private sector will systematically underinvest in research and development.

This provides the justification for governments to support basic science, where the outcomes are highly uncertain, and the benefits often only materialise in the long term. But there is much less consensus about how much governments should be involved in supporting more applied research and development. In the UK, there has been a major, but underappreciated, change in the government's position on this point.

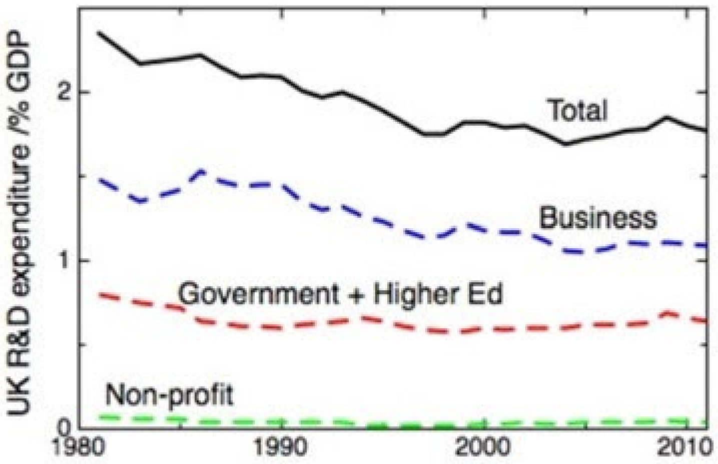
As the historian of science Jon Agar wrote in his definitive study of science policy under Thatcher[10], there was a sharp shift in science policy in the late 1980s: "there was a crystallisation of policy: government funding for near-market research was abruptly curtailed (because private industry should step up), and, to balance this, the science base, especially 'curiosity-driven research' was heralded."

One can see this in the statistics: from the 1980s onwards, there has been a major reduction in the R&D carried out by government departments and their agencies. The research done here was typically applied research in support of the direct goals of those agencies. From 2000 onwards, there was a significant increase in the R&D government supported in universities through the research councils, while departmental research continued to fall.



The period 1980 to 2010 saw a systematic shift of UK government supported R&D from government applied research to "curiosity driven" research in HE. From R.A.L. Jones, 'The UK's Innovation Deficit & How to Repair it'[11].

This provided an empirical test of the view of some free market evangelists, who argued that state spending on research "crowds out" research by the private sector. In fact, over the same period, instead of seeing private industry "stepping up" to fill the gap, there was a substantial decrease in business R&D intensity over the same period, supporting the current consensus view that state spending on R&D in fact tends to "crowd in" additional private sector R&D spending. It is important to recognise that, at the same time, privatisation moved some important sectors from the public to the private sectors; in most cases this coincided with a substantial reduction in R&D activities by the new owners.



Between 1980 to 2010, the decline in total government support for R&D was mirrored by a decline in private sector R&D. From R.A.L. Jones, 'The UK's Innovation Deficit & How to Repair it'[12].

Where does business R&D take place now, and how is it financed? The broad-brush answer is that business R&D is concentrated in a few sectors of the economy, it's carried out by big businesses, and it's financed by their own internal cash resources.

In the UK, the dominant sectors are pharmaceuticals, automotive, aerospace, machinery and equipment, precision instruments and optical products, and chemicals. In addition to these manufacturing sectors, there is substantial R&D spending in services, in telecommunications, computer programming and software, and the provision of technical testing and R&D as services in themselves. Of course, these services are often driven by and provided for manufacturing sectors, emphasising the difficulty in a modern economy of making a clean separation between manufacturing and services[13].

Given the rhetorical emphasis in discussions of innovation on the role of venture capital financed start-ups and highly innovative small businesses, it is important to understand the relative scale of the contributions of large and small companies. In 2020, total business R&D was reported as £27 billion; of this just £1.5 billion happened in SMEs. Total venture capital investment in 2020, as reported by the BVCA, was £1.7 billion. The Venture Capital sector is itself heavily subsidised by the state, both through direct investments and through tax reliefs.

What kind of R&D does business do? It is natural to assume that it will be focused on short term improvements of existing products and processes, with any longer-term work directed at the introduction of entirely new products, such as new drugs. But one can point to some quite fundamental discoveries made in industrial laboratories in the past.

The most well-known example is Bell Laboratories in the USA, which produced the transistor, the UNIX operating system, laser trapping and cooling of atoms, and the discovery of the cosmic microwave background. Other breakthroughs in basic science – of the kind that attract Nobel Prizes – were also associated with other industrial laboratories in the USA, such as General Electric and IBM. Important industrial laboratories in the UK included those run by the chemicals company ICI and the electronics firm GEC.

Neither ICI nor GEC is in existence anymore, while in the USA Bell Laboratories is now a much smaller and more business focused operation, owned by Nokia. There are still contributions to basic science from industry-owned laboratories – for example Alphabet/Google's subsidiary DeepMind has made a major contribution to biology through its AlphaFold programme for predicting protein structures. But the perception – backed up by some evidence – is that business R&D has become much more focused on short-term, product focused R&D rather than more basic research[14]. This is understandable given changes to the business landscape over the last few decades.

Bell Labs in its heyday was sustained in effect by the monopoly rents of its parent organisation, the Bell Telephone Company, and when that monopoly was broken up there was naturally less room for expenditure that benefitted wider society without contributing much to the company's bottom line. The demise of GEC and ICI as major companies at a scale that could justify and finance more speculative research reflects both some individual corporate misjudgements, but also a wider climate of primacy of maximising "shareholder value" in corporate governance[15].

The side-effect of this, though, is more of a division of labour, with basic research more exclusively the province of universities and research institutes, and industry focusing entirely on shorter-term applied work, and something has been lost by this separation.

2.3. Is the productivity of the science enterprise slowing down?

If the UK has focused government support on curiosity-driven research, does that mean that its basic research enterprise is in a correspondingly strong state? There are certainly some things to be proud of in the UK's research base – by measures such as share of highly cited research papers, the UK system seems to deliver internationally competitive results well out of proportion to the money the government puts in[16]. The UK in many ways has worked to optimise its system to deliver "excellence" as defined by the academic community, and the outcome reflects what the country has chosen to optimise.

But that does not mean that everything is fine in the basic research enterprise, in the UK or more widely. There are a number of linked worries, some specific to the UK, some with a wider international relevance. The wider background is a sense that international science is suffering from falling productivity, with diminishing returns in terms of fundamentally new results, from ever increasing investments.

This argument was made in an influential piece by Patrick Collison and Michael Nielsen – *Science is getting less bang for its buck*[17], arguing that despite exponential increases in the number of people involved, the amount of money spent, the number of articles published, the rate of production of significant new ideas static or indeed falling. This argument is difficult to quantify – how can one define "significant"? There are linked arguments about whether the rate of innovation more widely defined is slowing (e.g. an influential paper by Bloom, Jones, van Reenan and Webb – *Are ideas getting hard to find?*[18]) though of course this also calls into question the effectiveness with which basic science is turned into products as well as calling into question the productivity of the basic science enterprise itself. But despite the difficulty of quantifying this, it is worth taking seriously.

There are two quite different views about what might be wrong with basic science, that are at first sight in contradiction, though in my own opinion there are elements of truth in both. One is that a slow-down could reflect too much control over science. Rather than just giving talented scientists resources and freedom to pursue their own priorities, in this view the UK system has become bogged down with too much bureaucracy and poor incentives. Systems such as peer review have led, in this view, to conservatism and a stultifying consensus which acts to suppress genuinely radical new ideas and approaches.

The other view is that, rather than being over-controlled, academic science has had too much freedom. By drifting apart from the kind of applied science that is subject to the discipline of having to deliver devices and systems that actually work in the world, the argument is that science is in danger of becoming an entirely self-referential system, prone to swings of fashion and producing too much work which is at best poor quality, and at worst irreproducible or just wrong. In this view, most forcibly argued by Dan Sarewitz in his piece *Saving Science*[19], it is technology which keeps science honest, and an increasing separation between science and technology is unhealthy for both sides.

These issues are international in their scope – how do they apply to the specific circumstances of the UK's science system? There are some consequences of the UK's structural shift away of government support from departmentally driven applied science to university focused basic science that are worth dwelling on.

One suggestion is that government support has shifted from applied research to more basic science. Another more widespread perception is that the shift has been in the other direction – from the perspective of university-based scientists, the pressure has been to demonstrate more practical relevance – more "impact", in the favoured term of art in UK science policy – of their research.

Broadly speaking, the UK went from a situation in the 1960s and 1970s where there was a very large cadre of government supported scientists and technologists doing explicitly applied research, and a relatively smaller group of university-based scientists with more freedom to follow their own research priorities. By the end of the 2000s, the cadre of explicitly applied scientists was very much smaller, and the university research base was substantially bigger and better resourced. But the continuing rhetorical commitment to science and technology as the driver of economic growth and international competitiveness led to an obvious pressure on the now dominant university-based science to demonstrate its contribution to those goals.

This pressure has had some positive outcomes. It is good that universities have become more professional about technology transfer and creating spinouts, that the very positive aspects of collaborations between scientists in industry and academia are more widely recognised, and that the civic universities are rediscovering their mission to support their regional industries and economies.

But the downside is when academic scientists, who are not close enough to the market to understand its real needs, opportunities, and constraints, feel compelled to generate unconvincing quasi-commercial motivations for their work. At its worse, the result can be to steer research in directions that are neither fundamentally interesting nor practically relevant.

2.4. The geography of science and innovation

It has never been easier to access the latest scientific ideas from anywhere with an internet connection, yet the world is not flat. Economic opportunity is highly unequally distributed, with technological innovation concentrated, not just in a few highly developed nations, but in very specific cities and regions within those nations. Information may travel at the speed of light, but know-how moves with people, and the result is that there is a very distinct geography of science and innovation.

The discussions about innovation reflect the data collected, and because data is collected at the level of nation states, it's thought the nation to be the right unit to analyse science and innovation at. But it is not obvious that this must be the case.

Instead, talk should be about an "innovation system" – the collection of people and institutions who collaborate, informally or formally, to create ideas, assimilate them from elsewhere, and turn them into value.

These systems can be transnational. Multinational companies represent such a transnational innovation system, with manufacturing and R&D sites across the world linked by formal management systems and the mobility of people. Beyond the formal limits of a single multinational, there is a penumbra of companies supplying goods and services, and of business customers, all of whom help drive innovation. Think, for example, of the leading semiconductor company TSMC. This sits at the centre of a global network of highly innovative companies. Some are providing inputs to the production process, including the suppliers of highly sophisticated equipment, like the Netherlands's ASML, and the suppliers of materials of enormous purity. Meanwhile customers such as Apple, working with their designers in ARM, pressure TSMC to innovate to meet their very demanding requirements.

On the other hand, innovation systems can also be subnational in scale, driven by concentrations of institutions and infrastructure, and above all their attractiveness to people with the relevant skills. There are a couple of related concepts here.

One is the old idea, going back to the 19th century economist Alfred Marshall, of "industrial districts" – places where concentrations of related industries cluster. These can have deep historical roots and their evolution is strongly path dependent. For example, Sheffield has been a centre of production for steel and steel products since the Middle Ages. In Manchester, an early specialisation in textiles created a demand for chemicals, including fine chemicals like dyestuffs, from which a pharmaceutical industry subsequently emerged.

The other is the more recent phenomenon of science-and-technology-based clusters – in the USA, Boston for biotech, and Silicon Valley for semiconductors and information technology; in Taiwan, Hsinchu for semiconductors and electronics hardware; in the UK, Cambridge for both biotech and ICT.

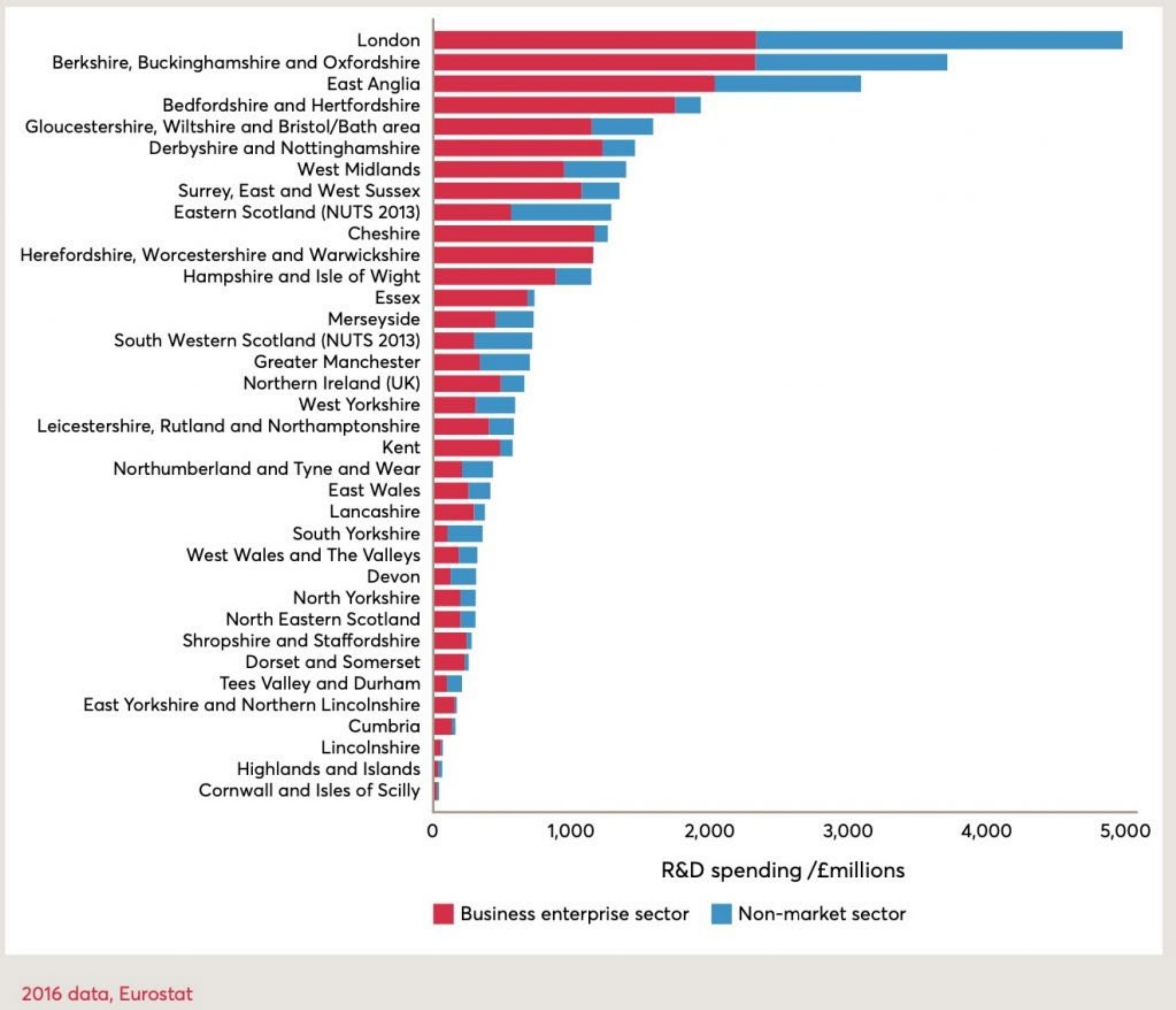
The success of these examples has led many policy makers around the world to try and create new clusters from scratch, without universal success. To make a successful cluster, many ingredients must come together – relevant research institutions, access to finance, strongly expanding markets for the cluster's products (sometimes, as in the case of the early days of Silicon Valley, driven by very large-scale government procurement).

Above all, there needs to be a concentration of appropriately skilled people. This includes high quality scientists, but scientists by themselves are not enough. There need to be high quality managers and financiers, skilled technicians, and other intermediate skilled occupations. A successful cluster will have high quality institutions for developing skills at all levels, from research universities to technical colleges. It must also have a vibrant labour market, attracting skilled people from elsewhere, and with people going from job to job taking their know-how with them.

What is the role of research institutions in developing clusters and regions of highly productive technology-led industrial specialisation? The evidence suggests that a strong and relevant research base is a necessary, but perhaps not sufficient condition, for the success of a cluster. It is certainly true that both in Boston, MA, and Cambridge, UK, those clusters are built on a very long history of substantial investment in research in very strong research universities. Meanwhile, the government-funded Institute Technology Research Institute was pivotal in getting the Hsinchu, Taiwan cluster established (TSMC was itself a spin-out company from ITRI).

The Hsinchu example shows that the key capability that R&D capacity provides is not always the generation of new ideas, but the ability to assimilate and integrate ideas from elsewhere – to provide "absorptive capacity". The availability of skilled people and the spread of know-how between them is crucial to develop this.

Is there a more general relationship between R&D spending and productivity at a regional level? The UK's pronounced regional productivity disparities are mirrored in very substantial differences in regional R&D intensity, as detailed in the report *The Missing £4 Billion*[20].



R&D spending in the market and non-market sectors by NUTS 2 region (except London presented at NUTS1 level). From "The Missing £4 billion"[20].

This plot shows three outliers – London and the two subregions containing Oxford and Cambridge, which between them account for 46% of all public and charitable spending on R&D, but just 31% of business R&D and 21% of the population. Another nine subregions show respectable levels of total R&D. These include Bristol, Hampshire, Derby, Bedford, Surrey and the West Midlands, Worcestershire, and Cheshire. Except for East Scotland, all these subregions are characterised by above-average ratios of private to public sector R&D spending. Two subregions stand out for significant private sector R&D and almost no public sector activity – Cheshire, with its historic concentration of chemical and pharmaceutical industries, and Warwickshire, Herefordshire, and Worcestershire. Then there is a long tail with much lower public and private investment in R&D, including all of Wales, Northern Ireland, the North of England, Lincolnshire, South West England beyond Bristol, and Kent and Essex in the South East.

This regional imbalance in R&D spending mirrors the regional disparities in economic productivity. The most prosperous and productive parts of the country – broadly, Greater South East England, comprising London, the South East, and parts of the East of England – have the greatest concentrations of R&D investment, while less productive regions in the North and Midlands, and in Wales and Northern Ireland, have substantially less investment in R&D. Curiously, the imbalance is greater for public sector R&D than in the private sector.

If investments in research and development do contribute to productivity growth, and the beneficial effect of those investments is at least in part geographically bounded, then the spatial aspects of the UK government's R&D policies have been acting as an anti-regional policy for some decades.

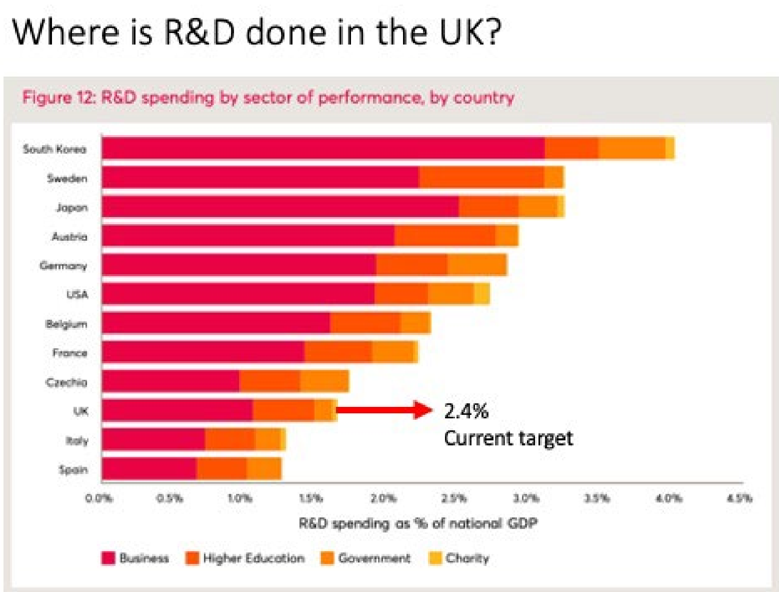
Part 3: The institutional landscape

3.1 Who does R&D, and who pays for it?

It is an obvious, but nonetheless important, point to note that there isn't an exact match between who funds research and where it's carried out. Business can pay for research in its own laboratories, but it can also sponsor research in universities. Likewise, some research done research done by private business is paid for by the government. R&D statistics differentiate between sector of performance and financing sectors. The overall funding flows for the UK are summarised in an excellent flow diagram from the ONS[21], covering Business Enterprise, Government and UK Research and Innovation, Higher Education Funding Councils, Overseas, Private Non-Profit and Higher Education.

3.2 Where is R&D done in the UK? The institutional landscape

R&D can be carried out in a number of different kinds of institution with different missions – universities, government-funded research institutes, charitable research institutes, and private sector laboratories run as part of profit-making enterprises. The next figure shows how the mix of R&D performing institutions in the UK compares with other countries.



International comparison of the breakdown of R&D spending by sector of performance. From The Missing Four Billion.[20]

The UK stands out in two ways – one is its overall low R&D intensity, as discussed in the last section. Big increases in both public & private R&D are needed to meet the UK's current R&D intensity target of 2.4%. But in addition to this overall low level of R&D, the UK is an international outlier in the degree to which non-business R&D is concentrated in universities, with a much lower proportion in non-university government laboratories.

The UK, Germany & USA all do similar amounts of R&D in universities, relative to the overall size of their economies. But Germany and the USA do much more R&D in government owned R&D institutes, which tend to focus more on applied and mission focused R&D. This reflects a positive policy choice by UK governments to withdraw from this kind of research.

3.2. University research

The dominant role of universities in the UK's public research system has positive and negative features, arising from the way university finance operates and the competitive pressures they operate under. As far as the government is concerned, they deliver research very cost-effectively, because they subsidise their research activities from other sources of income. Because the environment they operate in is very competitive, both nationally and internationally, they respond in a very focused way to the incentives and pressures that competition puts them under. Up to now, those incentives have largely favoured the production of academic science that is highly ranked by measures such as citations and recognition by international academic peers. Thus, they do well in international league tables. But this does not come without cost.

It is important to understand that, in the UK, universities are independent corporate entities (usually regulated by charity law), not direct arms of the state. This is in contrast with, for example, universities in Germany, and state universities in the USA. They can own their own assets, and their employees are not civil servants. So (to the occasionally obvious annoyance of ministers), the government cannot directly tell them what to do. The government does, however, have great influence on them through the very substantial funding that they provide, and the regulatory framework they can impose.

There are more than 100 universities in the UK, but not all of them are strongly focused on research, and indeed research is very concentrated in a relatively small number of institutions. Just four institutions – Oxford, Cambridge, and the two large London universities, UCL and Imperial – account for nearly a third of all research contract funding. Adding to these a further 5 large civic universities takes the fraction to a half, while 80% of the funding goes to 27 institutions.

Where does the funding for a research-intensive university come from? On the research side, there is a so-called "dual support" system, through which the university receives a block grant, which can be used at the university's discretion, but which is linked to the amount and quality of research it does, as measured through the "Research Excellence Framework" (of which, more later). Then there are research grants and contracts, competitively awarded to pay for discrete research projects, from research councils, and to a lesser extent charities and businesses.

On the teaching side, there are some remaining block grants for subjects that are particularly expensive to teach (e.g. medicine), but the bulk of funding comes through student fees. For home students, these are paid for through the student loan scheme, where the upfront cost is paid by the government and (partially) recouped through income-contingent payments from graduates. The maximum tuition fee is set by the government at £9,250. Fees for overseas students are not capped in this way and are in effect set by the international market for higher education and the pricing power of individual institutions, which is naturally related to their reputations. To give one example, Imperial College currently can charge more than £30,000 per year for an undergraduate engineering degree. This is at the high end of the scale, but most UK research intensive universities will charge overseas students substantially more than double the home fee.

Finally, income from endowments, derived from philanthropic donations over the years, and income from licensing intellectual property, do make contributions to the finances of some institutions. In contrast to the situation in the USA, where many universities have multibillion-dollar endowments, only in Oxford and Cambridge in the UK does this kind of other income make a material difference.

To summarise the financial situations of UK universities, teaching home students more or less breaks even (though there are variations by subject, and the position is worsening due to the freezing of the fee). Research loses money; overall the combination of the block grant and research grants covers perhaps 70-80% of the true costs. Teaching overseas students makes a substantial surplus, which is recycled into making up the losses on research. A justification for this situation is that it is the institution's research that contributes to its international reputation, which in turn is what attracts international students and gives the institution its pricing power.

The order of magnitude of this cross-subsidy from international students is comparable to the total research block grant to universities. Thus, it is not a "dual funding" system for research, it is a triple funding system, where the government's contribution to core costs of research is matched by the surplus from the fees of international students.

The university research environment is shaped by the highly competitive world that they occupy, much of it by the design of successive UK governments. There is competition for home students, since the Coalition government removed central government controls on the total number of home students each institution can accept. The competition for international students is itself international; the Chinese students who comprise the majority of these customers can choose their country of destination, with the main competition coming from the USA and Australia.

In research, the competition is played out in the proxy medium of the various international university rankings. These statistically dubious aggregations of fundamentally incommensurable metrics are irresistible to trade journalists and university publicity departments, unignorable by managers and governing bodies, and undoubtedly influential in the perceptions of university quality by prospective students. Quantitative measures such as research income and citation data are combined with indicators such as number of papers published in so-called "top journals" and prizes awarded to faculty members, and the outcomes of reputation surveys. The choice of metrics and measures is itself an implicit definition of what in research is valued and what is not, and this in turn will influence the strategy and operations of those universities who seek to compete on these measures.

In the UK, the government-run assessment of research quality – the Research Excellence Framework – is more carefully constructed, with extensive peer review of the research outputs at the level of individual publications from each university. It is also much more expensive. From the government's point of view, it provides some kind of assurance of the value for money of its investment in research, and because it is directly linked to the funding universities receive, it can be used as a lever to change the behaviour of institutions in directions the government wishes. For example, in the last two iterations of the scheme, the "impact" of research – on business, through the formation of spinouts, on policy, on health outcomes, etc – is measured and incentivised.

What has all this competition done? Much has been written about the positive and negative aspects of features of the landscape such as the Research Excellence Framework and it's plausible that any kind of metric-based assessment system will drive up performance in those aspects that are measured, while leading to relative neglect of those aspects that are not directly measured, even if in the long term this neglect will probably have a detrimental overall effect.

In UK universities, a run-down of technical support for research, and a poor career structure for staff scientists, could be seen as examples of these kinds of negative consequences.

3.3. Basic research institutes

In many other countries, basic research is carried out not just in universities, but in specialised research institutes. For example, Germany has the government-funded Max Planck Institutes, while in the USA, the Janelia Research Campus, funded by the Howard Hughes Medical Institute's $27 billion endowment, has many admirers. These have been much less important in the UK system, with the Medical Research Council's Laboratory of Molecular Biology providing a rare example of a purely discovery research focused institution. There has been a recent move towards such institutes in the UK.

Central facilities, like the Rutherford Laboratory and the Diamond Light Source in Oxfordshire, represent slightly different type of non-University laboratory. These provide expensive large-scale scientific facilities that are used by university scientists on a shared-access basis to pursue their own research programmes. The largest facilities are too expensive even for a single nation, and the UK has shares in overseas facilities of this kind too – the neutron source ILL, and the synchrotron radiation facility ESRF, both in Grenoble, France, and perhaps most famously, the high energy physics laboratory CERN, in Geneva, Switzerland.

These laboratories do of course have staff scientists – and, although their purpose is primarily basic science, they concentrate substantial amounts of technological capability. This means that they do provide substantial economic spillovers in their locations. For example, the Harwell technology campus has developed around the Rutherford Appleton Laboratory and the Diamond Light Source, serving as the nucleus of a powerful tech cluster in rural Oxfordshire. Thus, location choices for these facilities can have big implications for regional economic growth; in the case of the Diamond Light Source, the alternative location was at the Daresbury Laboratory, near Runcorn in the North West.

The last decade has seen the foundation of new, dedicated upstream R&D laboratories. The largest of these is the Francis Crick Institute in London, now the largest biomedical research establishment in Europe. Other new laboratories include the Rosalind Franklin Institute, on the Harwell Campus in Oxfordshire, the Alan Turing Institute in London, and the Henry Royce Institute at Manchester.

Is basic research better carried out in focused institutes, or in research universities? It is important to distinguish factors that are specific to the funding environment from anything more fundamental. It is certainly true that a researcher wholly focused on doing science in an institute, with the highest quality equipment and technical support, will achieve more than a university researcher with substantial teaching and administration duties and a poorer research infrastructure.

The difficulty for the UK, though, arises from the way it finances basic research. Universities can do basic research at a lower cost to the state because of the cross-subsidy from teaching overseas students. This cross-subsidy is not available to research institutes, so if they are financed on the same basis as universities, they will not be financially sustainable.

The alternative would be to finance all research based on what it actually costs; without unrealistic budget increases this would lead to a substantial reduction in the volume of research carried out in the UK. On the other hand, it would allow universities, if they chose, to reproduce many of the positive features of research institutes, such as better technical support and more stable career structures for staff scientists.

3.4. Public sector research establishments

The first state-run scientific establishment in England (predating the foundation of the United Kingdom) was the Royal Greenwich Observatory. At the time, astronomy was a science of strategic importance to the state. The projection of England's naval power across the Atlantic, and then across the world, to underpin trade and colonialism, relied on accurate astronomical measurements for navigation. But state-run scientific establishments whose purpose was applied science in support of the state's strategic priorities took off on a larger scale in the late 19th and early 20th centuries, with the foundation of institutions such as the Meteorological Office, the Laboratory of the Government Chemist and the National Physical Laboratory. Such establishments flourished particularly in the Cold War "Warfare State"[22].

While this sector of the research landscape is amongst the oldest, it has perhaps seen the most change and disruption in recent decades. With the move towards a smaller state, many of these institutions have been reorganised, some taken over by universities, some converted into "arms-length bodies", some transferred into private sector management, some privatised outright. The result has been a public research sector that is smaller, more atomised, and less well connected to the strategic priorities of the state. As written in a government report commissioned by the Government Chief Scientific Advisor in 2019 (*Realising our potential through science*[23]):

"The wide range of Public Laboratories that are owned by government present a significant resource for government in the leadership of outstanding 'directed' R&D, but several decades of their devolution from central government have created obstacles to a more strategic deployment of this resource".

Inevitably, defence has been one of the main motivations behind the public sector research establishments, so institutions like the Atomic Weapons Research Establishment are the quintessential Warfare State research laboratories. AWRE was merged into the Atom Weapons Establishment, which in 1989 was taken into private management. This partial privatisation was reversed in 2021.

It may be surprising to some that such a core part of the deep state as nuclear weapons was contracted out to the private sector in this way, and it is probably fair to say that this is not the place to look for the biggest spillovers into the private sector. Other defence establishments have, however had a bigger influence on the wider economy. The Royal Signals and Radar Establishment, at Malvern, was important in the development of liquid crystal displays and semiconductor optoelectronics. RSRE was privatised, with other defence laboratories, in 2001 as the company Qinetiq, which is now a publicly listed defence-focused contract R&D company.

In the post-war period, civil nuclear energy was another major driver of state funded strategic research. The UK Atomic Energy Authority, in the 1960s, was a huge enterprise running the both the civil nuclear energy enterprise and the weapons programme. The weapons programme was split from the civil nuclear energy programme in 1973; with the privatisation of energy in the 1980s and the completion of the last new nuclear power stations in the early 1990s, UKAEA was split up; responsibility for the decommissioning of its old sites was given to the Nuclear Decommissioning Agency, much of the R&D expertise was privatised as AEA Ltd, a contract R&D organisation which went into administration in 2012. What was left was the nuclear fusion programme, which now forms the core activity of the remaining UKAEA, based in the Culham Laboratories in Oxfordshire.

In another area of government – the criminal justice system – the evolution of research and development in support of forensic science makes an interesting case study. The Home Office's Central Research and Support Establishment at Aldermaston historically provided forensic services to police services and other government departments, as well as developing new technologies (for example, developing and implementing the DNA profiling techniques invented by Leicester University's Sir Alec Jeffreys). This was converted first into an executive agency – the Forensic Science Service – in 1991, then into a government-owned company. As a government-owned company, the Forensic Science Service provided forensic services for a fee, in competition with commercial operators.

In this environment, it was unable to cover its costs, and in 2012 the government decided to wind it up totally. Forensic science support for the criminal justice system is now provided by private providers in a highly competitive market. Research and development – both to validate and develop existing methods, and to develop entirely new techniques – has suffered (see this Lords Select Committee report[24]). The private providers operate on margins that are too thin to sustain any long-ranged research, while forensic science research in universities has received little public funding, possibly because it is not perceived as being at the cutting edge of academic science, as measured by citations and publication in the most prestigious journals.

Similar stories of atrophy, if not complete liquidation, could be told about government supported research in other areas, such as public health, agriculture, and food. The common feature is research in areas that, while societally important, lack both academic glamour and lucrative business opportunities.

3.5. Business R&D

As the majority of research and development happens in the private sector, to what extent can business R&D be thought of as part of a national innovation landscape? Most business R&D is done by large, multinational companies – and as such is part of a multinational system. The international nature of the UK's business R&D is underlined by the fact that around half of it is done by overseas-owned companies.

The dominant R&D companies in the world are ICT companies from the USA, Korea and China, automobile companies from Germany and Japan, and pharmaceutical and biotech companies from USA, Switzerland, and Germany. Only two UK companies make it into the top 100 of world R&D companies – the pharmaceutical companies GSK and AstraZeneca.

Does this relative lack of UK-owned companies in the top world tier of R&D performing companies matter? The fact that the UK is an attractive destination for overseas companies to open R&D facilities in is often cited as evidence of the strength of the UK's innovation system. The worry is that these investments are footloose; the UK is competing for these investments with other countries, which might offer other advantages such as lower labour costs, or access to larger markets. On the other hand, when corporate strategies change and "rationalisations" are demanded, proximity to the head office often seems to be a factor favouring the survival of R&D facilities.

Of course, the R&D performed by overseas-owned companies in the UK is important; it anchors in the UK wider high value economic activities, such as design and manufacturing, and it has wider spillovers in those innovation economies. In the West Midlands, for example, the auto company Jaguar Land Rover, a subsidiary of the Indian company Tata Motors, has a major R&D centre in Coventry.

At the opposite end of the spectrum to large multinational companies with the scale needed to sustain large, internal R&D efforts in support of their own business activities are firms that specialise in supplying R&D as a service to other companies, quite often as part of a wider package of knowledge intensive business services including design and consultancy. This sector accounted for about 6% of business R&D in 2020; David Connell and colleagues have persuasively argued[25] that R&D service companies play a central role in successful innovation economies such as that around Cambridge.

3.6. The Catapult Centres

The most recent entry to the public R&D landscape are the "Catapult Centres" – translational R&D centres launched by the Coalition Government in response to the 2010 Hauser Review. This called for the establishment of centres to focus on applied R&D in emerging technology areas, on the explicit model of Germany's Fraunhofer Institutes.

The idea was that these centres would combine publicly funded R&D and innovation programmes with contract research. This would include the development and scaling up of manufacturing processes, and the production of technology and application demonstrators. The intention was that they would bridge a gap in a linear technology development process, conceptualised in terms of the notion of "technology readiness levels" introduced in the aerospace industry.

There are now nine Catapult Centres (though one, the High Value Manufacturing Catapult, incorporates seven geographically dispersed centres which each operate with a considerable degree of independence. There does seem to be a consensus that the Catapult Network has helped fill a gap in the UK's RD&I landscape (though the scale of the network is still relatively small).

There is still a lack of clarity about what their mission should be. Originally, this was defined as doing applied R&D in emerging new technology areas. There is a danger here, that they will end up competing with commercial contract R&D providers. There are some bad precedents here: one of the abiding sins of UK technology policy is to expect public R&D centres rapidly to become financially "self-sustaining"; this effectively just creates another SME, rather than having a wider impact on the national and regional innovation system.

On the other hand, a number of the Catapult Centres have taken on a wider remit, developing human capital through vocational training, in manufacturing advisory services, and in various networking and sector development activities, even though this is not part of their core mission as originally defined.

Eoin O'Sullivan and I have argued[26] that there should be institutions that take such a wider role in developing innovation capabilities through technology diffusion, skills development, and the building of absorptive capacity are important for developing the weaker innovation systems that characterise those parts of the UK that economically underperform. The Catapult Centres could take on this role, given a formal widening of their remit – and additional resources.

3.7. Taking a look at the whole institutional landscape for R&D

It should be clear that the UK's institutional landscape for R&D is complex and has undergone big structural changes over the last few decades. The effect of these changes does not appear to have been thought through at the time they were initiated, and it isn't obvious that the system that is left is optimal given the expectations people have of science and innovation to deal with the problems outlined earlier.

The government is currently conducting a review of this landscape, led by the Nobel Laureate Professor Sir Paul Nurse, Chief Executive and Director of the Francis Crick Institute. This should report in the very near future, that will hopefully address several different problems, including:

- How best to do basic, discovery science
- How to get public sector research establishments working well to address cross-government priorities
- How to fill in the "missing middle" of applied research

- How to develop regional innovation systems to increase productivity in economically lagging regions
- How to support and grow private sector R&D

It is a good moment for change, with many conventional wisdoms dissolving. Given the consensus that the UK's R&D intensity needs to be substantially increased, it will be necessary both to expand and modify existing institutions and, perhaps, to create new ones. There will need to be a balance, however, of the current balance of institutions, and how that needs to change to meet today's challenges.

Part 4: Science priorities – who decides?

4.1. The broad flows of research funding in the UK

In 2019, total spending on R&D was £38.5 billion. The largest single contribution to this was from business, which spent £20.7 billion, mostly on R&D carried out in the business sector.

The government spent £10.4 billion, including £1.8 billion to support R&D in industry, £6 billion on university R&D, and £2.3 billion in its own laboratories.

Overseas sources of funding accounted for £5.5 billion. £1.5 billion of this overseas money went into universities; of this, its estimated around half of this came from the EU (and is thus properly thought of as originally coming from the UK government), with the rest from overseas companies, charities, and other governments.

Finally, £1.8 billion was spent by the non-profit sector, dominated by the Wellcome Trust and medical research charities such as CRUK.

It is worth adding two glosses to these official figures. Firstly, businesses receive a substantial subsidy for their R&D spending through the mechanism of R&D tax credits. These were worth £7.4 billion in FY 19/20[27]. Although there is not an exact alignment between the R&D tax credit statistics and the Business R&D statistics, it can be estimated, putting together the cost of tax credits and direct government funding of industry research, that roughly 35% of business spending on R&D is ultimately paid for by the state.

Secondly research carried out in universities is not fully funded by the government, but in effect is cross subsidised by other activities, especially teaching overseas students. It is difficult to precisely quantify this additional contribution to university-based research, but it's likely to be of order an additional £1 billion across the whole HE sector.

4.2. Who should decide what science is done?

Science funding is about making choices and deciding priorities. Who, in principle, should be making these decisions?

(a) *Scientists.* One view is that it is only that scientists who are in a position to judge the quality of the work of other scientists, and to make informed choices about what science should be done. This view underlies the prevalence of "peer review" as a mechanism for judging the validity and quality of scientific publications, and the practical procedures by which science project proposals are judged and ranked by science funding agencies. Typically, a project proposal will be sent to referees from the science community, who will make a critique of the proposal, and a panel will rank a set of proposals by reference to these referees' reports.

From a practical point of view, the argument is that it is only expert, practising scientists who are in a position to assess the novelty of a proposal in the context of the existing body of scientific knowledge, and who can make a judgement of a proposal's technical feasibility. The potential counterarguments are that reliance on the judgement of other scientists promotes conservative, consensus-driven research rather than projects with truly transformative potential, and disadvantages cross-disciplinary research, because of the difficulty of finding potential referees whose expertise ranges across more than one area.

This view was given an ideological framework by Michael Polanyi, who compared the international scientific enterprise at its best as a "market-place of ideas" in which the best and most profound ideas would naturally prevail. In this view any attempt by non-scientists to steer this "independent republic of science" is likely to be counterproductive and destructive. This point of view is popular with elite scientists.

(b) *The Government.* On the other hand, if the reason the government funds science is because it believes this supports its strategic objectives, then one can argue that the government should direct science in ways that support those objectives. In fact, over the last century and a half, this is exactly what has happened for most government supported science. The most pressing strategic goal behind which the government has directed science has always been military power; behind that at various times support for agriculture, for colonial activities, and for civil industry has also been prominent.

(c) *The people.* In a democratic society, the government's support for science should reflect widely held societal priorities. There is an argument that representative democracy doesn't provide a very effective way of translating those societal priorities into decisions on science funding, simply because so many other issues – health, crime, the economy etc – are likely to be much more salient in influencing citizens' votes. This makes the case for giving more direct forms of deliberative democracy – citizens' assemblies and such like – a role in setting science priorities.

Often this has been framed in a defensive way, to head off potential public opposition to controversial new technologies. But there is case for thinking of the direct involvement of citizens in setting priorities in a more positive way, challenging expert groupthink and bringing new perspectives to set a direction that commands widespread public support.

(d) *The market.* According to many economists, if you want to find out what people want, you should look at what they do, not what they say. In this view, the true test of whether people want some innovation is whether they buy it. Following Hayek, one can regard the market as the most efficient way of aggregating information about societal wants and needs. In this view, the government should simply step out of the way, and let private firms explore the space of possible innovations, with the market deciding which are successful and which not.

The difficulty with this view is that many radical innovations need large investments to get to the point at which they can be brought to market, with no certainty not just as to whether demand for them materialises, but as to whether they will work in the first place.

There is a more general point here; what works for applied research, with a clear and relatively short route to commercialisation, is likely to be less useful for more basic research, where any applications are highly uncertain, unpredictable and often don't manifest themselves for many years after an initial discovery.

4.3 What kind of science policy choices are being talked about?

In thinking about who makes decisions about what kind of science gets done, and who influences those priorities, different levels of decision-making should be distinguished.

There have been major strategic shifts – for example the shift from applied research to "curiosity driven" research in the late Thatcher government. In effect this involved shifts of many billions of pounds, and was driven from the centre of government, under the influence of a single powerful advisor (George Guise, in that case). The post-Cold War shift of emphasis from defence to health and life sciences was on a similar scale, though this is probably more difficult to pin on a single individual or agency.

On a slightly smaller scale, there are long-term strategic programmes, with funding at the level of hundreds of millions of pounds. Examples of this could include the fusion programme, recent initiatives on batteries and quantum technology, and the new funding agency ARIA. Here the initiative usually does come from some part of central government, with Government Chief Scientific Advisors and other influential policy actors (for example, in the recent case of ARIA, Dominic Cummings) often being a driving force.

Programmes at the level of tens of millions of pounds have generally been initiated by research councils, though they may form part of the research councils' pitch to government in the budget negotiations around spending reviews. Priorities at this level may emerge from the scientific community through the various advisory bodies that research councils draw on; there may also be an element of research councils anticipating what they think the government of the day is interested in, whether that is driven by formal government strategy documents or more informal interactions with key actors.

Within these programmes, it is the individual projects that are awarded to researchers that are awarded through peer review.

4.4 The "Haldane principle" and the political independence of science funding agencies

How closely should politicians be able to direct research priorities for government funded science? The conflict between the long-term nature of science and the short-term imperatives of electoral politics has long been recognised and makes the case for inserting some distance between science funding agencies and central government. It's not just in science that this conflict between the long-term interests of the state and short term electoral politics is recognised; the decision to give the Bank of England the power to set interest rates independently of the Treasury presents an analogy. In the UK, the symbol of this distance in science policy is a semi-mythical arrangement known as the "Haldane principle".

The Haldane principle is interpreted in different, often self-serving, ways by different constituencies. Some scientists interpret it as meaning that the government should have no involvement in any aspect of science policy, apart from signing the cheques. For government ministers, on the other hand, it legitimates their right to make big funding announcements while leaving operational details to others. The historian David Edgerton has stressed (see *The Haldane Principle and other invented traditions in science policy*[28]) its relatively recent rise to prominence in science policy discourse, and the fact that most government funded science has never been within its orbit.

The origins of the "Haldane principle" are purported to lie in an important and influential report[29] from Lord Richard Haldane published in 1918. This defined many of the principles by which the modern civil service is run, including principles for both the way state-funded science should be administered and the way scientific evidence should be used in government.

The principle that the government should be involved in science had been established in the late 19th century, through reports such as that of the Royal Commission on Scientific Instruction in 1870, and the establishment of institutions such as the National Physical Laboratory and the Laboratory of the Government Chemist. The First World War brought new urgency to government-driven science, both to meet the technological demands of the new industrial warfare, and to accommodate the medical demands of dealing with its terrible human cost.

This was the context of the Haldane review, which brought attention to the slightly ad-hoc way in which different government departments had ended up supporting scientific research in support of their various goals. The report focused on two new bodies that had arisen to deal with these pressures: the Medical Research Committee and the Department of Scientific and Industrial Research. In each case a pattern had been established – a minister taking responsibility, but with decision making devolved to a committee of experts, taking advice from a wider advisory council. This did set the pattern for something like a modern research council, and indeed the Medical Research Committee morphed into the Medical Research Council, which survived until its incorporation into UKRI in 2018. Other research councils – first the Agricultural Research Council, followed. But the focus of the Haldane recommendations was on the best way to bring expert advice to bear onto the problems of government, rather than any principle of scientific autonomy.

As David Edgerton has stressed, in the post-war period, the research councils were relatively small parts of an overall R&D system dominated by the requirements of the "Warfare State". One major innovation was the introduction of the Science Research Council in 1965, which first evolved into the Science and Engineering Research Council, and then was broken up following William Waldegrave's 1993 White Paper. This coincided with the big shift in UK where the state substantially withdrew from applied research. The 1993 White Paper did invoke a "Haldane principle" but reasserted a right for the government to make strategic choices:

"Day-to-day decisions on the scientific merits of different strategies, programmes and projects should be taken by the Research Councils, without Government involvement. There is, however, a preceding level of broad priority-setting between general classes of activity where a range of criteria must be brought to bear."

The government asserted much more direct control over the research system in the 2017 Higher Education and Research Act, which incorporated all seven research councils into a single organisation, UK Research and Innovation (UKRI). The act does give a nod to a "Haldane principle", which it defines in a rather diluted form:

"The 'Haldane principle' is the principle that decisions on individual research proposals are best taken following an evaluation of the quality and likely impact of the proposals (such as a peer review process)."

However, the act makes explicit where it thinks power should lie. Section 102 of the Act states, *"The Secretary of State may give UKRI directions about the allocation or expenditure by UKRI of grants received…"*, and, in case the situation isn't already clear enough, *"UKRI must comply with any directions given under this section."*

It can be argued government does have a right – indeed, a duty – to steer the overall science enterprise in support of the strategic goals of the state -the need to return to productivity growth, to manage the energy transition to Net Zero, to keep the nation secure in a hostile world, to support the health and well-being of its citizens. The government has given itself the power to do this.

The danger, though, is that nobody does the strategy, but that instead governments succumb to the temptation of micromanaging the implementation for short-term political advantage.

Part 5: Tax incentives for R&D

5.1 R&D tax credits

HM Treasury is now one of the UK government's largest direct funders of R&D, through the R&D tax credit schemes, which had a cost to government of £7.4 billion in FY 2019/2020[27]. This cost has increased dramatically in recent years – in 2010/11, it was just £1.1 billion, rising to £3 billion by 2014/15. This is as a result both of increases in the scheme's generosity, and of increases in take-up by business.

The way R&D tax credits work is that firms report their spending on R&D to the government, which partially offsets the cost of the R&D by reducing the amount of corporation tax the firm has to pay. Corporation tax is paid on the profits made by a company; this is potentially a difficulty for start-ups in the stage where they are investing money in R&D before significant revenues arrive. In these circumstances, where companies are not yet making a profit and are not liable for corporation tax, the government partially recompenses them for their R&D expenses with a cash payment.

The logic behind R&D tax credits is simple. Economists argue that firms do not capture all the benefits to society that doing R&D brings, so left to itself the private sector will invest less in R&D than is optimal for the economy more widely. R&D tax credits correct this market failure, with the state in effect paying for the spillovers that benefit the economy more widely. But, the argument goes, the market knows what people want better than the government, so it is necessary to funnel money directly to businesses seeking to exploit innovation to meet market opportunities that they have detected.

Supporting business R&D this way means there's no need for the government to make any decisions about what kind of R&D to support; there's no danger of being accused of trying to "pick winners". This means that the scheme is very cheap to administer, and there is no need for the government agencies to have any specialist expertise or to develop a strategy.

What are the downsides? One is that the scheme almost certainly has a significant deadweight cost – in effect, giving companies money for R&D they would have done anyway. There is a huge incentive for companies – and the industry of consultants that has grown up to help them claim this government money – to stretch the definition of R&D to include the kind of business as usual that isn't likely to generate much in the way of spillovers for the economy more widely. And, of course, there is a very real risk of outright fraud.

One strong signal that all is not right with the scheme is a growing mismatch between the total amount of business R&D that forms the basis for these claims, and the independent ONS estimate of Business R&D that comes from survey data. In 2014/15, R&D tax credits were claimed based on £24.4 billion worth of R&D, a bit more than ONS's estimate of £20 billion for business R&D. But by 2019/20, the comparison dramatically diverges: the ONS estimate for business R&D was £25 billion, but businesses told the taxman that they had done R&D worth nearly double that, £47.5 billion.

There are differences in definition between the two measures of R&D. For example, it is possible to claim tax credits for R&D that is carried out abroad. This does not make a lot of sense from the economic point of view. It is suggested that the ONS survey undercounts R&D in the financial services and insurance sector; this, however, accounted for only £3 billion (7%) of R&D expenditure for tax credits in the year ending March 2019. But neither of these factors seem sufficient to explain the gulf between the two measures.

A recent note from the ONS[30] concludes that the primary reason for the discrepancy is an undersampling of the small business population. On this basis, it has adjusted its previous estimate for business R&D substantially upwards – in 2020, the revision is from £26.9 bn to £43 bn. It's certainly possible that there is a population of small and medium businesses that have been carrying out R&D not captured by previous surveys, and ONS back this conclusion up with a detailed comparison of the microdata from the ONS survey and HMRCs returns.

On the other hand, the suspicion remains that the incentives of R&D tax credits have caused businesses to stretch the definition of R&D so they can get money for activities that are part of normal business (e.g. market research, working out how to use new equipment). The discrepancy between the level of business R&D implied by tax credit claims and that detected by the ONS survey hasn't remained static with time, as one would expect if it was simply a question of missing a population of firms who had always been doing R&D at a constant rate, but who have only just been discovered.

The gap has risen from £7.3 bn in 2014, to £16.6 bn in 2018. So for this explanation to hold, we need to believe not only that there is an existing population of SMEs carrying out R&D that has previously been undetected, but that this population has been substantially growing. One has to question whether R&D growth in the SME sector at a rate of £2.3 bn a year is plausible. One might expect to see an increase of this scale to have implications on the labour market for researchers, for example.

The incentives for businesses to stretch the definition of R&D, with the help of the growing population of specialist consultants, to claim free money are obvious. HMRC accept that some claims are outright fraudulent, estimating that 4.9% of the cost of the scheme is attributable to error and fraud. But there's a big grey area between outright fraud and creative interpretation of the "Frascati" definitions of R&D[31].

It seems likely that both factors are playing a role. The situation will become clearer once the ONS's new sampling methodology has produced a complete data set identifying the sectors and geographical locations of R&D performing firms.

The R&D tax credit scheme is currently under review by HM Treasury. Crucial background for this review is a recent paper by David Connell, *Is the UK's flagship industrial policy a costly failure?*[32]. (Connell's answer to his own question? "Yes").

But even if this kind of scheme was perfectly run, there is a more fundamental question. This approach to funding R&D in business leaves the choice of what research to do entirely to the businesses, with no attempt at all to align the spending with the priorities of the state. This makes it attractive for governments that do not have any priorities or strategic goals.

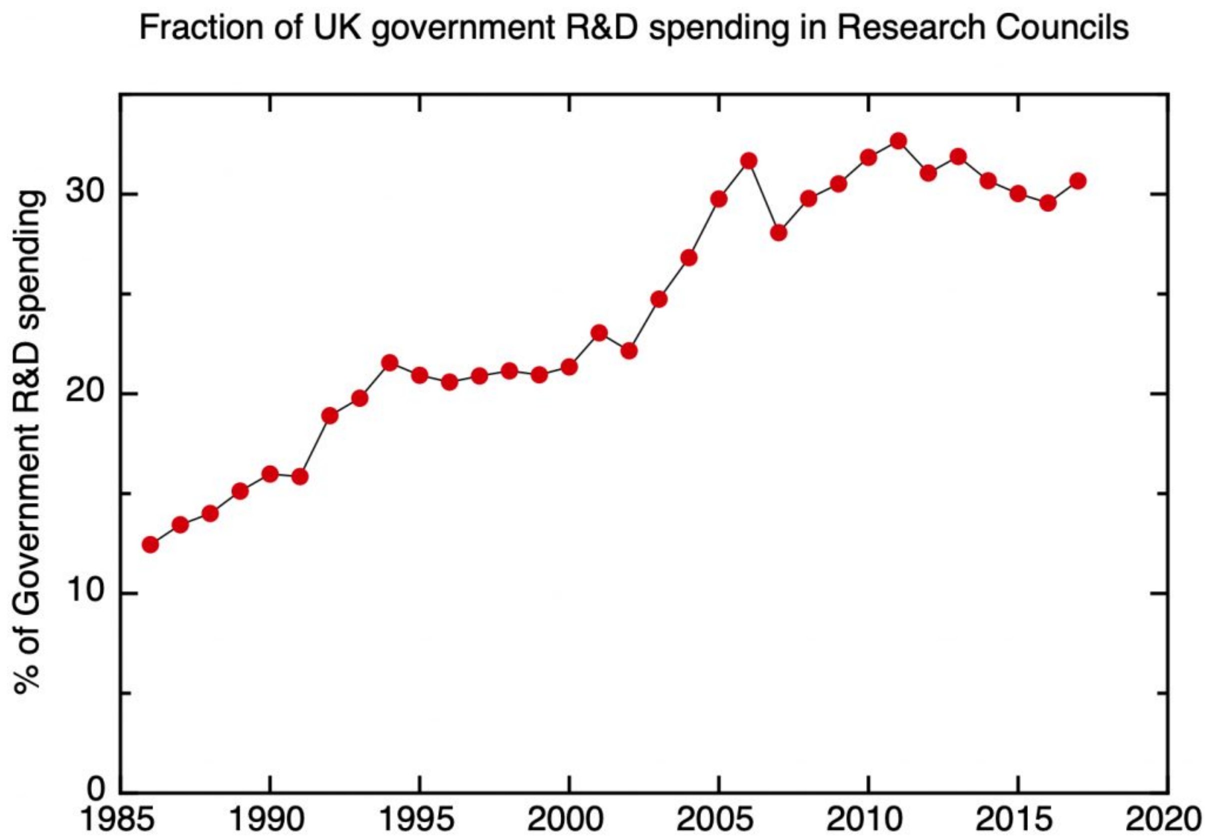
Part 6: UK Research and Innovation

This R&D funding system has seen substantial changes over the last few years, with the introduction of a new agency, UK Research and Innovation (UKRI), in 2018, and will see yet more in coming years, for example through the new agency, the Advanced Research and Innovation Agency (ARIA). The future of the UK's association with the European Union research funding programme, Horizon Europe, also remains in question which makes it timely to think about the funding system as a whole.

6.1 UKRI: the Research Councils

The 2017 Higher Education and Research Act created UK Research and Innovation (UKRI) as an umbrella organisation into which were folded the existing seven research councils, the innovation agency Innovate UK, and Research England, which looks after the higher education research system in England (though not in the devolved nations).

The Research councils arose as expert panels to advise government on how to fund research outside government departments. For most of the twentieth century, they constituted a relatively small part of the government's overall R&D effort. However, in recent years their relative importance in the system has grown – my plot shows the fraction of government R&D expenditure managed by the research councils from 1986 onwards. This shows a marked increase from 1986 to 1994, reflecting the rundown of government applied research in the late Thatcher period, and a further increase in the early 2000s, reflecting the New Labour government's simultaneous increase in research council budgets and decrease in departmental R&D budgets.



Fraction of total government R&D spending in the control of research councils. Data: ONS Research and Development expenditure by the UK government (2009 – 2019), BIS Science Engineering and Technology Indicators (before 2009).

As the research councils have become more dominant in the UK's research system, their visibility – and the expectations placed on them – has increased. This has led to a progressive widening in the range of organisational goals they have.

For most academic researchers, the core goal of the research councils is to keep research in the academic disciplines moving forward. The very organisation and naming of research councils reflects this; the seven research councils are arranged on a disciplinary basis:

- **BBSRC** Biotechnology and Biological Research Council
- **MRC** Medical Research Council
- **EPSRC** Engineering and Physical Sciences Council
- **STFC** Science and Technology Facilities Council
- **NERC** Natural Environment Research Council
- **ESRC** Economics and Social Research Council
- **AHRC** Arts and Humanities Research Council

The core mechanism for achieving this goal is called "responsive mode" – essentially, inviting proposals from researchers and seeing what comes in, allocating funding to the best proposals as judged by peer review. The difficulty of running an effective peer review process should not be underestimated – quite a lot of domain knowledge is needed to be find the right referees for a given proposal, and in putting together expert panels to rank a batch of proposals in a single sub-discipline on the basis of the referees' reports.

Much of the most innovative research is not to be found in single disciplines, though, but where the insights of different disciplines are brought together. But interdisciplinary research is more difficult to judge and support; there is always the potential for proposals to fall between the cracks. The cracks can be between the single discipline-based panels within research councils; for interdisciplinary proposals, it is all too common to find referees who will dismiss the part of the proposal they understand, while failing to see the added value that bringing together ideas and methods from different disciplines.

This is perhaps even more difficult for proposals that fall between the remits of different research councils, where the budgetary incentives are against such research. Take a proposal to apply machine learning to a problem in medical science; it is all too tempting for the MRC to say, this is all very interesting, but it's the business of the EPSRC to support machine learning proposals (and it should come from their budget), while the EPSRC says the same thing in reverse.

In the past, interdisciplinary proposals were handled through cross-council programmes overseen by the coordinating body RCUK. Most of these cross-council programmes were motivated by societal issues rather than academic priorities; they can be thought of as "mission-driven" research.

Following the formation of UKRI, the Strategic Priorities Fund was introduced to fund such proposals in thematic areas – my example would have fallen within the remit of "AI and Data Science for Science, Engineering, Health and Government". Over the current budget period, according to the recent UKRI allocations document (PDF)[33], the Strategic Priorities Fund is being wound down; there is not yet clarity in the recent UKRI strategy[34] how cross-council research will be funded in the future.

Research councils do not just respond to the demands of the UK's research community; they also actively shape the overall landscape. This is inevitable given their importance in the overall system; by what the Research councils choose to fund, they influence the priorities both of institutions and individual researchers. If a university perceives that a particular discipline is no longer in favour with the research councils, they will be less likely to recruit academics in that area, while the choices of research direction of individual researchers will be influenced by what they think they can get funded.

The influence research councils have on the research landscape is inevitable. The issue is how purposefully the Councils use it, and how much their choices are informed by any kind of larger national strategy.

Beyond their role funding individual researchers and groups in universities, the research councils are also responsible for maintaining hard and soft infrastructures. Hard research infrastructures include research facilities that are too large for an individual research group to manage – for example high performance computing, large scale neutron and x-ray sources, telescopes, and research ships; soft infrastructures, including large scale data sets and long-running observational programmes, are arguably less well cared for.

In addition, there are a number of national laboratories, often with very long histories, that have ended up under the care of individual research councils – for example the British Antarctic Survey and the British Geological Survey fall into NERC's stewardship, while the BBSRC's Pirbright Institute has been a leader in studying animal diseases for a century.

The issue here is that these institutes often have national strategic purposes distinct from the focus on the high-status discovery science that many in the academic community think should be the core function of the research councils. This puts the survival of these institutes in periods of tight budgets under pressure, and over the years a number of such institutes have shrunk, merged, or been transferred into the university sector, where they end up under inevitable pressure to conform to the norms of academic research. On the other hand, entirely non-scientific pressures to keep certain facilities funded can lead to political influences overriding scientific factors in decision making.

Research councils also play an important role at the upper end of the skills system, by supporting PhD programmes in universities. A high proportion of UK-domiciled PhD students are supported financially by the research councils, and recent years have seen this aspect of their work being put on a more formal footing, by the creation of "Centres of Doctoral Training", often in collaboration with businesses, where the research training that has traditionally formed the core of a PhD programme is combined with training in more transferrable and business-focused skills.

The role of research councils in driving economic growth has become much more politically prominent in the last couple of decades as their relative importance in the overall research system has grown. The case for sustaining science spending during the early 2010s period of austerity was based on its claimed importance for economic growth, and the increases in public spending that began in the May government were explicitly tied to the need to restore productivity growth to the UK economy.

The economic role of research councils operates both at a strategic level, shaping the research landscape to meet the needs of R&D intensive businesses, and at the operational level, encouraging research partnerships between academia and business in research projects and PhD training programmes, and promoting spin-out companies that use intellectual property created by the academic research they support.

This growth in prominence of the "impact agenda", as it has come to be known, has been unpopular with many academics, who interpret it as a shift away from basic, discovery science in favour of more applied research. But it is more accurate to see it in the wider context of the way much larger government applied research programmes were run-down in the 80s, 90s and 00s, and the perceived vacuum that left.

To sum up, research councils have the following core goals:

1. Advancing disciplinary-based research through competitively awarded research grants
2. Promoting interdisciplinary and mission-driven research
3. Shaping the UK's overall R&D landscape
4. Maintaining an infrastructure of research facilities and institutes
5. Driving economic growth by supporting research in collaboration with UK businesses and promoting spinouts exploiting IP developed through research they support
6. Maintaining a pipeline of highly skilled people by supporting PhD programmes

In balancing these goals, they need to satisfy four quite different constituencies:

- They need the research community, as the source of insights about the directions in which science and technology are heading, to provide the expertise that the peer review system depends on, and, most importantly, as the people who actually carry out the research they fund.
- But they have to respond to the government, as the organisation that writes the cheques, making the case for supporting research, in competition with the many more pressing political priorities that governments may have.
- If they are to be convincing in their arguments that the research they support contributes to economic growth, they have to work in partnership with the businesses that can turn research progress into new and improved products and services.
- And they must reflect the wider values of society.

It is a challenge to create a structure which maps onto this many goals, and which needs to respond to such a wide variety of stakeholders.

6.2 UKRI: Innovate UK

Besides the research councils, UKRI now incorporates the innovation agency Innovate UK. This was formed as a free-standing agency in the late 2000s, as the Technology Strategy Board, taking a number of funding instruments for R&D in business from the Department of Trade and Industry. Now it operates a combination of sector-based networking organisations (the Knowledge Transfer Networks), small scale collaborative grants for industry and academia (Knowledge Transfer Partnerships), and larger scale grants for business R&D (including the SME focused, responsive SMART grants). It also is responsible for core funding of the Catapult network of translational R&D institutions.

The key principle underlying Innovate UK is that it is "business-led". This puts clear water between it and the research councils, with their focus on funding research in universities. But it does lead to some tensions and dangers of its own. A close connection to businesses in R&D intensive sectors can lead to the danger of capture by incumbents and raises the question of who speaks for emerging companies and sectors.

It would be natural to think of Innovate UK as a vehicle for implementing an industrial strategy (and its original name – the Technology Strategy Board – reflects this). A good case can be made that its sustained support for the automotive sector has played a significant role in that sector's relative recovery.

But being perceived as an instrument of industrial strategy carries political risks. Innovate UK received a significant setback as an organisation in the first period of the 2015 Conservative majority government, when a Secretary of State opposed in principle to the idea of industrial strategy – Sajid Javid – imposed significant cuts and introduced a policy of replacing grants by loans.

A more fundamental question remains: who or what is a business-led innovation agency like Innovate UK for? One does not go far in discussions like this without hearing the phrase "UK plc", and the assertion that the role of Innovate UK is to make sure "UK plc" benefits from new technology.

But there is no UK plc. Fifty years ago, one might have talked about a national capitalism consisting of major industrial concerns based in the UK, quoted on the London stock market and largely owned by UK residents or their fund managers and pension funds. But that world was left behind in the 80s and 90s, when the UK embraced globalisation with an enthusiasm unmatched anywhere else.

Today, around half of the UK's business R&D is done by overseas owned firms; this is a very high proportion in comparison to other similar sized developed economies. Very few UK owned firms are to be found amongst world R&D leaders – according to the EU R&D Scoreboard, only two UK firms are in the world top 100, the pharma companies GSK and AstraZeneca.

Large UK technology intensive companies, like GEC and ICI, were broken up and sold in the early 2000s. Exit and entry of companies is not a bad thing in a dynamic economy, but the UK hasn't done well in sustaining and growing new companies. In ICT, the chip design house ARM was sold to the Japanese fund Softbank in 2016, while AI start-up DeepMind was bought by Google in 2014. In life sciences, the Cambridge spin-out Solexa, which developed the currently dominant technology for sequencing DNA, was bought by US company Illumina in 2007. A next generation sequencing technology has been developed by Oxford Nanopore, which remains a rare example of a non-software technology start-up determined to scale-up as a UK owned, UK based company, but its R&D investment remains about a factor of ten less than Illlumina's.

The trajectory of two privately held companies is instructive. The electrical goods company Dyson was founded in 1991, and while it maintains significant manufacturing and R&D presence in the UK, it moved its headquarters to Singapore in 2019, together with a significant fraction of its R&D and engineering effort. The chemical company INEOS emerged from a buyout of the commodity chemical operations of ICI and BP; it moved its HQ from the UK to Switzerland in 2010 for tax reasons. It did move its tax domicile back to the UK in 2016, but it is today a global company whose manufacturing and R&D are mostly now in overseas locations.

So, with the UK's industry base so dominated by multinationals with little or no natural allegiance to the UK, what is the role of a business-led innovation agency? Given the very high dependence of the UK's innovation system on R&D carried out by overseas owned firms, Innovate UK's role in attracting inward R&D intensive investment and keeping it anchored in the UK remains important. A focus on supporting new companies in scaling up is also crucial, but the possibility of these companies relocating to the USA or mainland Europe is a constant risk – and such a move may be entirely logical from a business point of view, by giving access to bigger markets and deeper ecosystems.

On the other hand, a new focus on resilience and security of supply, driven by the experience of the pandemic and much more threatening geopolitics, presents a whole set of new challenges for an innovation agency. While an attempt to retreat into some kind of "Juche UK" vision of self-sufficiency is obviously doomed, there may be a need to purposefully build industrial capacity in a few key areas where that capacity has been lost –already seen with vaccine manufacture. In this environment, Innovate UK may need move a little away from being business-led, and be more proactive in leading business.

6.3 Place based research and innovation funding

The UK's profound regional disparities in economic performance has been recognised by the government, with a commitment to an increase in R&D intensity outside the Greater South east being identified as "Mission 2" in the Levelling Up White Paper[35]. To support this, UKRI has been given a new organisational objective, to *"Deliver economic, social, and cultural benefits from research and innovation to all of our citizens, including by developing research and innovation strengths across the UK in support of levelling up"*.

This is a more significant change than it might appear, because in the past the key elements of UKRI have been committed to a "place blind" approach to funding. For the research councils, the primary consideration has always been "excellence", while Innovate UK and its predecessor the Technology Strategy Board has up to now, always focused on the innovation landscape at a national level. These agencies now have an instruction to *"increase consideration of local growth criteria and impact in R&D fund design."*

The one part of UKRI that does have a track record of thinking about local and regional innovation systems is Research England. Research England was formed in 2017 from the part of the Higher Education Funding Council of England that dealt with funding research in universities. As its name suggests, its writ runs only in England. Its function is devolved in Scotland, Wales, and Northern Ireland, exercised there respectively by the Scottish Funding Council, the Higher Education Funding Council Wales, and the Northern Ireland Executive's Department of the Economy.

Research England is responsible for the formula driven funding discussed earlier, it runs the "Research Excellence Framework", and then administers the formula by which the results of this exercise are converted into block grants to universities. In addition, it awards strategic funding for research infrastructure.

Research England has been responsible for delivering a specifically place-based funding mechanism, the "Strength in Places Fund". The aim of this is to support existing or emerging innovation clusters across the UK (including in the devolved nations). After two funding rounds, to a total value of £316m, UKRI has decided not to continue this scheme beyond the 12 currently supported projects.

This means the only currently open explicitly place-based intervention is the "Innovation Accelerator" pilot programme announced in the Levelling Up White Paper. In this, £100m is split between three city regions, Greater Manchester, Glasgow, and West Midlands, *"intended to boost economic growth by investing in R&D strengths, attracting new private investment, boosting innovation diffusion, and maximising the economic impact of R&D institutions."*

In practise, Innovate UK's Catapult Centres have played a significant role in developing regional innovation clusters. But this has happened largely in an unplanned way - developing regional innovation capacity has not been an explicit part of their mission, despite arguments it should be[26].

Finally, it is worth mentioning the important role the European Union's structural funds have played in supporting innovation activities in economically lagging parts of the UK, especially Wales, Northern Ireland, Cornwall, and parts of northern England. These funds will be partially replaced by the Shared Prosperity Fund, though it is still not clear how that will work in practise, and how much emphasis on innovation it will have.

6.4 UKRI four years on

UKRI formally came into being on April 1st 2018, a product of the 2017 Higher Education and Research Act; its formation was prompted by the 2015 Nurse Review[36]. But to what extent have the goals of the Nurse Review been realised?

The central recommendation that Nurse made was to merge the seven existing research councils into a single organisation. The research councils were government organisations, but with a degree of institutional autonomy conferred by their status as "Royal Charter" bodies. The research councils were formally independent of each other, but in practise they would present a common front to central government for spending reviews, and an umbrella organisation – "Research Councils UK" – acted as a coordinating body, developing joint interdisciplinary programmes.

The effect of the Higher Education and Research Act was to merge all seven research councils into a single body, with one accounting officer. Two other, rather different, organisations were also folded into the overall structure – Research England, with its systemic oversight and funding of research in English universities, and Innovate UK. The act imposes much more direct control from central government on UKRI than had been the case for the research councils.

What was the Nurse review trying to achieve? In part, it was to create a closer strategic connection between the research landscape and central government, with a single organisation being better able to engage with and influence departments across the whole of government. Other motivations were operational – *"reducing the complexity and increasing the agility of operations"*. There was a hope that a single organisation would reduce bureaucracy and strengthen governance.

But a key motivation was to break down the walls between different parts of the scientific endeavour – *"Establishing mechanisms to deal with cross-cutting issues such as the support of multi-disciplinary and inter-disciplinary research, grand challenges and the redistribution of resource between Research Councils in response to new developments, advances and priorities in the research endeavour"*.

How effective has UKRI been at achieving these goals? The government has just published an independent review of UKRI by Sir David Grant[37].

In short, there are findings both of operational shortcomings, and a lack of strategic coherence. One very worrying finding is a combination of high staff turnover with poor results from staff surveys - any knowledge-based organisation relies on the commitment of highly qualified and experienced staff.

The lack of strategic coherence is associated with a muddled organisational architecture. The Grant reports concern *"about the extent to which the board makes strategic decisions around the direction of UKRI which then translate into meaningful activity within the organisation. For example, there is little evidence that UKRI has made strategic decisions to prioritise particular goals and the bulk of spending has not shifted between different councils, activities within councils or activities across UKRI."*

The role of the "councils" of the constituent research councils is now not clear. Before UKRI was established, these were, in effect, the governing bodies of the individual research councils; in UKRI they are in effect advisory bodies to each council, but their role within the wider organisation isn't well defined: to quote the Grant review, *"across UKRI, there are over a hundred council members sorted by domain expertise but with no clear way to engage with UKRI strategic decision-making and governance and with uncertainty over if they need to"*.

How have these difficulties affected the way UKRI has operated? I would identify five key issues.

The first is the promise of UKRI to improve support for interdisciplinary research has not been realised. The Industrial Strategy Challenge Fund (ISCF), which did bring together research councils and Innovate UK in support of some interdisciplinary areas, had some successes, but is now being wound down. To quote the Grant Review again: *"the potential for interdisciplinary research has not been fully realised. The most successful example is the ISCF which put new money into the system to support inter-disciplinarity. In practice, with most councils' budgets committed into future years and systems that limit cross-council working, UKRI is unable to maximise the full potential for interdisciplinary research or transform the collective UK approach to this outside of specific programmes such as the ISCF."* Meanwhile, it was never clear how the eight themes and 34 (generally small scale) programmes supported by the Strategic Priorities Fund were arrived at, and this fund is now being wound down with no clarity on its successor.

The second is that there does not seem to have been much integration between Innovate UK and research councils. As the Grant Review says, *"the advantages of having Innovate UK within UKRI have not been fully realised. With the exception of specific programmes such as ISCF we note that there have been examples and pockets of joint working between councils and Innovate UK, however this was often driven by passionate individuals and not by a strategic plan."* Innovate UK's new plan for action[38] barely mentions the research councils, making few connections between its own technology priorities and the upstream science priorities of the research councils. Meanwhile the research councils have their own priorities for engagement with industry, both in the university research they support and in their own institutes and research campuses, but there is a risk that this is seen as being in tension with a lead role in innovation for Innovate UK.

The third is a patchy degree of connection between skills policy and innovation policy, which reflects some wider difficulties in policy in England (the situation is different in the devolved nations, though here a lack of high-level connectivity between UKRI and devolved nations causes other problems). The splitting of HEFCE into Research England, within UKRI, and a free-standing Office for Students, conceptualised as a regulator of higher education as a consumer service, means that no-one owns responsibility for the HE system in England as a deliverer of the skills needed for the innovation agenda. Historically Innovate UK has not regarded skills development as being part of its brief; there is some change here, with more involvement of the Catapult Network with regional skills systems, but this is hampered by the disconnect between BEIS and its agencies and a chronically neglected FE sector. Only in the provision of PhD training is there evidence of UKRI being able to take a more holistic view than its predecessors.

Fourthly, there still seems to be some lack of conviction within UKRI on addressing regional imbalances in R&D. If nothing else, the signalling does not look good. UKRI's only dedicated instrument for place-based R&D up to now, the Strength in Places scheme, is being wound down, with around £70m a year allocated for continuing funding of existing programmes. The three new "Innovation Accelerators" are allocated £50m a year, but only for two years, with no commitment to continuation beyond 2024-25 or to expansion beyond the three cities funded in the pilot scheme. These figures look like very small commitments in the context of an £8 billion a year budget. If the emphasis now is going to be on adapting existing programmes to deliver UKRI's new organisational goal, of *"developing research and innovation strengths across the UK in support of levelling up"*, there needs to be some clarity about how this is going to work in practice.

Fifthly, and a little more tentatively, there is a decreasing level of confidence in the wider scientific community in the ability of the research councils to run a credible peer review system, that does manage to support excellence in the core disciplines. One symptom of this is, perhaps, the great anxiety in the scientific community about the UK being cut off from the European Research Council, and the lack of confidence in the community that UKRI could run a credible replacement.

Finally, what are the broader implications of the way in which the Higher Education and Research Act removed the autonomy of research councils, giving government more direct control over them? The goal was to make the system more responsive to the strategic goals of the government, and in turn give the science community a stronger voice in influencing those strategic goals. But the risk was that it would hobble the research councils' freedom to operate and experiment, by imposing more Whitehall bureaucracy.

There has certainly been quite a lot of the latter. According to the Grant Review, *"UKRI reports receiving a high volume of ad-hoc requests from government"*, and *"UKRI has identified a non-exhaustive list of 40 different reports they must produce for government either annually, quarterly or monthly".*

The impression is of a whole set of extra hoops UKRI is made to jump through, absorbing management attention and creating friction and delays. Again, from the Grant Review: *"the business case for the second wave of COVID-19 funding went through UKRI approvals in a week, BEIS in two weeks and HMT in six weeks consecutively, which is less than ideal in an emergency response situation"*, and *"UKRI's SHARP programme must go through internal controls in addition to external assurance from four separate organisations (GIAA, IPA, BEIS Portfolio Office Gateway Reviews, CDDO) and approvals from BEIS commercial board, BEIS investment board, and ministers from BEIS, Cabinet Office and HMT".*

Yet there does not seem to be much evidence of a strong strategic connection to government priorities that is influencing the operation of UKRI. Once again, the Grant Review comments that *"there is little evidence that budget allocation advice from UKRI is made on a clear analysis of its goals and what the right allocation is to achieve those goals.*"

What has happened by the removal of autonomy, though, is that UKRI is more exposed than the research councils to rapid political shifts, due to the inability of recent governments to sustain consistent policy over the long term.

For example, in November 2020 the government announced that it was suspending the target of spending 0.7% of GDP on foreign aid. This led to large and abrupt cuts to UKRI's Global Challenges Research Fund, which supported collaborative R&D with developing countries in support of international development. This in turn led to many grants being cut-off in midstream, and substantial damage to the UK's international reputation as a reliable research partner.

One way in which there had been a connection between UKRI programmes and wider government strategy was through the Industrial Strategy Challenge Fund, which responded to priorities set in the 2017 Industrial Strategy White Paper and did bring together research councils and Innovate UK in support of some interdisciplinary areas. But this industrial strategy was in effect replaced in March 2021 by a Treasury driven "Plan for Growth", with a subsequent Innovation Strategy defining priority "technology families". The Industrial

Strategy Challenge Fund is now being wound down, with little clarity on what might replace it.

Perhaps there will now be a period of political stability, where long term priorities, informed by the science and innovation opportunities identified by UKRI, are set by government, and these in turn set long term directions for the UK's public research enterprise. Maybe the long-term missions and 2030 goals defined by the Levelling Up White Paper will form a basis for some of these directions. Perhaps the new National Science and Technology Council (about which, more later) will give a clearer way of connecting UKRI strategy with wider government priorities.

Part 7: UK Government Departmental Research

There is a tendency for analyses of the UK public R&D system to focus on the research councils that make up UKRI, because they are the most visible. But the UK government funds R&D in several other ways – for example through government departments.

7.1. Other departmental science

Despite the systematic shift of UK government supported R&D from government applied research to "curiosity driven" research in HE between 1980 to 2010, a substantial amount of government R&D is still routed through government departments, in support of those departments' priorities.

Departmental science has always been vulnerable to budget cuts. The effects of cutting a research budget will only show up at some unspecified time in the future, so the temptation will always be for a department to sacrifice science in favour of immediate operating expenses. The 2010-2015 policy of austerity produced some dramatic falls in already small departmental research budgets. For the environment, the DEFRA R&D budget fell by 58% in real terms between 2010 and 2015, to £82 million a year, and since then has fallen further to £58 million a year. Transport R&D experienced a 22% real terms cut, education 53%, and the Home Office 60%, over the duration of the Coalition Government. It is difficult to argue that all necessary innovation in these areas has already been done.

However, the biggest departmental spenders remain Defence, Health, and Business, Energy and Industrial Strategy (outside the latter's formal responsibility for the UKRI budget). These departments hold key responsibilities for the big challenges of productivity, energy/Net Zero, security and health.

7.2 The Ministry of Defence

The Ministry of Defence had a 2020-21 R&D budget of £1.1 bn, and this is expected to rise substantially as the overall Defence budget itself increases. In Defence R&D, there is a distinction between more long-ranged science and technology, and the expense of development and deployment of systems that are closer to application.

The 2020 Ministry of Defence science and technology strategy[39] committed to spending 1.2% of the overall defence budget on science and technology, under the control of the MoD Chief Scientific Advisor. The total defence budget is projected to increase from £41.2 billion in 2020-21 to £47.7 billion in 2024-25, so this implies a 15% increase in the science and technology budget, to £570 million. One should also mention rising sums of money for R&D in the security services – with an allocation of £695 million over 3 years.

It is inevitable that in a more threatening world, there will be a return to higher direct spending directly on R&D for defence in its broadest sense. So, the question now should be, are these increases enough, and are they directed in the right areas?

A recent article in Nature[40] highlighted some interesting comparisons. According to this, the USA spent about $80 billion in 2020 on defence R&D, a factor of 60-fold larger than the UK. The USA's economy is about 8 times larger than the UK, but this remains a massive gap.

A country that the UK would more commonly compare itself, both in the overall size of its economy and the importance it attaches to defence, is France. France spent €5.6 billion on defence R&D in 2020, more than four times the UK figure, despite roughly comparable overall expenditures on defence.

Definitions of the boundary between R&D and deployment make comparisons difficult, but it is tempting to interpret this as a consequence of France's traditionally more Gaullist approach to defence, preferring to develop its own systems rather than relying on allies. In an increasingly uncertain world, it is going to be important to get this balance right.

7.3. Department of Health and Social Care

As defence R&D was run down, the relative beneficiary was research for health and life sciences. One big institutional manifestation of this shift was the foundation in 2006 of the National Institute of Health Research, to bring together R&D funded directly through the Department of Health in association with NHS England. This remains distinct from the Medical Research Council, which is now incorporated in UK Research and Innovation; NIHR's focus on England means that the devolved nations have their own budgets. For health research, NIHR is now a major component of the public R&D system – in 2019-20 it spent £1.1 billion on research, infrastructure and research training, accounting for about 90% of DHSC's research spend.

The mission of NIHR is *"to improve the health and wealth of the nation through research."* This statement neatly encapsulates the twin goals of the UK's overall Life Sciences strategy, to improve the delivery of health and social care to the nation's citizens, on the one hand, and to support the pharma, biotech, and medical technology sectors on the other. These goals are often not sufficiently differentiated, meaning that the potential tensions between them are not resolved. On perspective is that NIHR's close relationship with the National Health Service should mean that NIHR's focus should remain on improving the health outcomes of the UK's citizens, with the support of any commercial opportunities that flow from this a secondary goal.

Health R&D was a big beneficiary of the 2021 Spending Review, and if NIHR's budget rises in line with the overall DHSC R&D budget, this should bring a £730 million uplift in NIHR funding compared to flat cash.

One issue that could be addressed in the context of this overall funding uplift is the geographical concentration of NIHR research, which historically has been even more focused on the Golden Triangle of London-Cambridge-Oxford (and, within that, on London in particular) than research council funding. In 2018, around 52% of NIHR funding went to London and the South East, with 35% of that in London, whose share of England's population is 16% (Source: UK Health Research Analysis[41]).

NIHR has a vision of a population *'actively involved in research to improve health and wellbeing for themselves, their families and their communities'*. It is obviously impossible to deliver this vision with such great geographical concentration, particularly given the mismatch between the parts of the country with the worst health outcomes and the geographical location of much of NIHR's research.

It's good, therefore, to see in NIHR's latest strategy document Best Research for Best Health: The Next Chapter[42], recognition that *'people in regions and communities where the burden of need is greatest are often under-served by research'*, and a commitment to *'Bringing clinical and applied research to under-served regions and communities with major health needs'*.

To achieve this will require the development of research capacity outside the Golden Triangle. It is good, therefore, to see a commitment to *'nurture new NHS and non-NHS research sites located in regions that have high health and social care needs and have historically been less active in research, introducing new initiatives to enhance their capacity and capabilities.'*

It is important that NIHR follows through on these welcome commitments as the UK's health inequalities are unacceptable in principle, but also a serious drag on the productivity of those regions where health outcomes are worst. The strengthening of existing and emerging clusters of life sciences and health technology industries outside the Greater South East will be an additional benefit.

7.4. Business, Energy and Industrial Strategy (excluding UKRI)

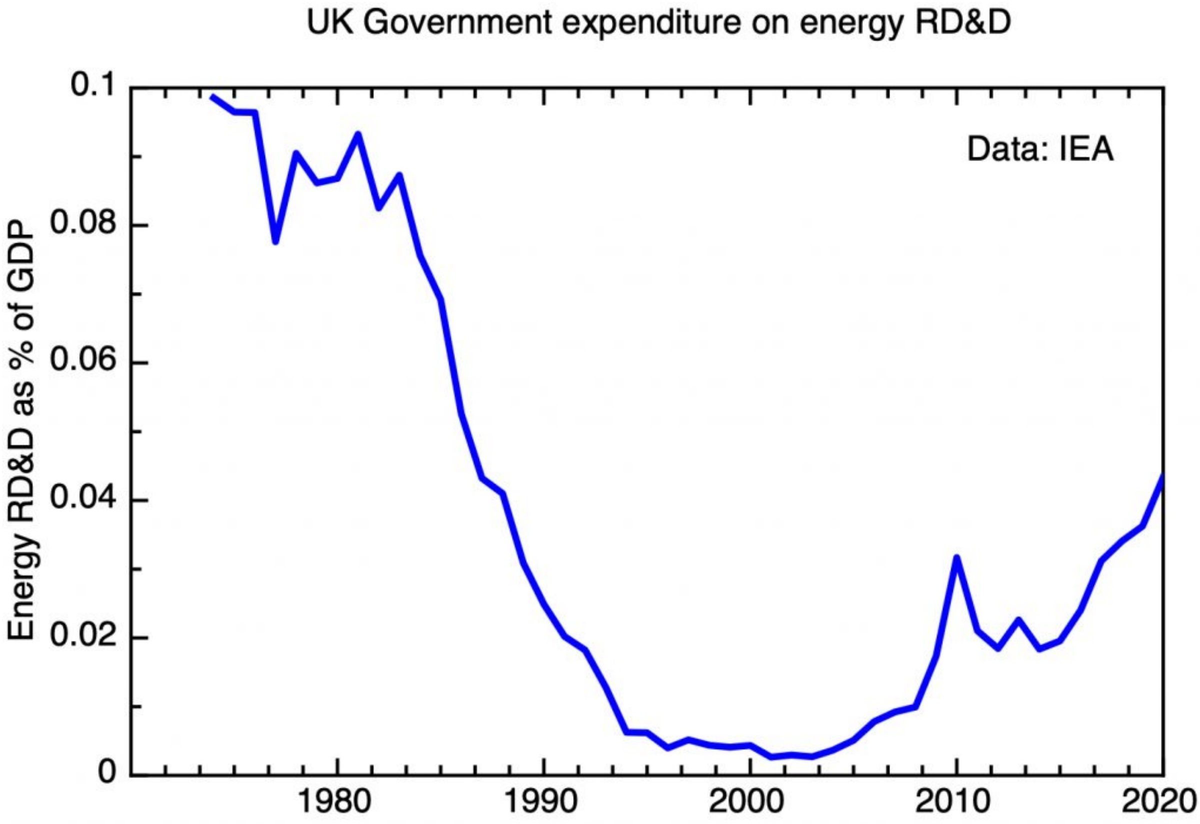
BEIS has the largest R&D budget of all departments, but this is because it is the official department sponsor for UK Research and Innovation. Nonetheless, it does have a significant R&D budget of its own, outside UKRI. In 2020, this amounted to just over £1 billion.

In part, this is used to support some important remaining components of state R&D infrastructure. The National Physical Laboratory is responsible for the standards and metrology that underpin commerce and industry, for example maintaining the national system for measuring and defining time accurately. The Met Office produces increasingly accurate weather forecasts, relying on the processing of massive amounts of data and high-performance computing, and is increasingly concerned with modelling the effects of climate change. The UK Atomic Energy Authority, much shrunk in scale since the 1980s, is now exclusively concerned with research to develop nuclear fusion as a source of electricity. UKAEA is one of the few remaining parts of civil government that retains the capacity to undertake large scale, complex engineering projects at the frontiers of technology.

As its name suggests, BEIS is responsible for applied R&D in support of industrial strategy. Following the 2017 White Paper, the government established "sector deals" in support of specific sectors, often involving R&D programmes jointly funded by government and industry. The Aerospace sector deal is possibly the most mature, with the Aerospace Technology Institute established as the vehicle for that joint research programme. The future of the "sector deal" approach seems to be in doubt now; the 2017 Industrial Strategy was superseded in 2021 by a new, HM Treasury driven, *Plan for Growth*, which turned away from so-called "vertical" strategy focused on specific sectors.

BEIS took over responsibility for energy and climate change in 2016, when the formerly free-standing Department of Energy and Climate Change was amalgamated with the department. Thus, it inherited the DECC R&D budget, which at that time stood at £47 million. Given the scale of the challenge of moving to Net Zero, and the need for innovation to make what will be a wrenching economic transition affordable, this seems a small level of funding.

It is worth stressing just how low the UK government's spending on energy research fell in the 1990s. The low point, of just £30 million, was in 2001. The scale of the collapse in state spending is made clear in the figure below, which shows total government spending in research, development and demonstration as a fraction of GDP. It is likely to have arisen from a combination of the complacency that arose from having discovered a large supply of oil and gas, and an ideological conviction that energy supply could and should be entirely left to the market.



UK government spending on energy research, development and demonstration as a faction of GDP. Data: International Energy Agency.

These totals include the UK Atomic Energy Authority's spending on fusion research, together with more upstream research funded by the research councils (mainly EPSRC). It's good that they are increasing again; the government now has a Net Zero Research and Innovation Framework[43] and a Net Zero Innovation Portfolio[44] supporting the UK Government's *"Ten point plan for a green industrial revolution"*.

Part 8: Horizon Europe (and what might replace it) and ARIA

The two most uncertain areas of UK government-funded R&D, are the future of the UK's participation in the EU Horizon programme and the new agency ARIA, the Advanced Research and Invention Agency, set up by Act of Parliament[45] in early 2022, and currently just establishing itself.

8.1. Horizon Europe – past participation and future prospects of association

In the past, the UK government has funded R&D indirectly through the EU Horizon programme, which provided research grants to UK researchers in HE and to UK businesses, often as part of larger collaborative programmes with researchers and businesses from elsewhere in Europe. EU research funding to UK universities and businesses has been on a very material scale; ultimately this money came from the UK's contributions to the overall budget. In the UK's national accounts, this was accounted for by a notional cost that reached a high point of £1.46 billion in 2019.

Because EU research money was allocated competitively, there was not a direct relationship between the money the UK put into the budget and the research money the UK received. In fact, because of the UK's relative research strength, the UK got back significantly more money than it put in. According to an analysis of the 2007-2013 cycle[46], the UK's indicative contribution to the budget was €5.4 billion, but it received €8.8 billion of funding for research, development and innovation.

After the UK decided to leave the EU, a consensus developed that the UK should seek to stay associated with the EU's R&D programmes, an option already taken up by other non-member states such as Switzerland, Norway, and Israel. The Trade and Cooperation Agreement[47] between the EU and the UK contained a draft protocol establishing the UK's association with Horizon Europe (with the exception of the European Innovation Council).

"The Parties affirm that the draft protocols set out below have been agreed in principle and will be submitted to the Specialised Committee on Participation in Union Programmes for discussion and adoption. The United Kingdom and European Union reserve their right to reconsider participation in the programmes, activities and services listed in Protocols [I and II] before they are adopted since the legal instruments governing the Union programmes and activities may be subject to change. The draft protocols may also need to be amended to ensure their compliance with these instruments as adopted."

If the UK does associate, it will need to contribute financially to the Horizon Europe programme. In contrast to the situation when the UK was a member state, when it received more back from EU R&D programmes than it notionally contributed, as an associated country it would need to cover not only the full cost of R&D activities funded in the UK through Horizon UK, but also a substantial additional overhead. The money for this was set aside in the 2021 Comprehensive Spending Review; it amounted to £1.3 billion in 2021-22, rising to £2.1 billion 2024-25.

As of late 2022, the draft protocol has not yet been finalised by the EU side, and given the wider political situation, it seems increasingly unlikely that it will be finalised any time soon. The UK government made a commitment at the time of the 2021 CSR that, in the event of the UK not associating, the money set aside would be retained in the science budget, redeployed in a set of programmes that reproduced the benefits of EU association – the so-called "Plan B". On July 20th, the government released more details of "Plan B"[48], restating the commitment to use the Horizon money for alternative science programmes.

"In the event we are unable to associate, we will use the funding allocated to Horizon Europe at the 2021 Spending Review to build on our existing R&D programmes with flagship new domestic and international research and innovation investments to support top talent, drive end-to-end innovation and foster international collaboration with EU and global partners."

8.2. The Three Pillars of Horizon Europe

The EU's R&D programmes are agreed for seven-year cycles; the current cycle – Horizon Europe – assigns €95.5 billion for the period from 2021-27. The overall goals of the programme are specified in terms of the strategic goals of the European Union – tackling climate change, meeting the UN's Sustainable Development Goals, and boosting the EU's competitiveness and economic growth.

To support these broad goals, Horizon Europe supports three pillars. The first of these is 'Excellent Science'. This includes the European Research Council, together with schemes supporting early career researchers and collaborative research and training for PhD students. The European Research Council supports investigator-led basic science and humanities research and this has a very high reputation in the scientific community. However, it is important to remember that it is a relatively small part of the overall Horizon programme – it's been allocated €16 bn in the current cycle.

The second pillar is for 'Global Challenges and European Industrial Competitiveness', which supports research collaborations built around sectors, challenges and missions. These typically involve both academic and industrial researchers in multinational collaborations.

The third pillar is new to the current cycle – 'Innovative Europe' is focused on developing more high-tech start-up companies, with a new European Innovation Council, a European Institute of Innovation and Technology, and support for regional innovation ecosystems. In the event of association, the UK will opt out of the "EIC accelerator" – that part of pillar 3 which provides investment funding to companies.

Underpinning the whole programme is an aspiration to create a European Research Area, with free and easy movement of people and research groups across the continent, lubricated by exchange schemes for scientists (particularly at early career stages) and cross-border transferability of grants. In the past the UK has benefitted from this, with a scientific and institutional infrastructure that has made the country an attractive destination for scientists from other European countries.

8.3. Why scientists love the European Research Council

Amongst elite scientists in the UK, the main driving force for an enthusiasm for the UK to associate with Horizon Europe is to be able to continue to participate in the European Research Council. This, in part, simply reflects how successful the UK has been in winning competitive funding through this route. For example, in the competition for the most established researchers – the Advanced Grants, which provide €2.5 million over 5 years for a single investigator and their team – UK based researchers won 22% of all grants between 2008 and 2020, compared to 16% and 12% to the two next most successful nations, Germany and France, respectively.

But beyond the self-interest of UK scientists, why is the European Research Council so highly thought of? It has a clarity of purpose, with a single-minded focus on investigator-driven basic research, with no predetermined priorities, but with an emphasis on supporting high risk/high gain proposals. It is correctly perceived as highly competitive, attracting proposals from the most outstanding researchers across Europe – currently its grantees have won nine Nobel prizes. Its decisions are made by a peer review process which is widely considered to be fair, rigorous, and well executed.

Peer review is not easy to do well. It can lead to conservatism and suppress radical new ideas and can suffer from credibility issues from the scientific community. So, what does European Research Council get right about peer review, while recognising that even the ERC's process is probably not perfect, for example in tricky areas like handling highly interdisciplinary proposals.

The ERC process involves committees of experts (and, to declare a personal interest, I recently served on the expert panel for Advanced Grants in my own field of Condensed Matter Physics). Those panels invite written comments on proposals from worldwide specialists they choose for their appropriateness to judge individual proposals. In a final meeting, the panels consider the referees' reports, with interviews with the proposers to give them the chance to respond to criticisms and come to a collective judgement about which proposals to give highest priority for funding.

What makes this work? The starting point must be high quality panels, with a good range of expertise, the ability to take a broad view, and an effective chair. At its best, the ERC has developed a virtuous circle, in which the high quality of the proposals means that outstanding scientists are prepared to put the time in to serve on panels, while in turn it is the credibility of the process that attracts applications from the best scientists from across a whole continent. It is the researchers on the panels who select the remote referees, using their knowledge of the field to select the most appropriate ones, and then applying their own critical scientific judgement to resolve any discrepancies and differences of opinion between referees. Sufficient time is set aside for in-depth decisions – a single proposal round will involve two panel meetings, each of which can take up to a week.

Meanwhile administrative support is provided by high-quality subject specialists working full-time for ERC as programme managers. In the UK, the research councils were forced to make serious cuts on their office staff in the early 2010s, because it was mistakenly believed that these subject specialists represented an administrative overhead, rather than being a precondition for the most effective allocation of R&D funding. This mistake should not be repeated (and, indeed, should be corrected).

8.4. "Plan B" for non-association

The "Plan B" document published in July 2022[48] usefully sets out some principles for how the money set aside for association with Horizon Europe will be used in the event that association doesn't materialise. But details of implementation remain sketchy, and delivery may prove challenging to the existing agencies and bodies that will be charged with executing these schemes.

These agencies are mostly in UKRI, with a particularly important role for Innovate UK, with the National Academies potentially playing a role in the "talent" schemes. These are largely fellowships at various career stages, that will in part fill some of the role of the European Research Council, though without the benefits of the institutional strength that ERC has developed, as outlined in the last section.

The emphasis of measures taken so far has been on stabilising the system, in particular keeping in the UK outstanding scientists who have been awarded ERC grants, but who cannot take them up without moving to an EU member state. The commitment has been made to guarantee the funding of any Horizon UK grant awarded to UK-based researchers for the lifetime of the grant. It is going to be important to ensure that this happens without bureaucratic hurdles, in perception or reality, as HE institutions in the EU will be making energetic efforts to recruit these researchers.

The last point emphasises the importance of making sure the UK remains an attractive destination for overseas scientists and promoting researcher mobility to make sure that the UK is centrally integrated in international networks of expertise. The plan here remains vague but states the intention to fund *"bottom-up collaborations with researchers in partner countries around the globe; multilateral and bilateral collaborations; and Third Country Participation in Horizon Europe"*.

Measures for supporting business R&D will be funnelled through Innovate UK; it seems these will largely build on existing schemes. The aim is to support both domestic and international collaborations. The international dimension will be particularly important in supporting high technology SMEs to participate in trans-national supply chains and innovation systems, many of which, of course, involve EU member states.

The local and regional dimension of support for innovation systems is also important. EU funding – including structural funding as well as direct R&D funding – has been important in developing clusters in economically lagging parts of the UK, such as Northern England, Wales, and Northern Ireland. The Shared Prosperity Fund is likely to offer only a partial substitute for EU structural funds, so it is encouraging to see a commitment to drive *"the development of emerging clusters throughout the UK"*, and the statement that the "Plan B" portfolio *"will support our mission of levelling up the UK and build on our commitment to increase domestic R&D investment outside of the Greater Southeast by at least a third over the spending review period and at least 40% by 2030.*"

Moving forward with the association of the UK with Horizon Europe would seem to require a breakthrough in wider EU/UK relations that currently does not seem very likely. In the absence of such a breakthrough, the priority needs to be for the new administration to confirm the funding of plan B and move very quickly to turn what are currently rather high-level plans into deliverable programmes.

8.5 The Advanced Research and Invention Agency (ARIA)

The most recent addition to the UK's R&D funding landscape is the new funding agency, the Advanced Research and Invention Agency. This was established by an Act of Parliament[45], finalised in early 2022. It was a personal priority of the Prime Minister's former chief advisor, Dominic Cummings, who emphasised the need to have a funding agency with the freedom to take big risks, modelled loosely on the US agency ARPA. ARPA was set up in the late 1950s to ensure technological supremacy for the US armed forces, and research it supported has underpinned world-changing technological innovations such as the internet, the satellite location system that GPS evolved from, and stealth aircraft.

The Act of Parliament establishing ARIA does indeed give a huge amount of latitude in defining its goals and modes of operation; much is left to the discretion of the CEO and the board. The major lever the government retains is the level of funding allocated; the initial commitment is to spend £800 million by 2024-25. This is a relatively small amount seen in the context of the £20 billion total R&D budget planned for same period. That leaves only two years to get some entirely new programmes off the ground.

The Act does give the Secretary of State powers of intervention on grounds of national security, and it is easy to imagine that these could be used quite widely. Nonetheless, there is some irony in the way the independence from government that was taken away from the research councils has been given to this new agency.

Given that the appointments of the Chief Executive and Chair have only relatively recently been announced, there is not yet clarity about what the new agency will do. My views about how such an agency should operate in a piece were in an article written in January 2020, *UK ARPA: an experiment in science policy*[49].

"If we want to support visionary research, whose applications may be 10-20 years away, we should be prepared to be innovative – even experimental – in the way we fund research. And just as we need to be prepared for research not to work out as planned, we should be prepared to take some risks in the way we support it, especially if the result is less bureaucracy. There are some lessons to take from the long (and, it needs to be stressed, not always successful) history of ARPA/DARPA. To start with its operating philosophy, an agency inspired by ARPA should be built around the vision of the programme managers. But the operating philosophy needs to be underpinned by as enduring mission and clarity about who the primary beneficiaries of the research should be. And finally, there needs to be a deep understanding of how the agency fits into a wider innovation landscape."

A starting point would be to recognise that pluralism and diversity in funding agencies is a good, and there is a need to innovate in the way innovation is supported. ARPA at its best represented an approach to funding where the focus was on the programme manager – or better, programme leader as the creative force. These leaders should be tasked with assembling and orchestrating teams of talented people to achieve ambitious programmes with concrete goals.

The archetype of the visionary leader is perhaps J.C.R. Licklider, who accepted a position with ARPA in 1962, because if offered an opportunity to realise his vision of computer networking. The research he funded at ARPA laid many of the foundations of modern computing, including the principles of networking that led to the internet, and the principles of human/computer interaction that were further developed at the XEROX PARC laboratory to give us the graphical interfaces that are taken for granted.

ARPA benefited from a complete clarity of mission – its role was to ensure that the US armed forces enjoyed technological supremacy over any potential rival. That makes clear who its beneficiaries should be – the US Armed Forces.

What should ARIA's mission be, and who are its beneficiaries? This remains to be decided, but it is important to make clear that its primary beneficiaries should neither be the academic community, nor industry. Both communities will be crucial in delivering the mission, but it should not be primarily for their benefit. Instead, it could be argued that ARIA should focus on one, or a subset of one, of the important strategic goals that the UK state currently faces, the most obvious candidate being is the challenge of driving down the cost of achieving Net Zero greenhouse gas emissions to a point where the global transition can be driven by economics, rather than politics.

Part 9: Science and innovation policy for hard times

9.1 Understanding the UK's place in the world: A "science superpower"?

The idea that the UK is a "science superpower" has been a feature of government rhetoric for some time, most recently repeated in the Autumn Statement speech[50]. What might this mean?

If superpower status was measured by the share of world resources devoted to R&D (both public and private) by single countries, there are only two science superpowers today – the USA and China, with a 30% and 24% share of science spending (OECD MSTI figures for 2019 adjusted for purchasing power parity, including all OECD countries plus China, Taiwan, Russia, Singapore, Argentina, and Romania). If we take the EU as a single entity, that might add a third, with a 16% share (2019 figure, but excluding UK). The UK's share is 2.5% – thus a respectable medium size science power, less than Japan (8.2%) and Korea (4.8%), between France (3.1%) and Canada (1.4%).

It is often argued, though, that the UK achieves better results from a given amount of science investment than other countries. The primary outputs of academic science are scientific papers, and an estimate can be made of a paper's significance by asking how often it is cited by other papers. So another measure of the UK's scientific impact – the most flattering to the UK, it turns out – is to ask what fraction of the world's most highly cited papers originate from the UK[16].

By this measure, the two leading scientific superpowers are, once again, the USA and China, with 32% and 24% shares respectively; on this measure the EU collectively, at 29%, does better than China. The UK scores well by this measure, at 13.4%, doing substantially better than higher spending countries like Japan (3.1%) and Korea (2.7%).

A strong science enterprise – however measured – does not necessarily by itself translate into wider kinds of national and state power. Before taking the "science superpower" rhetoric serious, it needs to be asked how these measures of scientific activity and scientific activity translate into other measures of power, hard or soft.

Even though measuring the success of UK academic enterprise by its impact on other academics may seem somewhat self-referential, it does have some consequences in supporting the global reputation of the UK's universities. This attracts overseas students, in turn bringing three benefits: a direct and material economic contribution to the balance of payments, worth £17.6 bn in 2019[51], a substantial subsidy to the research enterprise itself, and, for those students who stay, a source of talented immigrants who subsequently contribute positively to the economy.

The transnational nature of science is also significant here; having a strong national scientific enterprise provides a connection to this wider international network and strengthens the nation's ability to benefit from insight and discoveries made elsewhere.

But how effective is the UK at converting its science prowess into hard economic power? One measure of this is the share of world economic value added in knowledge and technology intensive businesses. According to the USA's NSF[52], the UK's share of value added in this set of high productivity manufacturing and services industries that rely on science and technology is 2.6%. This can be compared with the USA (25%), China (25%), and the EU (18%). Other comparator countries include Japan (7.9%), Korea (3.7%) and Canada (1.2%).

Does it make sense to call the UK a science superpower? Both on the input measure of the fraction of the world's science resources devoted to science, and on the size of the industry base this science underpins, the UK is an order of magnitude smaller than the world leaders. In the historian David Edgerton's very apt formulation, the UK is a large Canada, not a small USA.

Where the UK does outperform is in the academic impact of its scientific output. This does confer some non-negligible soft power benefits of itself. The question to ask now is whether more can be done to deploy this advantage to address the big challenges the nation now faces.

9.2. The UK cannot do everything

The UK's current problems are multidimensional and its resources are constrained. With less than 3% of the world's research and development resources, no matter how effectively these resources are deployed, the UK will have to be selective in the strategic choices it makes about research priorities.

In some areas, the UK may have some special advantages, either because the problems/opportunities are specific to the UK, or because history has given the UK a comparative advantage in a particular area. One example of the former might be the development of technologies for exploiting deep-water floating offshore wind power. In the latter category, there is the argument that the UK does retain an absolute advantage in researching nuclear fusion power.

In other areas, the UK will do best by being part of larger transnational research efforts. At the applied end, these can be in effect led by multinational companies with a significant presence in the UK. Formal inter-governmental collaborations are effective in areas of "big science" – which combine fundamental science goals with large scale technology development. For example, in high energy physics the UK has an important presence in CERN, and in radio astronomy the Square Kilometre Array is based in the UK. Horizon Europe offered the opportunity to take part in trans-European public/private collaborations on a number of different scales, and if the UK isn't able to associate with Horizon Europe other ways of developing international collaborations will have to be built.

But there will remain areas of technology where the UK has lost so much capability that the prospect of catching up with the world frontier is probably unrealistic. Perhaps the hardware side of CMOS silicon technology is in this category (though significant capability in design remains).

9.3. Some pitfalls of strategic and "mission driven" R&D in the UK

One recently influential approach to defining research priorities links them to large-scale "missions", connected to significant areas of societal need – for example, adapting to climate change, or ensuring food security. This has been a significant new element in the design of the current EU Horizon Programme (see EU Missions in Horizon Europe[53]).

For this approach to succeed, there needs to be a match between the science policy "missions" and a wider, long term, national strategy. In my view, there also needs to be a connection to the specific and concrete engineering outcomes that are needed to make an impact on wider society.

In the UK, there have been some moves in this direction. The research councils in 2011 collectively defined six major cross-council themes[54] (Digital Economy; Energy; Global Food Security; Global Uncertainties; Lifelong Health and Wellbeing; Living with Environmental Change), and steered research resources into (mostly interdisciplinary) projects in these areas. More recently, UKRI's Industrial Strategy Challenge Fund was funded from a "National Productivity Investment Fund" introduced in the 2016 Autumn Statement[55] and explicitly linked to the Industrial Strategy.

These previous initiatives illustrate three pitfalls of strategic or "mission driven" R&D policy.

- The areas of focus may be explicitly attached to a national strategy, but that strategy proves to be too short-lived, and the research programmes it inspires outlive the strategy itself. The Industrial Strategy Challenge Fund was linked to the 2017 Industrial Strategy[56], but this strategy was scrapped in 2021, despite the fact that the government was still controlled by the same political party.
- Research priorities may be connected to a lasting national priority, but the areas of focus within that priority are not sufficiently specified. This leads to a research effort that risks being too diffuse, lacking a commitment to a few specific technologies and not sufficiently connected to implementation at scale – one example being too much research in support of low-carbon energy.
- In the absence of a well-articulated strategy from central government, agencies such as research councils and Innovate UK guess what they think the national strategy ought to be and create programmes in support of that guess. This then risks lacking legitimacy, longevity, and wider join-up across government.

In summary, mission driven science and innovation policy needs to be informed by carefully thought through national strategy that commands wide support, is applied across government, and is sustained over the long-term.

9.4. Getting serious about national strategy

The UK will not be able to use the strengths of its R&D system to solve its problems unless there is a settled, long-term view about what it wants to achieve. What kind of country does the UK want to be in 2050? How does it see its place in the world? In short, it needs a strategy.

A national strategy needs to cut across a number of areas. There needs to be an industrial strategy, about how the country makes a living in the world, how it ensures the prosperity of its citizens and generates the funds needed to pay for its public services. An energy strategy is needed to navigate the wrenching economic transition that the 2050 Net Zero target implies. As the UK's health and social care system buckles under the short-term aftermath of the pandemic, and faces the long-term challenge of an ageing population, a health and well-being strategy will be needed to define the technological and organisational innovation needed to yield an affordable and humane health and social care system. And, after the lull that followed the end of the Cold War, a strategy to ensure national security in an increasingly threatening world must return to prominence.

These strategies need to reflect the real challenges that the UK faces. The goals of industrial strategy must be to restore productivity growth and to address the UK's regional economic imbalances. Innovation and skills must be a central part of this and, given the condition large parts of the UK find themselves in, there needs to be conscious efforts to rebuild innovation and manufacturing capacity in economically lagging regions. There needs to be a focus on increasing the volume of high value exports (both goods and services) that are competitive on world markets. The goal here should be to start to close the balance of payments gap, but in addition international competitive pressure will also bring productivity improvements.

An energy strategy needs to address both the supply and demand side to achieve a Net Zero system by 2050, and to guarantee security of supply. It needs to take a whole systems view at the outset, and to be discriminating in deciding which aspects of the necessary technologies can be developed in the UK, and which will be sourced externally. Again, the key will be specificity. For example, it is not enough to simply promote hydrogen as a solution to the Net Zero problem – it is a question of specifying how it is made, what it is used for, and identifying which technological problems are the ones that the UK is in a good position to focus on and benefit from, whether that might be electrolysis, manufacture of synthetic aviation fuel, or whatever.

A health and well-being strategy needs to clarify the existing conceptual confusion about whether the purpose of a "Life Sciences Strategy" is to create high value products for export, or to improve the delivery of health and social care services to the citizens of the UK. Both are important, and in a well thought through strategy each can support the other. But they are distinct purposes, and success in one does not necessarily translate to success in the other.

Finally, a security strategy should build on the welcome recognition of the 2021 Integrated Review[57] that UK national security needs to be underpinned by science and technology. The traditional focus of security strategy is on hard power, and this year's international events remind us that this remains important. But the resilience of the material base of economy cannot be taken for granted. There needs to be a better understanding of the vulnerabilities of the supply chains for critical goods (including food and essential commodities).

The structure of government leads to a tendency for strategies in each of these areas to be developed independently of each other. But it is important to understand the way these strategies interact with each other. There won't be any industry if there are not reliable and affordable low carbon energy sources. Places cannot improve their economic performance if large fractions of their citizens cannot take part in the labour market due to long-term ill-health. Strategic investments in the defence industry can have much wider economic spillover benefits.

For this reason, it is not enough for individual strategies to be left to individual government departments. Nor is the UK's highly centralised, London-based government in a position to understand the specific needs and opportunities to be found in different parts of the country – there needs to be more involvement of devolved nation and city-region governments. The strategy needs to be truly national.

9.5. Being prepared for the unexpected

Not all science should be driven by a mission-driven strategy. It is important to maintain the health of the basic disciplines because this provides resilience in the face of unwelcome surprises. In 2019, there was a lack of realisation of the importance of epidemiologists. Continuing support for the core disciplines of physical, biological, and medical science, engineering, social science and the humanities should remain a core mission of the research councils, the strength of UK universities is something to preserve and be proud of, and their role in training the researchers of the future will remain central.

Science and innovation policy also needs to be able to create the conditions that produce welcome surprises, and then exploit them, with experimentation in funding mechanisms and in institutional forms. Support needs to be given to creative and driven individuals, and to recognise the new opportunities that new discoveries anywhere in the world might offer. There needs to be flexibility in finding ways to translate new discoveries into implemented engineering solutions, into systems that work in the world. This spirit of experimentation could be at the heart of the new agency ARIA, while the rest of the system should be flexible enough to adapt and scale up any new ways of working that emerge from these experiments.

9.6 Building a national strategy that endures

A national strategy is not something that can be designed by the research community; it needs a much wider range of perspectives if, as is necessary, it's going to be supported by a wide consensus across the political system and wider society. But innovation will play a key role in overcoming difficulties, so there needs to be some structure to make sure insights from the R&D system are central to the formulation and execution of this strategy.

The new National Science and Technology Council, supported by the Office for Science and Technology Strategy, could play an important role here. Its position at the heart of government could give it the necessary weight to coordinate activities across all government departments. It would be a positive step if there was a cross-party commitment to keep this body at the heart of government; it was unfortunate that with the Prime Ministerial changes over the summer and autumn the body was downgraded and subsequently restored. To work effectively, its relationships with the Government Office for Science, the Council for Science and Technology need to be clarified.

UKRI should be able to act as an important two-way conduit between the research and development community and the National Science and Technology Council. It should be a powerful mechanism for conveying the latest insights and results from science and technology to inform the development of national strategy. In turn, its own priorities for the research it supports should be driven by that national strategy. To fulfil this function, UKRI will have to develop the strategic coherence that the Grant Review has found to be currently lacking.

The 2017 Industrial Strategy introduced the Industrial Strategy Council as an advisory body; this was abruptly wound up in 2021. There is a proposal to reconstitute the Industrial Strategy Council as a statutory body, with a similar status, official but independent of government, to the Office of Budgetary Responsibility or the Climate Change Committee. This would be a positive way of subjecting policy to a degree of independent scrutiny, holding the government of the day to account, and ensuring some of the continuity that has been lacking in recent years.

9.8 A science and innovation system for hard times

Internationally, the last few years have seen a jolting series of shocks to the optimism that had set in after the end of the Cold War. There has been a worldwide pandemic, there is an ongoing war in Europe involving a nuclear armed state, demonstrations of the fragility of global supply chains, while the effects of climate change are becoming ever more obvious.

The economic statistics show decreasing rates of productivity growth in all developed countries; there is a sense of the worldwide innovation system beginning to stall. And yet one cannot fail to be excited by rapid progress in many areas of technology; in artificial intelligence, in the rapid development and deployment of mRNA vaccines, in the promise of new quantum technologies, to give just a few examples. The promise of new technology remains, yet the connection to the economic growth and rising living standards taken for granted in the post-war period seems to be broken.

The UK demonstrates this contrast acutely. Despite some real strengths in its R&D system, its economic performance has fallen well behind key comparator nations. Shortcomings in its infrastructure and its healthcare system are all too obvious, while its energy security looks more precarious than for many years. There are profound disparities in regional economic performance, which hold back the whole country.

If there was ever a time when science could be thought of as being an ornament to a prosperous society, those times have passed. Instead, science and technology needs to be thought of as the means by which society becomes more prosperous and secure – and adapt science and technology systems so they are best able to achieve that goal.

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