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The road to 2.4 per cent

Transforming Britain's R&D performance

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This pamphlet is a statement of his personal views and not any organisation with which he is associated.

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> "This agreement between the political parties is a once-in-a-generation opportunity to set our science and research budget on a new path

Boris Johnson has a clear, strong personal commitment to science and technology. In every major speech he refers to the achievements of British scientists and technologists. This reflects an important strategic judgement that if Britain is going to make its way in a tough and competitive world then the quality of our science and research is probably the greatest single asset we have got. Before the general election his government had already made specific announcements of extra funding for life sciences and nuclear fusion. But even more importantly than that, it set out its commitment to reach 2.4 per cent of GDP going on science and research and development (R&D) by 2027. This is a massive boost from the 1.7 per cent of GDP where it has been hovering for the last decade.

This is part of a wider political consensus. Labour have committed "to build an 'innovation nation' and achieve a target of 3 per cent GDP spent on R&D by 2030." The Lib Dems have also committed to: "Protect the science budget, including the recent £2 billion increase, by continuing to raise it at least in line with inflation. Our long-term goal is to double innovation and research spending across the economy."

This agreement between the political parties is a once-in-a-generation opportunity to set our science and research budget on a new path. Back in 2010, I secured from the Treasury a flat cash settlement for science and research that was a lot better than the cuts which were proposed. But after a decade of flat cash, the core budgets of the Research Councils are now inadequate and an increase in these is a high priority. The increase in spending when UK Research and Innovation (UKRI) was created all went on funding for the new "challenges" with nothing for core capability. We must not repeat this mistake. There needs to be a substantial increase in the basic budgets of the individual Research

Councils covering a wide range of disciplines. But the increase in spending should enable us to do more than just this. It is an opportunity to tackle our crucial and widely recognised weakness in successfully applying our brilliant research, which has dogged us ever since the government first discovered the value of R&D during the First World War. The very first White Paper on the subject in 1915 observed that in Germany, "science there has been more effectively applied to the solution of scientific problems bearing on trade and industry".[1] But we are less effective at applying and commercialising science than doing the original upstream research.

This paper sets out how we can most effectively boost R&D spending, with a particular focus on how we can improve the application of research. Overall, the system should be well-balanced between the pursuit of fundamental understanding and of usefulness, though it is possible to combine both, as Donald Stokes argues with the vivid example of Louis Pasteur.[2]

Chapter 1 sets out the political and financial framework for the 2.4 per cent target. It is unusual in including both public and private spend, making it particularly important to design public policy to promote private spending.

In Chapter 2, I turn to the current pattern of spending and the structures which shape it. With public spend relatively low by international standards, we have ended up, either by accident or design, putting most of our limited research funds into universities so as to keep them world-class. This was the right strategy when public spending was limited, but the uplift in spending opens up the strategic question of whether to use the extra spending to fund more applied R&D outside universities. This might be a good way to tackle the challenge of promoting more application of our research.

One way of putting this extra funding to use would be a British DARPA (Defense Advanced Research Projects Agency). So, in Chapter 3, I look at what the American DARPA does and what a British DARPA could do.

Behind these institutional issues there is an underlying problem which needs to be tackled – a surprising lack of confidence in our ability to identify and promote key technologies. That is what the world's other major economies do and unless we tackle our inhibitions about doing this, we will not be able to make serious progress.

Finally, I include a summary of practical policy initiatives to ensure the extra money is well spent.

These proposals are intended to promote one of Britain's greatest single intellectual and cultural achievements – the vigour and creativeness of our research community. It stretches from Nobel Prize winners to technicians maintaining and developing the kit which makes their discoveries possible. It also covers a wide range of disciplines from history to particle physics. We get a window on the world from studying a foreign language or a creature's genetic make-up. One of the nightmares I had, when big cuts in research spending were proposed, was that we would end up having to make painful and damaging decisions to cut funding for whole disciplines. The proposed increase in R&D spend means that instead we can support excellent R&D across a wide range of disciplines. This is an asset to be protected. One of the distinctive strengths of our research base is its sheer range. This itself is an asset. These disciplines are inherently worthwhile, fulfilling the fundamental, human urge to understand and make sense of things. But it so happens they are also crucial to Britain's future prosperity, given that our research capacity is one of our greatest assets. They are crucial for any credible strategy for creating the wealth to boost our living standards in the future. We all depend on them.

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1. The 2.4 per cent target

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British total public and private spend on R&D stands at about 1.7 per cent of GDP. This is below the OECD average of 2.4 per cent and further behind leading economies which are heading to 3 per cent. Theresa May's government therefore announced in 2017 as part of its Industrial Strategy that it aimed to increase our spend to 2.4 per cent of GDP in a decade. The Johnson government has strongly supported R&D and the Chancellor repeated the commitment in his spending announcement of September 2019:

"The government is committed to increasing levels of research and development (R&D) to at least 2.4 per cent of GDP by 2027. In the autumn, the government will set out plans to significantly boost public R&D funding, provide greater long-term certainty to the scientific community, and accelerate its ambition to reach 2.4 per cent of GDP."[3]

The abandonment of the Autumn Budget followed by the general election have changed the timescale for decisions, but there is broad political consensus behind an increase along these lines reflected in the commitments in the party manifestos. The Conservative manifesto states:

"Once we have got Brexit done, we will turn our attention to the great challenges of the future such as clean energy and advanced energy storage; a cure for dementia; and solving antibiotic resistance. To do this we will make an unprecedented investment in science so we can strengthen research and build the foundations for the new industries of tomorrow. We are committing to the fastest ever increase in domestic public R&D spending, including in basic science research to meet our target of 2.4 per cent of GDP being spent on R&D across the economy."[4]

The Labour manifesto states:

"Targeted science, research and innovation will be crucial to tackling the climate crisis, dealing with the plastic waste filling our oceans and addressing other societal challenges, such as an ageing population and antibiotic resistance. As part of our plan to usher in a Green Industrial Revolution, Labour will create an innovation nation, setting a target for 3 per cent of GDP to be spent on research and development (R&D) by 2030. We will achieve this target by increasing direct support for R&D and reforming the innovation ecosystem to better 'crowd in' private investment."[5]

The Liberal Democrat manifesto states that they will:

"Increase national spending on research and development to 3 per cent of GDP. We will publish a roadmap to achieve this ambition by the earliest date possible, via an interim target of 2.4 per cent of GDP by no later than 2027."[6]

This is an extraordinary cross-party agreement on the need to boost spending. It means that we are very likely to see a substantial increase in total R&D spend, both public and private, from about £33 billion in 2016/17 to around £70 billion cash in 2027/28. It is ambitious by our historical standards but doable when we look at what other countries do.

International comparisons

2.4 per cent is the OECD average for R&D spend as a proportion of GDP, though major economies such as Japan, Germany and the US are above it. The only G7 countries behind us are Canada and Italy. The chart below shows that it involves a significant improvement in the UK's performance.

R&D INTENSITY IN OECD COUNTRIES AND OTHER ECONOMIES IN 2017

Country	Gross domestic expenditure on R&D as % of GDP
Korea	4.553
Sweden	3.397
Japan	3.213
Denmark	3.046
Germany	3.038
USA	2.788
Finland	2.757
France	2.185
China (The People's Republic of)	2.145
Norway	2.093
UK	1.664

SOURCE: OECD ESTIMATES BASED ON OECD MAIN SCIENCE AND TECHNOLOGY INDICATORS DATABASE, AUGUST 2019

The British performance may not be as bad as it appears because of the different structure of our economy, which explains some of the variance in R&D intensity. An important book by Jonathan Haskel and Stian Westlake suggests that intangibles matter and the UK may be particularly strong in these.[7] It is even harder to define R&D in service industries than in manufacturing. And when countries do poorly at boosting business spend on R&D this may be more to do with the structure of their economies than their exact R&D policies. Nevertheless, even after adjusting for the different structure of our economy UK R&D spend still lags behind some other economies, notably Sweden, France, the US and Japan.[8] The UK is one of the laggards.

By the beginning of this decade over 40 countries had R&D intensity targets. Many achieved underlying increases in R&D intensity between 2000-2016 although very few actually hit the target. One reason is that their GDP might rise faster than forecast – a nice problem to have. Another is that business investment underperforms.[9] However, 14 countries have achieved the 0.7 percentage-point increase in R&D intensity which the UK is aiming for – including in order of scale of increase: Korea, Israel, Finland, China, Singapore and Australia.[10] It can be done. Most notably, China set itself the aim of getting to 2.5 per cent R&D investment by 2020 and is on track to reach this.

> “The target of 2.4 per cent is unusual as it combines public and private spend

The best single performer is Korea, with the highest absolute increase in R&D intensity in any country since 2000. It has a very different industrial structure than the UK. As a medium-sized economy which cannot do everything, it has focussed on technological competitiveness in selected key areas. Germany has also done well with an explicit high-tech "5G Strategy for Germany". China set itself the goal of "global leadership in emerging technologies".

We have been here before

Gordon Brown as Chancellor announced a very similar target in 2004. The Science and Innovation Investment Framework set the aim of increasing R&D intensity from 1.5 per cent to 2.5 per cent in the decade to 2014. But little progress was made towards achieving it and in some areas we went backwards. Defence R&D fell over the decade. In 2010, I faced a Treasury proposal, which the Department for Business, Energy and Industrial Strategy (BEIS) had accepted, for a cash cut in science and R&D spend. I personally urged Treasury ministers and Number 10 not to do this. One of the key pieces of evidence I cited was work showing how public spending on R&D, notably through the Research Councils, boosted productivity in the private sector.[11] This helped secure at least cash protection for science and research spend, but that was a defensive operation – it did not move us forward.

The target of 2.4 per cent is unusual as it combines public and private spend, and the Treasury assumed a very favourable ratio of private spend to public spend which justified modest public spending increases which were not substantial enough to promote private spend. The incentives for policymakers here are peculiar. On the one hand BEIS justifies more public spend by showing very favourable crowding-in effects. But this in turn can lead to public spending being left so low that there is little progress towards the overall target. Some sceptics deny there is much crowding in if any which might mean that to achieve the 2.4 per cent target, the contribution from public spending would need to be even higher. There have been times, such as during the 1980s, when the doctrine was that public spend on R&D crowded out private spend and that the state was supporting R&D which should be undertaken by business.[12] This doctrine emerges from time to time though the evidence does not support it and it can do real damage as companies are reluctant to invest if they do not see any public support alongside them. Credible independent assessments do suggest a positive link between public and private spend, though the question is what the ratio between them might be and how we can improve the effectiveness of the public spend in boosting private spend. Indeed the Conservative manifesto states: "We will use our increased R&D funding from Government to attract and kickstart private investment."[13]

The Conservative briefing went further: "We will incentivise a step change in private sector R&D investment. Even with this huge public investment in R&D, we will need to incentivise much greater private R&D in order to meet the 2.4 per cent target. So we will introduce a new Challenge Led Innovation Procurement fund which will provide innovative firms with capital and launch an extension of the innovation loans pilot which helps improve access to finance for small businesses."

These programmes could be of value, provided that they draw on the evidence from the many initiatives that have already been tried, which have proved most effective.

An independent report commissioned by BEIS in 2015 is the best overall assessment we have of how public spend can promote private spend. Two measures score particularly well. Over a period of 10 years Innovate UK provided £2.2 billion of funding for innovation to over 8,000 businesses and organisations. Industry match funding took the total investment spend to over £3.75 billion. It has led to £7.30 Gross Value Added (GVA) for every £1 invested. Tax credits have also had a positive effect though not quite as dramatic as the Innovate UK programmes – £1 of public subsidy stimulating an additional £1.50 to £2.35 in R&D activity.[14]

Separately, Professor Jonathan Grant of King's College London and others analysed the returns on public funding for medical research. Again, they found substantial crowding-in effects and other benefits which they summarise as follows:

"Overall, every additional £1 of public research expenditure is associated with an additional £0.83–£1.07 of private sector R&D spend in the UK; 44 per cent of that additional private sector expenditure occurs within one year, with the remainder accumulating over decades. This spillover effect implies a real annual rate of return (in terms of economic impact) to public biomedical and health research in the UK of 15–18 per cent. When combined with previous estimates of the health gain that results from public medical research in cancer and cardiovascular disease, the total rate of return would be around 24–28 per cent."[15]

This is an encouraging backdrop to the discussion of how we get to 2.4 per cent as it suggests there are indeed public policy initiatives which can work.

The Conservatives have set out some more detail about the increase in spending, making it clear that there will be a substantial increase in public spending, saying:

"We will launch the fastest ever increase in domestic public research and development spending in British history. This will increase spending so that it reaches £18 billion in 2024-25. This will be a doubling of public R&D spending compared to 2017 and will be approximately 0.62 per cent of GDP, higher than the OECD average of 0.6 per cent and up from 0.43 per cent currently."[16]

Boom and bust

There is one other important lesson from surges in spending in other countries – there are lots of ways of wasting money as well. The US in particular is prone to a boom and bust cycle in science spending which can be very wasteful. Science policy in the US rests on a commitment to be ahead of the rest of world in technology. This means it has been susceptible to scares about technological challenges from successively the Soviet Union in the 1950s and 1960s, Japan in the 1980s and now China. Michael Teitelbaum's *Falling Behind: Boom, Bust & the Global Race for Scientific Talent*[17] is an illuminating study of the surges in spending followed by periods of treading water or real cuts.

We need to consider the capacity of the system to grow. There can be short-term supply constraints so it might be easier to deliver rapid progress in some areas rather than others. It takes years to get physical infrastructure up and running. But procuring kit can be done quickly. For example, the biggest constraint on the UK's performance in artificial intelligence (AI) and machine learning is probably access to the GPUs (graphics processing units) developed in the games industry, which have become key to machine learning because they are strong on quick calculations and less oriented to memory. But all of the UK's universities together have fewer GPUs than Stanford University. Getting more as part of a wider investment in e-infrastructure would be a great way to boost performance quickly. Investing in e-infrastructure for which there is a coherent and well-developed plan already could be moved forward quickly.

We can grow numbers of doctoral students in a few years. But how many are then going to be able to make long-term academic careers? We can expect many of them will go into industry or create businesses of their own (the more you have studied after university the more likely you are to create a business). But if this is not clearly signalled and they all think they are going to become professors, serious problems pile up, as was experienced in the US at the height of the Japan scare:

"Exceptionally bright science PhD holders from elite academic institutions are slogging through five or 10 years of poorly paid post-doctoral studies, slowly becoming disillusioned by the ruthless and often fruitless fight for a permanent academic position. That is because increased government research funding from the US NIH and Japan's science and education ministry has driven expansion of doctoral and post-doctoral education – without giving enough thought to how the labour market will accommodate those who emerge. The system is driven by the supply of research funding, not the demand of the job market."[18]

> One area where we can look to spend money effectively and promptly is where there is capacity in the business community

One area where we can look to spend money effectively and promptly is where there is capacity in the business community. Innovate UK recently reintroduced its popular and well-regarded SMART awards for innovation in business. The demand has been so great that the success rate for getting funding has been as low as 5 per cent. It is very wasteful to have so much time and effort put into unsuccessful bids. Many of the bids from companies are of good quality and meet all the Treasury and BEIS criteria but the financial constraint means they cannot be funded. Increasing funding so that more quality bids succeed would make a lot of sense. **That would mean increasing annual spend on SMART awards from £100 million a year to perhaps £400 million.** There are similar academic research proposals which pass the quality threshold but cannot be funded by Research Councils – though there are of course supply constraints if academics are submitting many more bids than they could actually do because the success rate is so low. Increasing success rates here when there are already projects deemed fundable would make a lot of sense.

There have been times in the past when we had world-class infrastructure which could not be fully used because there was no money to pay the electricity bill – just as any parent knows there are tears at Christmas when there is a wonderful new bit of kit but batteries are not included. Current spending can be deployed quickly to get the most out of previous capital spending before new capital investment can be provided.

> "If we have built capacity in a discipline then there is an argument for sticking with it rather than writing it off

And there is some path dependency here – if we have built capacity in a discipline then there is an argument for sticking with it rather than writing it off. It is frustrating when there has been systematic investment in capacity, and it is rejected for new funding just because of the need for change or just because of funding pressures. Synthetic biology is regularly cited by the Prime Minister, but our fantastic network of synthetic biology received a five-year funding settlement and that is coming to an end because they do not neatly fit into the previous government's list of key challenges, so they need new support urgently. Losing them would be wasteful and would risk our lead in one of the key technologies of the future. The Science Minister Chris Skidmore has therefore rightly proposed addressing these types of problems by suggesting a funding settlement based on a long-term framework for growth in spending. This would make a lot of sense as it would make proper planning possible.

2. How the current model works

2. How the current model works

We all know the problem – we have great universities and win Nobel Prizes, but we don't do so well at commercialisation. This is not some peculiar puzzle: it is the direct result of the pattern of our public funding for R&D and the incentives we have created. Changing these within a fixed budget is hard but the commitment to growing R&D spend to 2.4 per cent of GDP is a real opportunity to tackle it.

> With public spend on R&D much lower than in other major Western countries we have put all our eggs in one basket – the university

Major Western countries devote about 0.4-0.5 percent of GDP to public spend on R&D in universities and the UK is in the middle of this pack. They then devote almost as much, about 0.3-0.4 per cent of GDP, to public spend on R&D outside universities – in national research labs, business-facing applied research institutes and funding research in businesses themselves. But the UK comes in with much lower total public spend on R&D by cutting this to 0.1 per cent of GDP – a third to a quarter of the level of our major competitors. With public spend on R&D much lower than in other major Western countries we have put all our eggs in one basket – the university. That has probably been the right strategy in our constrained circumstances. The table on the next page, from my book *A University Education*, shows the difference between the UK's allocation of funding and other major countries.

Our world-class universities are one of our greatest national assets. But having them so dominant distorts our national R&D because of the distinctive incentive structure for university academics – the emphasis on academic publication as the crucial measure of performance, for example. It is one reason for our poor performance in applying research and using it to grow big new companies.

We need to do two things: we can try to change the culture in universities in some specific respects, but above all we need to promote more applied R&D outside the university. It would be wrong to do this by cutting research funding for universities who face their own funding pressures and must remain a key part of the ecosystem. In particular, public research grants only cover 80 per cent of the full economic costs of research, hence the need for universities to cross-subsidise research, from international student fees for example. Tackling this by moving to funding of 100 per cent of full economic costs would be an important way to help universities. But that is only part of the picture. The government's commitment to increase total spend on R&D to 2.4 per cent of GDP is the best opportunity in a generation for a wider pattern of provision. We will look at the key features of the current system which have ended up narrowing the range of what we do.

TYPES OF R&D AS % OF GDP

	United Kingdom	France	Germany	United States
Total Gross Expenditure on R&D (GERD)	1.7	2.26	2.84	2.74
Business Sector R&D (HERD)	1.1	1.46	1.93	1.94
Higher Education R&D (HERD)	0.44	0.46	0.49	0.39
Government R&D (GovERD)	0.13	0.3	0.42	0.31

The dual funding model is regarded as one of the distinctive strengths of British research funding. It means that the bulk of the science or research budget is allocated in two ways. There is Research Council funding, which tends to be for projects and programmes, and secondly funding from Research England for universities based on their performance in the Research Excellence Framework (REF). It can be thought of as transactional project funding from the Research Councils and patient institutional funding from Research England.

We are so proud of this dual funding model that it has obscured a significant omission – there is little high trust funding for institutions outside universities. The Research Councils can fund research institutes, but the pressures on their budget mean that they focus mainly on projects. Moreover, they don't want to have permanent commitments to institutes that they are obliged to carry on funding, regardless of the quality of the institute's research. They are always looking around for the smart new performer. No institute can presume that they will get funded by a Research Council in the future just because they were funded in the past – with the possible exception of the extraordinary Laboratory of Molecular Biology in Cambridge. More usual is the treatment of the Constitution Unit at UCL which was doing a fantastic job but after two five-year funding settlements lost its core Research Council funding. This is a striking contrast with Germany or the US where there are much more substantial networks of non-university research institutes. So, there is a funding gap – we have dedicated funding for universities as institutions but not for non-university research institutes.

This is not the only feature narrowing the diversity of Britain's research ecosystem. Victor Rothschild's report in 1971 proposing the customer contractor model of applied research funding led to a reshaping of British R&D policy. Basic or fundamental research would be the responsibility of the Research Councils and the science budget. They were protected by the Haldane principle that ministers did not intervene in specific decisions on research funding. Applied research was different and government departments were to be the customers, buying applied research. The idea is that if you want research on social mobility for example, the Department for Education should be funding it. The Ministry of Agriculture was supposed to fund applied research on agricultural innovation. The Heath

Government took money from the Research Councils to go to departments to purchase applied research. But over the subsequent decades departments proved to be very poor protectors of their own R&D budgets. They behaved like short-sighted British businesses cutting their R&D budget whenever they were under financial pressure. As the customer who is supposed to be purchasing R&D regularly cuts their budget, that leaves behind only the science budget which is allocated under a different model and protected behind the Haldane principle. It means the science budget is under pressure to fill the gap in applied research left by departments. The only department which has ended up good at applying research is the Department of Health which after a great deal of trial and error has ended up with a £1 billion NHS applied research budget and an effective model for coordinating it with the Medical Research Council's rather more upstream research funding.

There is one more twist to this. The minister who received Rothschild's report was none other than Margaret Thatcher who was then Secretary of State for Education and Science. Some time after she arrived in Number 10, in the mid-1980s, the Rothschild doctrine that applied research requires a customer, was taken to its next stage. Business not Whitehall was to be the customer. The argument was that businesses should be buying applied research. Near-market research was the responsibility of business, and government should be focusing on upstream scientific research in the science budget. This was based on the belief that departmental applied research budgets were being poorly spent because they did not have market disciplines. So instead, companies become customers, and departmental R&D budgets fell yet further.[19] There are still ministers who do not believe as a matter of principle that their departments should be funding applied research. They believe the only role for government is to fund blue-skies research. This doctrine creates the funding gap called the "Valley of Death". It means public spending stops long before applied research is commercially viable.

Agriculture is a good example of the problem because Rothschild had previously been the chairman of the agricultural research council. The MAFF R&D budget was cut over decades to close to zero and you can see the effect. Britain used to be a world leader in agriculture. But applied R&D in agriculture has been close to zero and improvements in agricultural productivity in the last decade are close to zero too. I persuaded George Osborne to fund a £180 million agri-tech initiative to try to reverse that. We had the Department for Environment, Food and Rural Affairs as a partner but did not give them the budget for fear they would cut it as soon as their departmental budget came under pressure. Some of these applied R&D budgets could have been spent in universities of course – shifting the balance of their activities as a result.

All this leaves a massive gap between the pure science that is publicly funded and the kind of applied, immediately valuable R&D that companies are willing to pay for. That makes it hard for government to work constructively with the private sector to promote the development and application of new technologies. By contrast that is exactly what is done by German Fraunhofer institutes and leading departmentally funded labs in the US.

There are a small number of public sector research establishments which have nevertheless survived. Some of them are owned and operated by Research Councils and some owned and operated by departments. They fulfill a very important range of functions, which may not be the same as doing brilliant upstream research. The British Geological Survey for example is a fantastic resource, which keeps geological samples. They helped industry identify sites which might be suitable for fracking and if that is to be accepted again in the future it will be on the basis of a full understanding from geologists of earthquake risks. The National Physical Laboratory in West London is our custodian of measurements and standards.

But these public sector research establishments are in the public sector, unlike universities which have the good fortune to be in the private sector. This makes it very tough for them. They are, for example, bound by public sector pay rules whilst the university can participate in an international competitive market for researchers without that constraint. Pay rules in the public sector are a major problem for our research institutes. They were granted some increase in freedom to run their affairs by us in the Coalition, but these have since been reversed so the amount of Whitehall supervision has increased, threatening their performance. There is regular pressure to privatise them, so they end up as contractors dependent on specific research grants for their survival and their core capabilities are hollowed out – this happened to nuclear research for example. The best thing that you can do as a research institute in these circumstances is to find a way of being embraced by a university, where you miraculously escape the public sector and the vagaries of departmental politics. But universities change too; they have new policies; a new Vice Chancellor comes in and isn't interested in the same thing as their predecessor; the sexy research topic is elsewhere. Applied research institutes linked to universities, such as the excellent Advanced Manufacturing Research Centre linked to the University of Sheffield do not therefore enjoy the long-term stability of a Fraunhofer Institute in Germany. And whilst universities want these research institutes to boost them in the research rankings, they don't necessarily survive in the long run in a university environment. Recently there has been a very welcome recognition of this issue in a report from the Government's Chief Scientific Adviser.[20]

"We have ended up with an unusually thin network of free-standing research institutes

We have ended up with an unusually thin network of free-standing research institutes. Other countries maintain and grow their network of departmental research labs, for example America's network of Department of Energy labs and the Department of Defense. Germany has a fantastic network of Max Planck, Helmotlz and Fraunhofer Institutes. Ironically Germany's network of Fraunhofers was modeled on Britain's own post-war network of research associations who set up their own research agencies. Many of these research institutes were closed down in the 1970s and 1980s as the world moved on. Some survive in various forms, often with only the "RA" at the end of their name revealing their origins. MIRA, the motor industry research association, now belongs to a Japanese company. FERA, originally the Food and Environment research agency, has been partly privatised.

Three factors have therefore been very important in shaping the British environment:

- little funding for non-university research establishments because they do not fit neatly into the dual funding formula;

- no applied R&D budget because it's been the responsibility of departments who, over the years, have cut it back;

- heavy-handed Whitehall control over public sector research establishments leading to a weak network of national labs doing applied research.

That is the institutional problem behind our weakness in applied research. Germany and the US are very different. If you are working in a specific branch of German industry you are very likely to know a prominent research establishment, a Fraunhofer institute, doing applied research that is relevant to you. It has probably been around for decades and it is accessible to you. You can co-fund projects with it that are directly relevant to your business.

The unusual pattern of R&D activity in the UK inhibits applied research and commercialisation of technology. Most of the public money for research is going into universities which are autonomous private sector institutions. They provide a good environment for creative scientific research, but we have a very thin ecosystem of research establishments outside universities. That is one reason why applied research is harder to do. That so much of our research is based in our universities is good for our universities in the rankings, compared with other countries where the universities are a smaller player in overall R&D. But this model may be bad for innovation. There isn't some vague cultural problem that we are risk averse and do not want to apply research. It is rational behaviour given the set of incentives and institutional arrangements in this country. It is a result of the British model which has emerged as a result of policy decisions in the post-war period.

So, what can we do to promote innovation and applied technology in this environment? There are two approaches. One is to look at the kind of things you can do with universities to promote commercialisation and the application of technology. The second approach is to create a richer ecosystem with funding streams and institutional relationships that promote commercialisation outside the university environment.

Change within universities

For a start we need to try to shift the culture within universities. That is not to suppress blue-skies research but to match it with doing more to promote the successful application of this research. A new metric developed by the Lens calculates the citations of university research articles in patents owned by third parties. The UK has only one university in the global top 50 – the University of Dundee at number 26. Cambridge is next at number 51. Our universities are not the drivers of innovation they should be.

Here are three things government could do to change the pattern of incentives within universities. First, we have too many university spinouts and start-ups. This is because they are seen as a key metric of university success in promoting innovation. We actually have a higher rate of start-ups per $1 million of public R&D spend than the US. This is bad news. Projects which really need to stay in the academic lab for longer are spun out too soon without the funding or the professional management in place to ensure they thrive. They are research projects masquerading as companies. A lot of fledglings are pushed out of the nest when they are too vulnerable to survive. Moreover, as the work is still so close to original research, the academic inventor stays involved and tries to run the start-up despite lacking business expertise. These small fragile companies are hard to scale up. **Ministers should make it clear that university spinouts and start-ups are not a good way of measuring a university's performance in promoting innovation.** Contracts with outside businesses, for example, are an equally valid metric. This would be a very important signal from government.

> MIT does not try to pin down large equity stakes – it makes more money from the sale of its t-shirts than from stakes in spinouts

Secondly, the real fear in universities is not of failure but of success: they are terrified that one of these start-ups will end up worth a lot and they will be criticised for not owning enough of it. As a result they play a very aggressive game on IP ownership deterring commercial investors. The US has the Bayh-Dole Act providing a legal framework in which universities get to own IP from their publicly funded research, but they are then more pragmatic and reasonable about doing deals than British universities. MIT does not try to pin down large equity stakes – it makes more money from the sale of its t-shirts than from stakes in spinouts. MIT tends to go for a maximum stake of 10 per cent whereas Oxford goes for up to 50 per cent (MIT also focuses more on licensing technologies including to big companies rather than taking equity stakes in new start-ups). Our network of tech transfer offices is of mixed quality and needs to be given a clear message that **universities should not go for such big stakes in companies created by their academic staff**. There is no direct power to instruct universities on the stakes they take but nevertheless just monitoring it and publicly pressing for change could have an effect.

Thirdly, the Research Assessment Exercise of university research was first introduced in the 1980s. Now renamed the Research Excellence Framework, the REF has transformed the productivity of our university-based research. But it is based on a classic academic picture of research excellence – internationally significant research publications. The Coalition tried to offset this by requiring a proportion of REF submissions to show impact and this has probably helped but at the expense of more bureaucracy. Meanwhile in our prestigious Russell Group universities, academic promotion is driven by publication in the most research-intensive academic journals. It drives a certain type of research excellence where advances at the boundaries of a discipline are rewarded rather than useful application. We need both – for example economists advancing the theory and others applying current models to better understand their local economy. Politicians and the media regularly call the universities which do the first type of research "good" and the less prestigious ones doing the latter type "bad". Academics who are not getting research grants from government are more likely to describe their research as applied compared to those who are grant recipients (46 per cent to 29 per cent). This is what happens when the focus of public funding is a certain sort of academically excellent research. The Knowledge Exchange Framework – or KEF – is an attempt to plug this gap, but it is early days and could be quite clunky.

The government is now implementing Nick Stern's proposal that all research-active academics should be submitted to the REF. This is a step in the wrong direction. It will spread the monoculture further. **Instead it should be optional for research-active academics to be submitted to the REF.** We need a strong research ecosystem which is not the same as every individual scoring a world-class ranking.

There is one other important step to create a fair funding regime for research in universities or indeed outside of them. **This is to move to fund the full economic cost of a**

research project as opposed to only 80 per cent at present. This could cost around £1 billion but the increase in funding is an opportunity to tackle this anomaly, provided there are no off-setting cuts in other budgets. It would also show that universities are valued as a key part of our innovation ecosystem.

Invest in R&D clusters beyond universities – catapults and science parks

When the Conservative Party was in opposition, we commissioned James Dyson to do research on Britain's innovation problem. At the same time Peter Mandelson commissioned Herman Hauser to look at the issue. These two parallel reports both came out in 2009 with very similar solutions – that we needed something like a German network of Fraunhofers, and that's roughly what the Catapults are. Rather than seeing this ecosystem endlessly shrinking and thinning out, they are an attempt to create some more intermediate institutions, publicly funded and privately funded, doing applied R&D, and outside the university environment.

A big increase in public spend would create scope for a wider pattern of provision beyond universities. We can take practical steps to promote a wider network of applied research institutes such as the Catapults. Good examples of the Catapult network are the High Value Manufacturing Catapult centres, where, in places like Sheffield, manufacturers such as Boeing are bringing manufacturing to the UK, and McLaren are re-shoring key composite manufacturing from Europe. The Cell and Gene Therapy Catapult has a world-class facility in Guy's Hospital in London, in addition to a key manufacturing location in Stevenage. The Offshore Renewable Energy Catapult has the most advanced turbine blade and nacelle testing facilities at Blyth in Northumberland.

The Catapults were deliberately designed to be in the private sector with mixed public/private funding, but the unhelpful growth of public control means that they are in danger of being reclassified by the ONS to the public sector. They should enjoy the freedom to be kept in the private sector and more Catapults should be created.

We need to do more to make the Catapults a coherent network rather than just individual centres – together they add to a fantastic national resource which can attract business investment. We also need to raise awareness of the Catapults across businesses and make them easier to work with. The matched funding from the private sector is increasing but the danger is that it is the big firms which are most able to find the money. We need to invest more in Innovate UK programmes like collaborative R&D to make it easier for SMEs to work with the Catapults.

Science parks can be a great environment for mixing more academic research and commercial enterprise. They are at the heart of key innovation clusters but rarely commercially viable on their own – our property developers have traditionally preferred shopping centres. We do have some distinctive research parks dotted across the UK. They are widely spread across the country (see below, although this list is not exhaustive and excludes Catapults and science parks located in a specific university).

Research parks:

- Norwich Research Park (agri-tech)
- Cambridge (Babraham and Sanger Hinxton campus – biotech and genomics)
- Oxford (Culham, Harwell – physical sciences and space)
- Bristol (mixed including robotics)
- Manchester (Daresbury, Alderley Park)
- Edinburgh (Bio-quarter)

They are a diverse group. Most of them are outside the South East – partly because the South East was most vulnerable to German bombers during the Second World

War so many of the military R&D centres were pushed West – that is why Malvern beyond the reach of German bombers remains to this day a centre of expertise in cyber security. There is no single coherent model for them and that is no bad thing. Not-for-profit research institutes outside the public sector may be able to apply for specific project funding but with no access to capital for new facilities. TWI (formerly The Welding Institute) is a fantastic facility outside Cambridge which faces these problems because it is an independent not-for-profit organisation.

One of the unique features of the US system is the so-called Federally Funded R&D Centres (FFRDCs). Most government departments have a number of these. These FFRDCs have long-term 10-year contracts with a cost-plus model that encouraged the researchers to "speak truth to power". If major government departments in the UK each helped to fund at least one research institute outside a university, that would promote a more diverse research base. Moreover, in order to function effectively our public sector research establishments need to have the greatest possible operational freedom including over pay. After George Osborne and I visited the Laboratory of Molecular Biology he was so impressed with what they were doing and shocked by how public sector rules were impeding their performance that he granted greater freedoms to them and similar bodies. **These freedoms have now been removed by BEIS and the Treasury. They should be restored.**

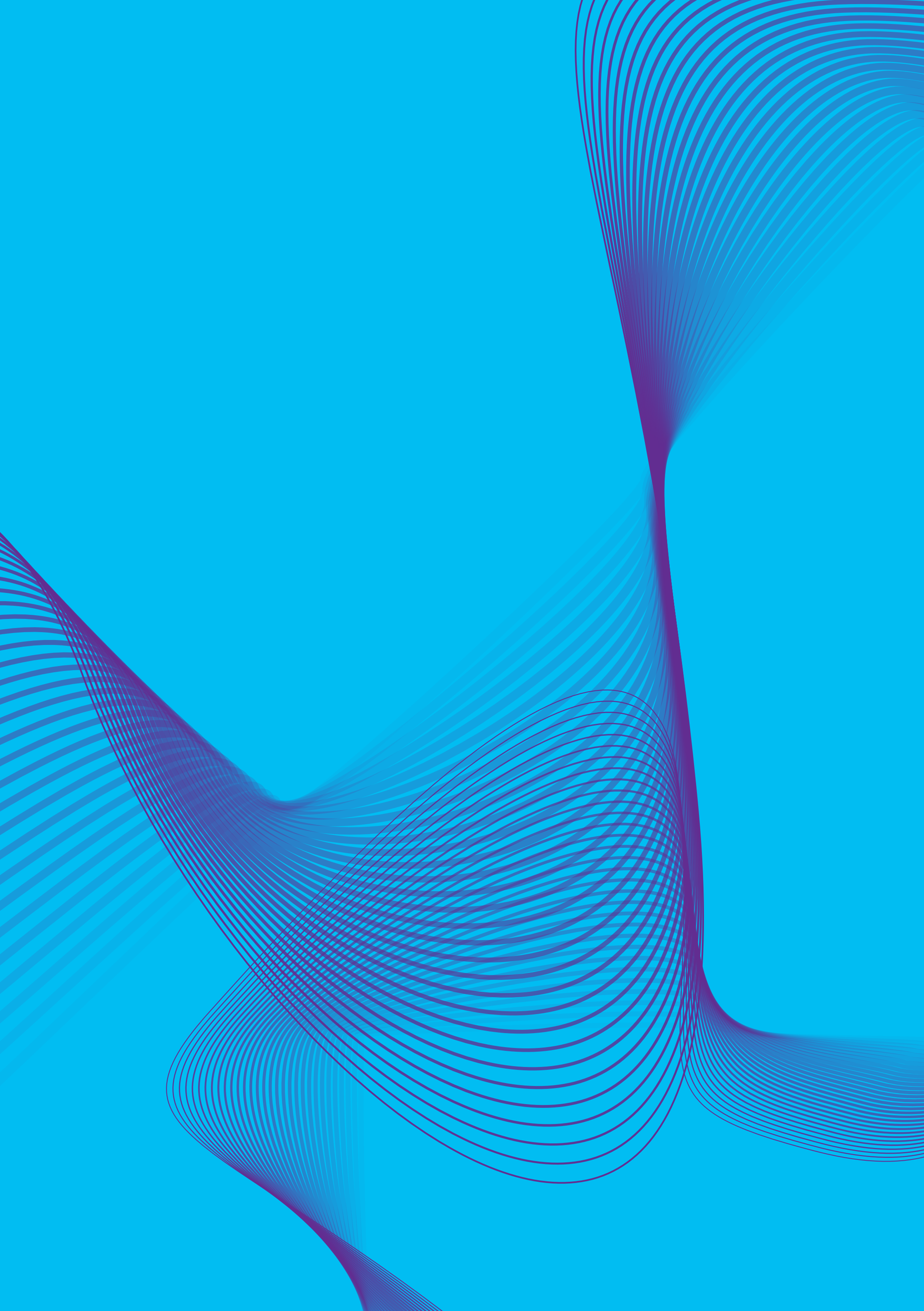
There should be a public commitment with substantially increased public funding supporting science parks and applied research institutes as part of our national infrastructure. They could become R&D enterprise zones. When the Department for International Trade (DIT) is pitching to overseas investors to come and set up here they should be armed with an attractive pitch document for these centres. They should be a priority for transport investment – as well as an Oxford/Cambridge rail link, both cities need much better local transport links to make their science and innovation centres easily accessible.

> We can change the incentive structure within universities so that more of this research is successfully applied

Quasi monopoly industries have historically created their own research labs such as Xerox's PARC and Bell labs. Our nationalised industries used to be heavy funders of R&D but privatisation changed that in ways we did not expect. The new regulatory regime for them was designed to stop "gold-plating" of expenditure so capital investment and spend on R&D is restricted by the regulator. The regulatory regime should be reviewed to ensure it is not a barrier to investment in R&D.

Conclusion

I have tried to explain the crucial drivers of the British problem, that we don't always seek to commercialise and apply some of the great ideas emerging from our science base. It is not because we are unusually cautious or have some vague cultural inhibition. It's certainly not down to a lack of will in universities, which do better than almost anywhere else in the world in promoting academically excellent cutting-edge research. And the 2.4 per cent target is an opportunity for better funding for our university research. But our British strategy as it has emerged has ended up with many more of our eggs in that particular basket than in most other advanced western countries. We can change the incentive structure within universities so that more of this research is successfully applied. But there is also a need to extend both a funding network and an institutional network that supports R&D outside the university environment as well.



3. A British DARPA?

3. A British DARPA?

The account of the British research model in the previous chapter shows that there is a gap to be filled to enable us to do better at turning science into innovation. If there is one agency in the world which is the master of innovation it is DARPA (Defence Advanced Research Agency) in the US. In the past decade its competitions for driverless cars and for humanoid robots have caught the imagination – and made it a YouTube phenomenon. The model is so well-regarded that the Federal Government has created DARPA-E for clean energy and I-DARPA for the intelligence services.

There is an obvious appeal for Britain to have its own DARPA. The Conservative manifesto states that some of the "new spending will go to a new agency for high-risk, high-payoff research, at arm's length from government."[21] That is one way of characterising DARPA. The Conservative briefing went a bit further:

"We will set up a British Advanced Research Projects Agency. We will invest £800 million over five years for a new research institution in the style of the US ARPA, which funds high-risk, high-reward research that might not otherwise be pursued, to support blue-skies research and investment in UK leadership in artificial intelligence and data."

But what exactly is ARPA/DARPA and what can we learn from it?[22] Originally there was ARPA created by President Eisenhower in 1958 after the Soviet Union's successful launch of Sputnik caught the US by surprise and shook its post-war complacency. ARPA's mission was to "prevent technology surprises for the US and instead to create them for others". A shorter version, which applies to this day, is to "prevent and create technological surprise".[23] Its first focus was space. The real significance of Sputnik was not the satellite but the power of the Soviet missile which launched it into orbit – powerful enough also to deliver a nuclear attack on the US. The American military had been ignoring Werner Von Braun but ARPA spotted the significance of his expertise in rockets and commissioned what was to become the Saturn rocket. That capacity in turn was what made it possible for President Kennedy to pledge in 1961 to get a man on the moon. It is a good example of investing in a technology before its mission has been defined. The moonshot was only possible because of prior investment in technology. ARPA lost most of its role in space when NASA was created to deliver Kennedy's lunar mission. At that point ARPA could have been closed down but instead there was the first of a series of transformations of the agency which have ensured its survival to this day – turning its focus to the Vietnam War. As a result, it is hard to define a single model for the agency – some historians detect a different ARPA or DARPA every decade. But even as the D for Defence comes and goes, the real underlying mission is national security, which for the US means a technological superiority. It is why China's rapid advance in technology is seen by the US as a direct strategic threat.[24]

"That capacity in turn was what made it possible for President Kennedy to pledge in 1961 to get a man on the moon

The 1960s saw ARPA focus on counter-insurgency as they tried to harness insights from the social sciences to help fight the war in Vietnam – Agent Orange was developed to apply sociologists' advice that Vietnamese peasants should be moved out of poorly policed rural areas where the Vietcong operated. More successfully ARPA also investigated the feasibility of monitoring underground nuclear tests (if they could do it, then it would be possible to agree to ban nuclear tests in the atmosphere under the confidence that they would still be able to know what the Soviets were up to as they literally went underground). ARPA succeeded and advised the President that it was feasible to agree the nuclear test ban treaty. As a side-effect their efforts transformed seismology from a backwater into a hot intellectual topic driven by rapid technological advance. Indeed "at one point they funded almost every seismologist in the world apart from two Jesuits at Fordham who would not take the money." These advances in seismology in turn confirmed the then eccentric theory of plate tectonics – a good example of technological advances driving scientific progress.

Meanwhile ARPA had also been funding the scientists tracking the original Sputnik who had realised that its speed and location could be calculated by the Doppler effect of its signal being compressed as it came nearer and extended as it went further away. That is the origin of GPS which today's DARPA counts as one of its great successes.

ARPA also investigated how better to link the network of American tracking stations for Soviet missiles and launch sites for counterattacks in the US. This was the origin of its drive to enable computer systems to communicate with each other which became ARPANET. Computer communications began when one computer transmitted the message "Lo" to another. (The message was supposed to be "Login" but it failed after the first two characters.) There was a fundamental security mission behind everything it did, and this was recognised when the Nixon administration added "Defense" to its name and it became DARPA. The great innovations such as GPS and computer communications were technological innovations driven by security policy – they were not the result of lone geniuses having brilliant thoughts, though they were helped by the fact they were operating as programmes outside the academic environment.

More recently DARPA has been associated with competitions, with prizes to demonstrate and promote innovation in key technologies. Prizes have a long and important history in innovation. For example, aeroplanes advanced in pursuit of the Orteig Prize for flying from New York to Paris won by Charles Lindbergh. More recently the AnsariX Prize has been awarded to the first private reusable manned rocket to be launched into space twice in a fortnight. There is now an economics literature specifically on the optimum design of prizes so that they set the right amount of challenge and I promoted NESTA as a centre of expertise on this. We drew on NESTA's advice as the Coalition designed the Longitude Prize. DARPA have made it clear that their prize competitions are only possible because of underlying capabilities funded in other ways. Larry Jackel, who ran the DARPA Grand Challenges race for autonomous vehicles, said of the Challenge "It's not self-sustaining...You can do it based on something that already exists, but if all we did was have challenges, then at some point we'd just stagnate."[25]

This reveals an important point about the ecosystem within which DARPA operates. Its budget is about $3 billion out of $150 billion of US Federal spend on R&D. DARPA is able to draw on an enormous amount of separately funded research. It is part of their model that they do not run institutes or employ researchers long-term. Instead they fund specific teams for specific projects. It is highly flexible and effective. It is only possible because the network of universities and research institutes on which it draws is already there and well-funded by other Federal agencies.

The contrast with the UK is stark. Our public spend on R&D as a proportion of GDP is about half that of the US. And our GDP is about a fifth of theirs. So, we end up spending about a tenth of what the Americans do. An equivalent British DARPA might therefore have a budget of about £200 million if the ratio to the US were maintained. That seems to be about what the Conservatives propose. And its focus would be innovation at the frontiers of technology.

There are other striking features of DARPA from which we can we learn.

First, they are not constrained by academic peer review (though of course the wider scientific base from which they draw does depend on it). The absence of academic peer review means that they can pursue oddball projects.

Indeed, another useful function they perform in the political system is that people with new or eccentric ideas can be referred to DARPA. And they are willing to try out much wilder ideas than a conventional research institute or university department. One estimate is that 85 per cent of their projects don't work. But that does not matter. This willingness to run risk and accept failure is a crucial feature from which we can learn.

The absence of peer review brings another benefit – it makes it easier to stick with a strategy. I have been involved in discussions funding more research on key strategic priorities such as anti-microbial resistance. One could argue we need to stick to the strategic priority, but a key bid for funds from the science budget can be rejected if it did not pass academic peer review. The science community rightly sets great store by peer review and it is a necessary condition for public funding of upstream research. But there comes a point when a strategy is being pursued and the science is being applied that it ceases to be the key test. Creating a distinct organisation which is not constrained in that way is a good way to recognise that reality without corrupting wider science and research funding.

> "DARPA's team of programme managers are clearly and deliberately intervening so as to boost technological and industrial capabilities in the US

The strategy which they are then free to fulfil is often what we would recognise as Industrial Strategy. DARPA's team of programme managers are clearly and deliberately intervening so as to boost technological and industrial capabilities in the US. Here is an account of one of their programmes developed in the days when the challenge was not China but Japan:

"In 1987, 14 US semiconductor companies joined a not-for-profit venture, SEMAT- ECH, to improve domestic semiconductor manufacturing. The next year, the federal government appropriated $100 million annually for the next 5 years to match the industrial funding. DARPA had since the late 1970s been supporting the development of 'silicon foundry' capabilities to allow cost-effective fabrication of new types of integrated electronic devices by designers lacking easy access to costly production facilities. With semiconductor manufacturing seen as vital to defence technology, the SEMATECH money was channelled through DARPA."[26]

That was happening in the heyday of Ronald Reagan's America. At the same time Margaret Thatcher was doing the opposite and reorienting British science and technology spend exclusively to upstream pure research, on the argument that there was no role for government in downstream applications.

At times, DARPA programme managers fund competing technologies aimed at solving the same problem. Here is one programme manager describing his approach:

"Take the case of thin-film technologies. In that case I funded two parallel programs. I funded IBM, because they were convinced that the parallel junction for thin-film SOI wasn't going to go on forever, and they wanted more thick-film SOIs for the company manufacturing purposes. And then I funded Lincoln Labs to do thin-film SOI...I pitted Lincoln against IBM...So, they both succeeded, and IBM is still manufacturing thick-film SOI today."[27]

The sheer bold confidence that they could intervene is what is striking. DARPA functions free from inhibitions and agonising about what governments can and cannot do which is such a frustrating feature of the British debate about technology and Industrial Strategy. The expert and confident programme manager is a key feature of DARPA's success over the years. They have an overview of how a technology is developing. They have the convening powers to pull together different experts and get them to share their ideas. This is increasingly important as vertically integrated technology companies become rare and there are more distinct commercial players at different stages of the chain taking a technology to market. Moreover, within the academic community competition between institutions and researchers intensifies, partly driven by pressures from public agencies to perform well in rankings, so a safe space where they can cooperate becomes increasingly important.

There is one other feature of the DARPA model which stands out. Their focus is of course technology. But they are not just trying to push technology out into the world. They want to see it actually applied. They stick with it as far as actual prototypes showing how it can be used. In the academic literature on different models of innovation, DARPA has been termed a "pipeline" model. This is how one academic researcher puts it:

"Vannevar Bush's…postwar organization of US R&D agencies was a 'technology push' or 'technology supply' model, with government support for initial research but with only a very limited role for government in moving resulting advances (particularly radical or breakthrough innovation) toward the marketplace. Because DOD [US Department of Defense] could not tolerate a disconnected model when faced with Cold War technological demands, it developed an 'extended pipeline'. This means support not just for front-end R&D but also for each successive 'back-end' stage, from advanced prototype to demonstration, test bed, and often to initial market creation, where DOD will buy the first products. This is a mission-oriented innovation approach, organized not simply around R&D but toward its implementation. While the government's support role in the pipeline model is disconnected from the rest of the innovation system, in this model it attempts to be deeply connected."[28]

It links support for R&D and for technology which is then supported for much longer on the journey to actual use. This is crucial. The humanities and the social sciences play a key role in all this. One point at which insights from these disciplines are crucial is when science becomes technology and human behaviour matters. There is of course the ethical and legal framework – the advance of AI requires sophisticated ethical advice. But it goes beyond this to understanding the role of funeral practices in the spread of Ebola through to what are the boundaries of acceptable genetic modification. And human needs themselves shape and drive innovation – from substitutes for plastic through to the social science I draw on to explain the gaps between the generations. A British DARPA needs to have this multidisciplinary principle at its core. Otherwise it would just be focussed on new technologies without thinking also of the problems that they might help solve and how humans are to interact with them.

ARPA/ DARPA has operated in different ways over the years. There are a range of different accounts of how it has worked. One picture is of it as a funder of blue-skies research. It has certainly been willing to go for the wild and wacky ideas which can sometimes have a touch of genius but would not have been recognised in conventional peer review. But in reality, ARPA has always served America's core long-term security strategy of having a dominant position in key technologies. Nevertheless, there is a need for funding free thinkers. Regardless of whether this has been a core mission of ARPA, its very free-booted willingness to operate at the frontier beyond the conventional wisdom reflects that spirit. There are some key messages which can be distilled from the evidence on the environment in which this blue-sky research flourishes: fund individuals not programmes, be patient and be forgiving of failure. These are all lessons which can be applied to the funding of UK research as well. The current exercise at UKRI in cutting bureaucracy is an excellent example of what can be done. But it needs to go further – the last few years have seen a surge in bureaucratic control as part of the framework of Industrial Strategy. BEIS assess proposals from UKRI. The Treasury has to assess the business case. The National Productivity Investment Fund, which funds a lot of the new projects, has its own clearance procedure. Added together this means that proposals from UKRI can take over a year before any money can actually get spent. Any new DARPA should not be a unique haven free from bureaucracy – the real challenge is to remove it from the rest of the system.

How a British DARPA might work

The most important lesson of DARPA is the confidence with which US federal agencies have tracked and invested in technology ever since Sputnik. This is where Britain seems strangely hampered, with a lack of confidence and doubts about our capacities. This is where we find the clue to our failure to drive and commercialise innovation and it is to this which we now turn.

We have an agency, Innovate UK, originally called the Technology Strategy Board, which is the business-facing arm of UKRI. But Innovate UK has been hobbled by heavy budget cuts. It also suffers from intermittent hostility to it actually making any judgements about priorities, which leads to a preference for general initiatives to schemes, rather than funding particular technologies. However, the two approaches are actually complementary.

Stephen Roper at Warwick Business School analysed the effects of public funding for corporate R&D from the Engineering and Physical Sciences Research Council (EPSRC) and Innovate UK on British business, and found they increased their turnover and employment 6 per cent faster in three years and 28 per cent faster six years after, compared with similar firms which did not receive support. He found particularly strong effects for small firms and those with lower starting productivity (turnover per employee). Having tried a range of business-promoting grant schemes over the years, we can now see which ones work and are popular with business.[29]

The pursuit of simplification in 2015/16 led, wrongly, to the elimination of most programmes aimed at technologies or sectors or clusters (such as small launch-pad competitions for automotive SMEs in Oxfordshire/Northamptonshire or Tech City start-ups). This has increased demand for Innovate UK's technology-neutral responsive-mode SMART programme, although this was also cut at the same time. It was originally introduced back in the 1980s to help small start-ups fund the cost of proof of concept and proof of market. The success rate for companies applying for SMART, our remaining programme of business-facing innovation funding, has fallen to a new low of 5 per cent. This creates enormous unhappiness amongst companies as they waste a lot of time and effort applying for a scheme which is far too small relative to demand. Programmes of support for technologies and clusters should be reintroduced and SMART itself significantly expanded.

Catalyst funds provide grants for innovation all the way from the research lab to commercialisation – the main one was the Biomedical Catalyst which scores very high returns on evaluation. But it is now closing as no new funding is being provided. The Biotech Industry Association are strong supporters and they would warmly welcome the rescue of the scheme. It should be replenished, and the same model applied to key sectors.

"The success rate for companies applying for SMART, our remaining programme of business-facing innovation funding, has fallen to a new low of 5 per cent

These schemes used to run at up to £400 million a year before the 2015/16 cuts and are now down below £100 million and shrinking. A substantial increase of at least £300 million for the Innovate UK budget is key.

As well as extra funding, Innovate UK as an organisation needs a significant boost. As our innovation agency it should be a centre of expertise on business and technology developments and on programme design. It has been shedding staff and has lost a lot of expertise in the process. They need high-calibre individuals to enable strategic funding of complex projects. They need to move more quickly which in turn means more discretion. Their culture is very different from the Research Councils and they need to be able to act energetically. If we were to create a British ARPA it would need to be complemented by an agency like Innovate UK, which maintains a broadly-based technological capability just as American public agencies such as the National Institute for Health and the National Science Foundation do.

Innovate UK should not just be a grant funder but a valued early stage investor working with private and public investors. This should include a partnership with the British Business Bank (BBB) to accelerate the successful exploitation of innovative technologies. This will also require Innovate UK to develop better assessment tools to better identify transformative ideas/companies. But it also needs a broader role for the BBB. The patient capital agenda is currently based on encouraging more investment in venture capital (VC) by boosting returns by the public agency coming in as a passive investor in VC funds. There are welcome proposals in the Conservative manifesto to make it easier for pension funds to invest in venture capital as well. It is much harder for the BBB to support specific technology sectors or missions. But one reason our VC model is not very successful is that it is weak in domain and technology expertise. Between them Innovate UK and the BBB could also promote funds around technologies and missions. Alongside these agencies, there is the Business Growth Fund (BGF) set up by the banks which is now establishing a strong record and is increasingly confident and effective. With the resources of the big clearing banks behind it, it has great potential as a provider of scale-up funding. **Government should encourage Innovate UK, the BBB and BGF to align better so a new technology company can more easily access funding schemes to help it get started and grow.**

4. A technology strategy for the UK

4. A technology strategy for the UK

Our failure to properly promote new technology, the appliance of science, is the biggest single gap which can be plugged with the increase in R&D spend. Systematic support for new technology has been largely abandoned over the past five years. We need to understand why this has happened and then seize the opportunity of the commitment to increase research funding to create a new technology strategy.

> “Our failure to properly promote new technology, the appliance of science, is the biggest single gap which can be plugged with the increase in R&D spend

There are already some promising moves. The British government is using technology more ambitiously than ever – having discarded the old assumption that technology was fixed for the period covered by a policy decision. The US/China dispute over Huawei has revealed the strategic significance of key technologies. Many ministers and advisers rightly believe that three key ingredients to raising Britain's growth performance are infrastructure, skills and technology. Boris Johnson talks with genuine enthusiasm about new technology. And the Conservative manifesto has a new commitment to invest in "critical national technologies". This is an important and very welcome advance. In the rest of this chapter we will consider how to deliver on that manifesto pledge.

Governments have an Industrial Strategy, whether acknowledged or not. Industrial strategies usually operate on four dimensions – places (Northern Powerhouse, Midlands Engine, deprived coastal towns), sectors (automotive, aerospace), challenges (anti-microbial resistance, ageing, clean growth), and technologies (the Eight Great Technologies from AI and robotics to cell therapies and energy storage). The last few years have seen more focus on the first three dimensions and a diminished support for technology, although qualified by the device of dressing up AI, which is really a technology, as a challenge in order to get it funded through the Industrial Strategy.

The route a general-purpose technology takes on the long road to market is complex and expensive. It is exciting when you first see heart muscle cells created from stem cells beating in a Petri dish. That is amazing science. It takes a lot more money and a different skillset to scale that up into a programme for growing billions of such cells consistently and using them for treating patients with heart disease. This is the point at which Britain loses out. We exaggerate the capacity of the private sector to scale up an invention before they can be confident it will work, and we fail to recognise the role of government in bearing some of the risk to make this happen.

Our major competitors display no such inhibitions about promoting technology. America's post-war security strategy positioned itself as the world leader in significant technologies. It invests an enormous amount of public money to do this – partly though by no means only through DARPA as we saw in the previous chapter. When we fail to turn a British scientific advance into a product for the marketplace, we think it is because our business is risk averse whereas the truth is that we expect business to bear more of the risk in developing a new technology than in the US, Germany or Japan. Behind America's rhetoric of a Jeffersonian state of sturdy individualists, there is the reality of a Hamiltonian state which spends and regulates to promote national greatness through science and technology. There are technologists in Cambridge who have public agencies from Singapore to Canada breathing down their neck because of the significance of the technologies they are working on, but since the cuts to Innovate UK there is little capacity in the UK's public sector to capitalise on this.

The UK policy community may have lost confidence in our ability to spot and promote new technologies because of the unhappy history of some major technology-based investments such Advanced Gas Cooled Reactors and Concorde. This has led to a belief that governments cannot “pick winners”. But governments have also delivered some rather successful strategies as well. Rescuing Rolls Royce’s RB211 engine was the right decision. Backing mobile phone technology and shaping the international standards to favour it, set Vodaphone on course to be a global company. Our major sectors from pharmaceuticals to the City have all benefited enormously from strategic government backing.

There is a surprising belief across Whitehall that future technology is unknowable. This is a peculiar doctrine which is not applied to other areas of government activity. We don’t say that as we can’t know how our enemies might fight us, we cannot do military planning. We don’t say that human behaviour and the development of financial services is unknowable so there is no point trying to “nudge” people to save more. But non-scientists in particular seem to think science is just random and unpredictable discoveries. It is true that there are unexpected flashes of genius and moments of extraordinary serendipity. The development of technology is not 100 per cent predictable. But there are clear areas of scientific activity where the research is very dynamic and where one can see new technologies emerging as a result. We cannot predict the future development of all technology but we can make a decent fist of it – partly because the development of a technology is a long process and the creation of a new start-up or new commercial investment comes years after the scientist in the lab started working on it. There is not a Rawlsian veil of ignorance behind which we have to take every decision on science and technology. But sometimes Whitehall’s approach reminds me of Warren Buffet’s observation that the efficient market hypothesis is like playing bridge against someone who does not look at his hand of cards.

The doctrine of unknowability is linked to the fear of actually taking a view. Peter Thiel brilliantly dissects this fear in his book *Zero to One*. He critiques “indefinite thinking”:

“If you treat the future as something definite, it makes sense to understand it in advance and to work to shape it. But if you expect an indefinite future ruled by randomness, you’ll give up trying to master it.”[30]

Part of Whitehall’s justification of the shift away from technologies to challenges – “moonshots” – is that future technology is unknowable and unpredictable so instead of deciding which ones to back we should define challenges and then see what technology arises to tackle them. But Mariana Mazzucato, the eloquent advocate of challenges and missions, makes it clear that this is to misunderstand her approach. She agrees we should back technologies as well as challenges and missions. Indeed, backing for technologies is a precondition of the possibility of investing in new missions. The NASA mission of getting a man to the moon was not a sudden political ambition, decided independently of any technological assessment, after which President Kennedy looked around and discovered that by happy accident the US government had been systematically investing in rocket technology. The mission emerged from a technology opportunity and had full state backing from the start.[31]

These failures of understanding and of nerve arise in my view from one of the greatest weaknesses of the English education system – early specialisation. These peculiar doctrines about unknowability of technology arise because our policymakers have not had a broad education and regard science and technology as scary and difficult to get to grips with. The missions approach is much more comfortable for a PPEist (like me) than presiding over decisions on key technologies, even if they are based on expert advice. And this problem can also affect scientists and technologists too who can fall prey to a kind of STEM reductionism, which ignores the importance of understanding human behaviour and what follows is a pure supply push-model of technology.

The only way forward is a genuinely interdisciplinary approach and that also means one in which governments both identify key challenges and also key technologies. Neither approach will do on its own.

Britain cannot afford to follow the US example of trying to do everything: we have to be selective. This means we face even more acutely the need to make real decisions and cannot just hide behind process. Sometimes we get it wrong but if we all avoid backing any actual technology then we get nowhere. But if we act on evidence and respect experts, we can do it. I took the view for example, on expert advice, that the heat exchanger at the heart of the Reaction Engine was a crucial British technology which we would lose to the US if we did not back its development with public funding. The Treasury hated it and tried to stop the funding, but George Osborne advised by Neil O'Brien stood his ground and subsequently when Philip Hammond became Chancellor, he went on to praise this great example of British innovation.

The Conservative manifesto shows a very encouraging willingness to identify real challenges and critical technologies. It states:

"We will focus our efforts on areas where the UK can generate a commanding lead in the industries of the future – life sciences, clean energy, space, design, computing, robotics and artificial intelligence. In particular, we will make the UK the leading global hub for life sciences after Brexit. We will use our £1 billion Ayrton Fund to develop affordable and accessible clean energy that will improve lives and help us to lead the world in tackling climate change."

"These unprecedented increases to the science budget will be used to drive forward the development of technologies of critical importance to the UK, by investing in clusters around world-leading universities and spreading knowledge."[32]

There is always the danger that politicians get seduced by shiny baubles and smart lobbying. The doctrine of unknowability increases that risk by excluding the possibility of rational evidence-based assessment. Instead we need to try to do it as best we can. The starting point for delivering the Conservative manifesto's welcome commitment to critical technologies would have to be technology horizon scanning.

Horizon scanning for new technologies

If we are to invest more in applying research, we need some organised understanding of what is happening and then the resources to back it. The previous government largely abandoned systematic support for new technology and focused all the extra funding on challenges and missions. These can be very effective but are not the whole story. The new government has an opportunity to **create a new technology strategy based on expert technology horizon scanning**. It is only recently that Whitehall has succumbed to the peculiar doctrine that future technological advance is unknowable and lost interest in long-standing exercises such as Technology and Innovation Futures. In turn that has left the UK grossly under-informed about our own potential as US and China compete over future technologies – both of them eyeing technologies emerging from UK research base which they know more about than the British government. As one of the great hockey players put it "Skate where the puck's going, not where it has been." But if the official doctrine is that nobody can know where advances are going then we end up short-termist and outmaneuvered by others. AI and Quantum Computing are the notable exceptions of technologies which find favour and get support.

"If the official doctrine is that nobody can know where advances are going then we end up short-termist and outmaneuvered by others

Nobody can be 100 per cent sure exactly how technologies can play out but drawing on the advice of scientists and technologists it is possible to identify key areas of advance where the UK has a real competitive advantage. The Eight Great Technologies was my own distillation of expert advice on emerging key technologies where we had a comparative advantage.[33] I identified them in 2012 by drawing on expert advice from the Technology and Innovation Future's exercise, Innovate UK's assessment of key technologies, and a Research Council exercise on key research areas in which to invest. It starts with "dry" technologies associated with the digital revolution (machine learning and big data; satellites and space; robotics, autonomous systems and the internet of things). There are three "wet" technologies associated with the genetic revolution (synthetic biology; cell therapies and med tech; agri-tech). Then there are two foundational technologies: advanced materials and energy saving and energy storage. Seven years on this still does not look a silly list – showing that it is possible to identify key technology trends. They were then backed by George Osborne with public spending of £600 million – not least because of the compelling argument by Mariana Mazzucato that governments are crucial to new general purpose technologies in their long journey to the market.

The US has never stopped doing such exercises even as the political viewpoints of its Executive shifts. Here is a recent set of R&D investment areas for the National Institute of Standards and Technology, part of the Department of Commerce:

i) Security,
ii) AI, quantum, strategic computing
iii) Connectivity and autonomy
iv) Manufacturing
v) Space
vi) Energy
vii) Medical innovation
viii) Agriculture

These priorities are set out in the United States Office of Management and Budget (OMB) 2020 Administration R&D Budget.[34]

Whitehall used to do substantial technology horizon scanning and still does to some extent with useful work by the Cabinet Office and the Government Chief Scientific Adviser's Office. However, there should be a much more ambitious exercise asking experts across disciplines what are the significant technologies emerging in their area. That itself is fascinating and creates political and media interest. It is valuable guidance for funders like UKRI and can promote business investment. It also informs government contingency planning and helps government departments understand how new technologies might change the way they carry out their missions.

It starts as a technical exercise across asking experts across disciplines what are the significant technologies emerging in their area. That itself is fascinating and valuable which as a minimum illuminates government contingency planning and can promote business investment. But this exercise needs to be about more than drawing up a random list, it needs to be shaped around some kind of intellectual framework emerging from the scientific community. This is made harder by the elision of "tech" to mean a certain subset of digital technologies. The crucial "life sciences" category is often taken to mean human medicine and thus excludes the bio-economy which is a very promising route for decarbonising conventional production of many goods but is never going to be a priority for the Department of Health. One classic American list is much wider: Bio, Nano, Info, Cogno. The broad categories of "dry" "wet" and "foundational" would be a good way to organise the key technologies, so that we are not faced with a random list and can ensure that a broad range can be considered systematically. It is important to range widely so it is hard to see how any technology strategy would not include these broad categories. Indeed, one of the strengths of the British research base is that it covers so many disciplines.

The government has said in its very useful White Paper on Regulation for the Fourth Industrial Revolution that "We will establish a Regulatory Horizons Council to identify the implications of technological innovation and advise the government on regulatory reform needed to support its rapid and safe introduction." This will involve "scanning the horizon for technological innovation and trends, building on existing work and data across Government." That is a welcome recognition of the need for technology horizon scanning. But it should be systematic and an explicit task for the Government Chief Science Adviser and UKRI. It is needed for a range of purposes as well as getting the regulations right.

Our comparative advantage – small and smart

"Our superiority complex on science is matched by an inferiority complex on technology

Identifying key technologies where we are amongst the global leaders is key. But it is not enough on its own. We are also trying to assess the prospects for future business investment. Which ones are indeed "critical" for example? This is not easy, and we inevitably get some things wrong. But if we wish to invest limited budgets in some technology support, we have to make these kinds of judgements. And again, it is possible to identify key sources of comparative advantage. Our superiority complex on science is matched by an inferiority complex on technology (and the capacity of government to promote it). Here are some possible sources of comparative advantage in technology which like school subjects can be labelled as history and geography and religious studies.

One source of comparative advantage is just that – our history. We have been doing stuff for a long time and this gives us advantages. For a start we have old kit and that can often set new challenges. As we were involved in nuclear power early on that means we are involved in nuclear decommissioning early on. Similarly, we were early into deep water oil rigs. That makes us leaders into technologies such as robotics for operating in hazardous environments. Our historic data sets are a resource of great value for machine learning.

As well as history there is geography. Europe does not yet have a good rocket launch site but the new constellations of Earth observation satellites are usually launched into polar orbit so it is very efficient to launch north of the ocean toward the Arctic. That is why I started the process of identifying potential UK launch sites and competition is now between us, Sweden and the Azores for Europe's first launch site. As it costs a lot of money to move a large rocket this is also a competitive opportunity for the Scottish space industry. Offshore wind is another example of the accidental advantages of our island location. We are world leaders in generating power this way, though with a thin representation of British companies – partly because of the privatisation of the Green Investment Bank which had been funding this sector. Tidal power is another opportunity. One of the problems with some of these energy sources is that they are unpredictable. But tides are predictable and as an island we have powerful tidal flows day and night. That means that investing in tidal power as a whole yields even greater returns than just one facility. And the application of these renewable technologies is distributed across the UK.

Thirdly there is religion or the relative lack of it. We are one of the world's more secular societies. By contrast the political power of religious fundamentalism means that the US regime for some life science innovation is much trickier. There are also European countries where opposition from the Catholic Church is an issue. And in Germany the horrors of Nazi attempts to create perfect human beings means that for example they are much more opposed than us to tackling disease by genetic manipulation – such as mitochondrial DNA. Of course, we do need careful regulation and our Human Fertilisation and Regulatory Authority has a world-wide reputation for this. All this means that we are in a strong position to be a world leader in cell therapies and synthetic biology.

Finally, on my list is the paradoxical advantage of being small. We just don't have the massive resources which the

US and China can throw at a problem. We have to be small, lightweight and nimble. We do not have powerful rockets, so we are world leaders in small, lightweight satellites. We do not have as much massive computing power, so we write smart software which gets to a result with fewer calculations. We do not have the world's biggest synchrotron, but we do have the most precise. Through all the travails of our civil nuclear industry we have remained world leaders in small modular reactors.

How to invest in technology with business opportunities for the British economy? What next?

Imagine we are once more at the stage where we have a sense of the key technologies emerging from Britain's research base which have good global business prospects. We want to back them with a mix of public and private money. Usually the best advice I give in these circumstances at the moment is "try to link it to a challenge and it might get funded for that." But this is to ask technologists to speculate on the future use of a general purpose technology when one of its most important features may be its very openness. They say synthetic biology will "feed us, fuel us and heal us". That very power makes it hard to fit into one specific challenge hence one recent rejection of funding for it on the grounds "it is not a challenge". Advanced materials are key to the new biosensors which will generate new sorts of medical data but they also key to advances in compound semi-conductors and it is hard to be sure which function will be of greatest significance. And the medical policy-advisers excited by new medical data may not even recognise that public support for a materials research lab is what made possible the new biosensor which collects the new data that means so much to them. Here are three practical policy tools which my experience suggests can be very effective.

First, commission a technology road map setting out how we expect the technology to develop and what exactly are the areas of current public and private spend. We did that with synthetic biology and satellites. It is not the be-all and end-all but rather an account of how research is shaping up and what government is already funding. This itself can prompt private investment as they can see what is being tried, and if funds permit it, then it gets more public funding too.

Second, we need commercialisation centres where public and private funding can be combined. This is why we created Catapults which I saw just as a generic model for technology centres based on German Fraunhofer Institutes. They could have a narrower focus on a particular industry, which would be too expensive for any one company to run, for example a satellite testing facility.

Thirdly Catalyst funds flow from a combination of Research Councils and Innovate UK so there is a single grant programme all the way to market. We are not supposed to think of innovation in such a linear way and the reality is more complex, but nevertheless it is helpful – captured in technology readiness levels. These Catalyst Funds are organised around broad technological areas. The biggest by far is the Biomedical Catalyst Fund which scores highly in appraisal. The Treasury did put in £100 million but they are now closing down the funding.

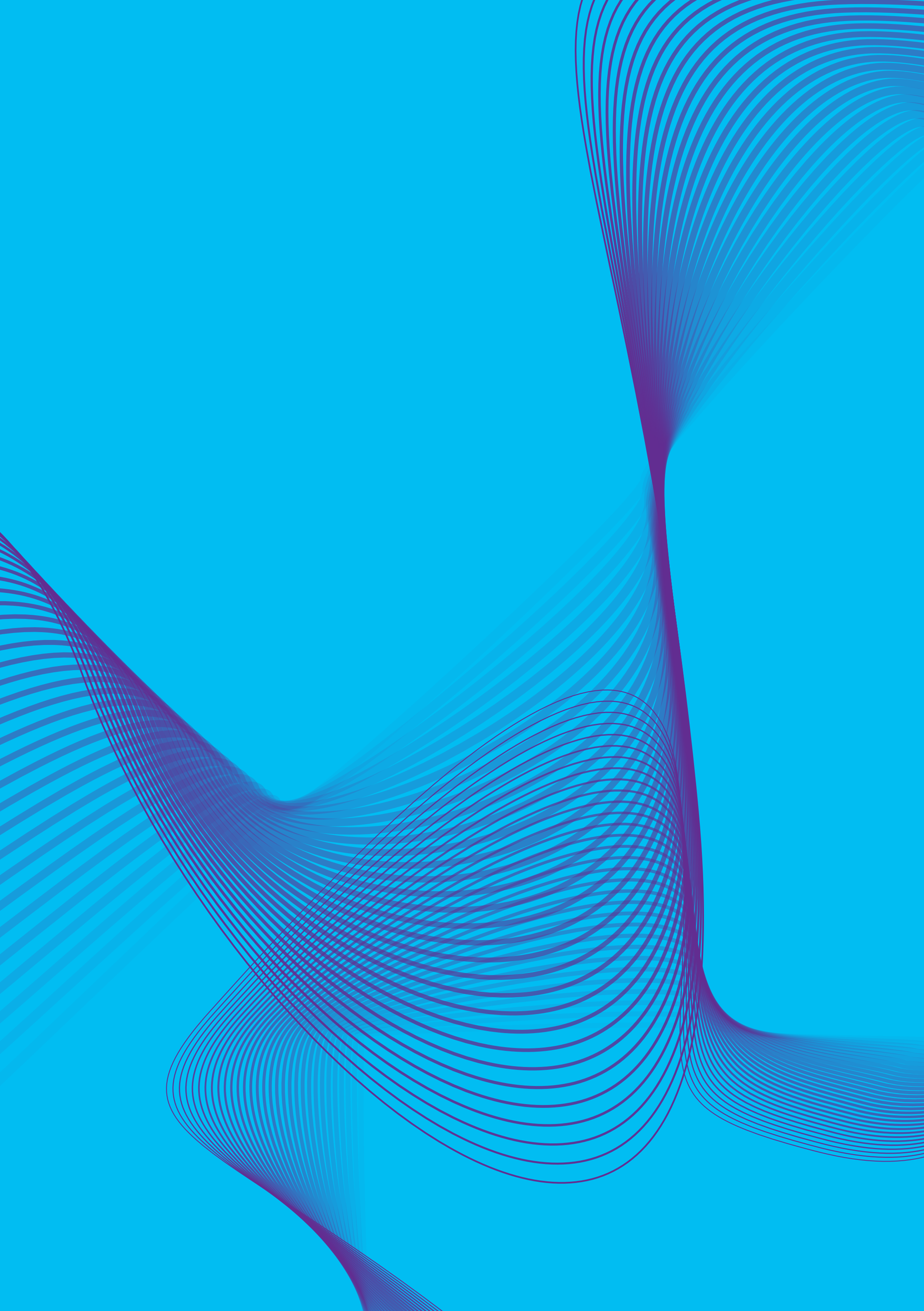
“We should use the big government procurement budgets to support innovation

There is one other policy option. These general purpose technologies will reach diverse markets. They are inherently disruptive – as Schumpeter said, “it is not the owner of stage coaches who builds railways.” Lead customers are crucial – look at how Waitrose led the creation of Ocado. We should use the big government procurement budgets to support innovation. We can learn from the US where the government is much more willing to drive innovation by acting as an “anchor customer”. We should have another go at learning from them. The Department for Transport for example has huge procurement programmes, where success demands innovation. **The Treasury could insist that 1 per cent of procurement budgets for their large infrastructure programmes is used to promote innovation.** This could be one way of interpreting the Conservative thinking in their background briefing on innovation and procurement. This could mean for example development of "digital twins" to transform design and management of new infrastructure. The money could also be used to develop and incorporate new technology in the infrastructure. This would boost shrunken Departmental R&D budgets and incentivise departments to think how new technology could help their large delivery programmes, from beginning to end. That would be applied to schools, prisons etc. Big contractors could also be required to secure and support innovation in their supply chain. The US is far better than us at using public procurement to pull innovative new technologies into use. It is a fantastic source of non-dilutive finance. Our Small Business Research Initiative (SBRI) is a pale imitation of America's SBIR which is described by their Small Business Administration as "America's Seed Fund." We should learn from them.

Why is this proving so difficult? What can we do about it?

This chapter is the whole story of Industrial Strategy in microcosm. We think we ought not to make these decisions but then find we have no framework or yardstick so then lose strategic insight. But this is not some experiment in socialism – it is just what they do across the advanced world from the US to Germany and Singapore. Indeed, it puts our patriotic technologists in a very difficult position when someone from a Singapore public agency turns up aware of exactly what they are doing and its value and wishes to invest in them when they cannot have any such dialogue with a British body. But it lies within our powers to make this happen and the 2.4 per cent target is an opportunity we can seize to spur it on.

There are already a range of key proposals for technology investment which have been appraised within Whitehall. The one risk with a further exercise scanning future technologies, is that it leads to more delay when the world is moving fast and we have already identified key technologies where we do have world-class research strengths and there are future business opportunities. We need to act now. The robotics strategy which has already been produced should be well funded. The network of synthetic biology centres should be sustained not run down. The biomedical catalyst fund should be replenished and other catalyst funds created. Advanced materials, a crucial foundational technology, should be funded as such. These are all options which have been carefully studied and appraised and can and should be supported now. **The government should immediately launch investment in key technologies**.



5. Conclusion and proposals

5. Conclusion and proposals

This paper sets out 12 specific practical proposals to boost British science and technology and get more value from it.

Some of our problems in applying research arise because much more of our research is conducted in universities where the incentives work against successful commercialisation. Three measures could shift them:

1. Announce that counting start-ups is no measure of a university's performance in promoting innovation

2. Universities should not go for such big stakes in companies created by their academic staff which is a barrier to private investment.

3. Remove the requirement that all elligible researchers should be submitted to the REF – to boost practical applied research, and also cut bureaucracy in academies.

   And, in addition, to ensure fair treatment of universities:

4. Move to fund the full economic cost of a research project instead of the 80 per cent at present.

   But also, an increase in spending would enable us to spend more outside universities in clusters where academic and business research come together. That needs a new mechanism to match the patient funding universities get:

5. Create a pot of public funding to support catapults, technology parks and other non-university institutes.

6. Restore greater freedoms to public research establishments.

We have failed to back new general purpose technologies on the long journey to market – expecting business to take more risk earlier than in the US. We can spot them (not perfectly but it is still worth doing) and then invest in them:

7. Create a new technology strategy based on expert technology horizon scanning.

   We should invest in these key technologies, galvanising private investment alongside public investment with programmes based on rigorous assessment of our comparative advantage:

8. The government should immediately launch new investment in key technologies.

   These are all bold objectives where Britain can be a world leader. Reinforce these by boosting popular innovation grants for business which have now been cut so much that only 5 per cent of applications are successful. And help fund these companies as they scale up:

9. Boost Innovate UK's SMART awards budget by around £300 million per annum.

10. Innovate UK, the BBB and BGF should align better so a new technology company can more easily access funding schemes to help it get started and grow.

11. Insist that 1 per cent of public procurement budgets for large infrastructure programmes is used to promote innovation.

    The processes for funding research can also be simpler:

12. Simplify cumbersome research council grant processes including the requirement to speculate on how research

might have impact. Equally important is to speed up the Whitehall process for reviewing and approving investments proposed by UKRI.

This is not an exhaustive list. There is, for example, a strong case for a sustained investment in infrastructure and e-infrastructure in particular, which could also be associated with investment in training the technicians who can operate the kit. Overall these proposals rest on an analysis of why we are failing to commercialise our research as ambitiously as we should and what we can do about it.

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