The idea of productivity

Author:
Diane Coyle
University of Cambridge[x]

Date:
June 2021

The Productivity Institute
Working Paper No.003

x Bennett Institute for Public Policy, The Productivity Institute

Key words
productivity, knowledge capital

Authors' contacts:
dc700@cam.ac.uk

Suggested citation

D. Coyle (June 2021) *The idea of productivity* The Productivity Institute Working Paper No.003

The Productivity Institute is an organisation that works across academia, business and policy to better understand, measure and enable productivity across the UK. It is funded by the Economic and Social Research Council (ESRC). The Productivity Institute is headquartered at Alliance Manchester Business School, The University of Manchester.

More information can be found on The Productivity Institute's website. Contact us at theproductivityinstitute@manchester.ac.uk

Abstract

Ideas fundamentally drive productivity, and hence living standards, over the long term. Ideas can contribute to innovative products and services, or to new ways of organising production and consumption. Knowledge capital, or the accumulation of ideas and know-how, therefore plays an important role in productivity growth, from research and inventions that are ultimately commercialised, to the way firms are organised and interact in markets, to the flows of knowledge in society. The production of knowledge itself is part of this wide scope of knowledge capital, which creates endogeneity, or feedback loops.

This means there is the potential for significant increasing returns to scale when new technologies are implemented. It also underlines the potential barriers created by co-ordination problems. A knowledge-based economy is one of virtuous or vicious circles, with policies playing an important co-ordinating role. This paper highlights key parts of the literature and sets out future areas for research.

This paper is part of a series of working paper outlining the key issues and questions of The Productivity Institute's key research themes. This paper covers the Knowledge Capital research theme. Other papers will provide an overview of Human capital, Organisational capital, Institutions & governance, Macroeconomic trends & policy, Measurements & methods, Geography & place and Social, environmental & technological transitions.

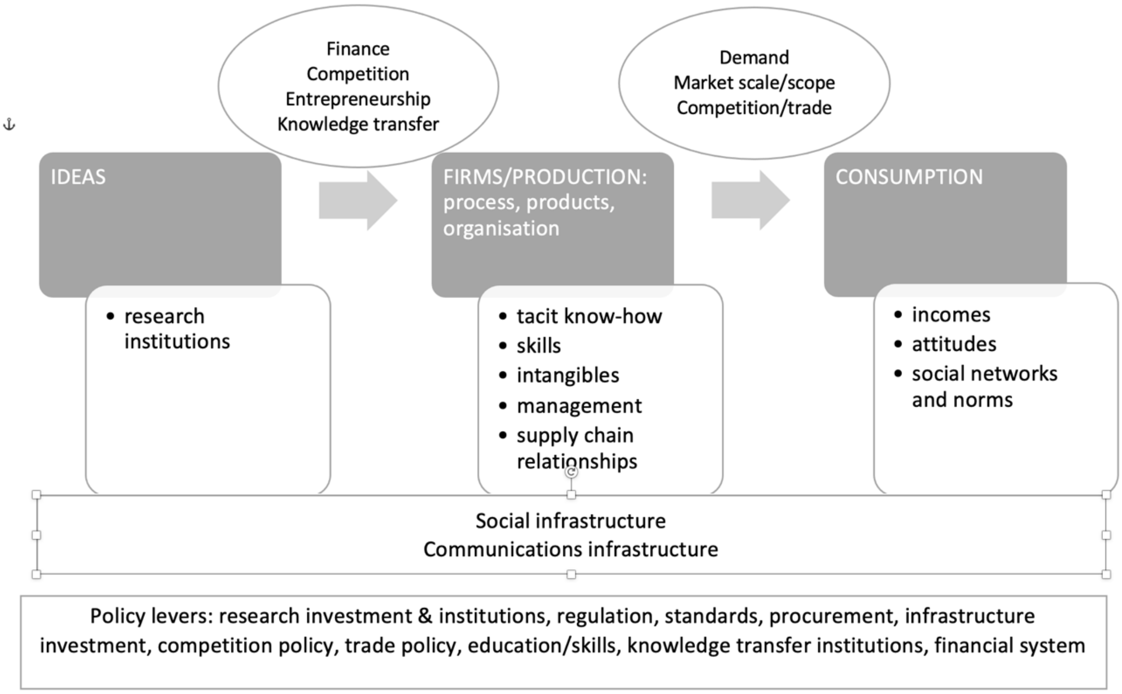
Introduction

Productivity is the engine of progress. Since economists began to ponder the process of economic growth and its translation into longer, healthier, happier lives, the creation and use of ideas has been central to the analysis. The history of technological progress, of invention and innovation, is a history of new ideas; so too is the history of production processes, business models, and consumer demands. These ideas can therefore include fundamental scientific discoveries, important inventions building on basic science, new ideas about improving products and services, or using them differently, or about methods of production and distribution. Ideas can be 'big' or 'small', either fundamental steps forward or tweaks. Economic historians have often focused on both the process of idea-generation itself, particularly at times of significant technological innovation (e.g., Mokyr 2009, Landes 2003), and alongside this, the institutions that enable ideas to be implemented (North 1999, McCloskey 2011), and the economic environment favouring them such as factor prices (Allen 2009) or financial conditions (Perez 2002). As Mokyr (2005) expressed it, "Economic decisions are made by individuals on the basis of certain beliefs they hold and knowledge they possess."

The economics literature identifies some particularly important inventions as general-purpose technologies (GPTs) that have applications across swaths of the economy, undergo continuing improvement, and therefore trigger broader waves of innovation (Bresnahan & Trachtenberg 1995). Examples include the printing press, steam power, electricity, and the internal combustion engine. The dynamic of their impact involves sometimes-long lags in standardisation, diffusion, and falling costs as production scales up; the pattern this generates has been characterised as a productivity J curve (Brynjolfsson et al 2021). Also essential are complementary innovation and investment, such as the cluster of ideas (smartphones, 3G mobile networks and 802.11 Wi-Fi, market design algorithms in apps) coalescing as today's always online everywhere world, or the cluster of innovations including the AC generation network, the dynamo, and the assembly line enabling mass factory and household electrification from the 1920s on (Paul David). A particularly significant type of GPTs consists of the inventions that are also methods of invention. One example is described in Zvi Griliches' classic study: "Hybrid corn was the invention of a method of inventing, a method of breeding superior corn for specific localities," (Griliches 1957). Another of relevance today is the cluster of artificial intelligence (AI) technologies, which are enabling new methods of discovery in other domains such as biomedical and materials research (Agrawal et al 2018).

The substantial innovation complementarities involved in the production of knowledge (as Arrow (1962) explained) imply the existence of co-ordination problems and increasing returns to scale. Their successful resolution through co-ordination will depend on market structures and institutions. It will also depend on the degree to which people are forward-looking, itself influenced by their institutional environment. The existence of co-ordination externalities and the feedback dynamics of endogenous growth with increasing returns imply the existence of multiple equilibria. As Bresnahan and Trachtenberg (1995) put it, markets will do too little too late; collective, co-ordinated action will determine the economy's trajectory. This is underlined by Stiglitz and Greenwald (2014), who build on Arrow's learning-by-doing in the context of information asymmetries to characterise economic development as the creation of a 'learning society'. Krugman (1991) shows that the selection will depend on how heavily the future is discounted, on the size of the external economies from co-ordination, and on the cost and hence speed of adjustment as economic activity shifts between activities. A considerable literature points out that increasing returns to scale for any reason imply multiple equilibria (Matsuyama 1991), such that the trajectory of the economy will depend on (the absence of) co-ordinated expectations. The scope for co-ordination – for example due to technologies whose wider adoption creates learning-by-doing or scale gains or the economies of scale arising from common standards – implies an opportunity for 'big push' policies that take the economy onto a higher growth trajectory, when low productivity implies the existence of distortions or misallocation of resources (Buera et al 2021).

Figure 1: The scope of knowledge capital



Ideas and knowledge – both codified and tacit – and the institutions that create and transfer them, are thus at the heart of the process of growth and productivity improvements. Productivity growth requires people in their capacity as both producers or workers and consumers to have new ideas, to accept and absorb ideas, to share them with others, and to act on them. The knowledge capital we are concerned with here, the accumulation and sharing of actionable ideas, applies end to end, from invention in the laboratory or in the computer, through innovation in production – the improvements in products and services and/or in the means of organising production – to the consumption or use of novel goods (Figure 1). For example, increasing productivity in food production through the use of GM seeds and the changes in farming methods enabled by them also requires consumer willingness to buy and eat foodstuffs made with the crops. Increasing productivity in cotton spinning and weaving in the 19th century benefited from a ready market for the fabric, but required the spread of skills among workers and changes to management systems during the transition to more capital-intensive factory production (Bessen 2003, 2015). Ideas require other ideas to come to fruition, implying that productivity gains as the result of new ideas require co-ordination, as ideas are attached to people, and often take the form of tacit knowledge rather than codifiable information. Co-ordination involves both individuals working in teams (Lam & Marsden 2017) and organisations in a system of innovation (Best 2018, Geels 2005). Knowledge capital therefore overlaps with human capital (Grimshaw &

Miozzo 2021), organisational capital (Driffield 2021) and also informs the possibilities for systemic transitions (Geels 2021).

This paper presents an overview of the role of ideas, or knowledge, in delivering improvements in productivity in this end-to-end framework, from the perspective of identifying open questions for research and policy. For despite an extensive economics literature, there is no obvious solution to today's productivity puzzle of near-flat productivity growth in the UK. Many potential ingredients have previously been identified, some such as skills inadequacy or poor management quality or weak institutions for commercialising basic research being very familiar in policy debates. Nevertheless, there has been less attention paid to the recipe for combining the various essential inputs to achieve gains in living standards across the economy.

The hypothesis here is that knowledge capital is an important missing link in understanding productivity performance; that it is attached to people as well as embedded in goods; and that it gains value from how people interact either as producers or consumers, or indeed as citizens in shaping political governance. This essay therefore addresses the key stages in the links between ideas and the use of products and services that improve people's lives. Research into knowledge capital will require greater understanding of the assets and economic activities involved, and also – because knowledge is not disembodied – the agency and social relations of people in their different capacities as inventors, producers, workers, consumers, citizens, and policymakers. This paper proceeds by setting out the general issues identified in the literature at the different stages of this end-to-end framework, summarising the UK-specific evidence, and identifying key research questions.

Research and invention

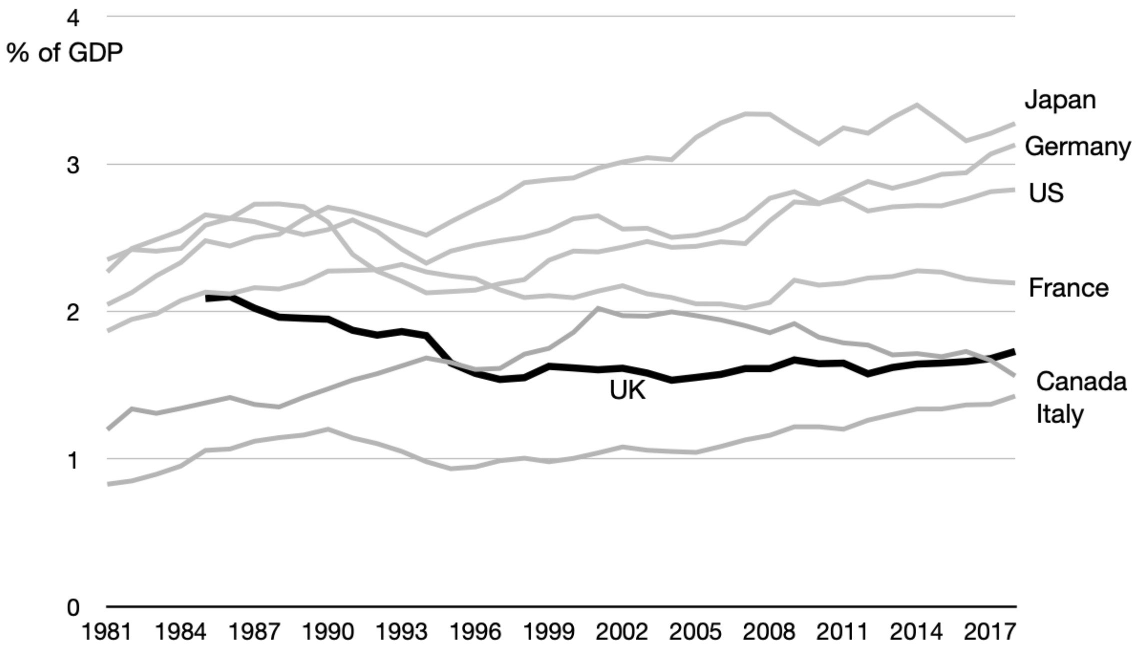
In this end-to-end process, the foundational step is basic research that delivers important discoveries and inventions (I adopt the convention that invention is a prior step to innovation, the latter referring to the development of commercialisable goods building on inventions. R&D refers to both basic research and early development on the journey to commercial application.) Basic research is considered a public good (as ideas are non-rival, although legal and technical devices such as patents or paywalls make them partially excludable) and governments accept the need for some public funding of research. There is a large literature ranging from case studies to cross-country regressions indicating that the social return measured by productivity gain to (private and public) investment in research is high. For instance, calculating the net social return as the discounted value of the per capita GDP gain divided by the share of research spending in GDP, and adjusting for non-R&D sources of productivity such as capital deepening or learning-by-doing, and for delays in diffusion, Jones and Summers (2020) estimate there is at least a fourfold long run average return to every R&D dollar spent in the US.

A historical approach to the measurement of the gains from technological progress often uses the concept of social savings: how much extra would society have had to pay to do what was possible after an invention if it had not existed? If demand is price inelastic, social saving is equal to aggregate consumer surplus; otherwise it exceeds consumer surplus, and by a large amount for inventions that cause large declines in price (Leunig 2010). Social saving is also equal to the rise in total factor productivity due to the invention weighted by the relevant industry's GDP share (Crafts 2004). In the cliometric literature, estimates of social saving are low, as their counterfactual is generally that society would have found other means to attain the same basic goods. However, estimates of social saving are challenging for a number of reasons, including the evidently flawed assumption that markets are competitive, such that price equals marginal cost, and that the initial factor allocation is efficient. For example, Fogel's famous (1962, 1964) work suggesting the social saving due to US railroads was small (as canals were a close substitute) has recently been challenged on the basis that the railroads enabled significantly more efficient resource allocation and production (Hornbeck & Rotemberg 2019). Crafts and Mulatu (2006) also point out that the location of firms, which is *endogenous* to transport infrastructure, affects their productivity. The deployment of a new technology, especially GPTs, can have large impacts on productivity when it triggers a more efficient allocation of factors across the economy. Finally, aggregate real growth and productivity growth figures can vary depending on the weights used, with chain-weighted figures growing more slowly after the base year than fixed-weight figures when there are significant price declines in some sectors, as is generally the case in periods of technological change (Whelan 2002): the trajectory over time looks different depending on the vantage point.

The empirical literature is and will likely remain contested, though, because there is a complex chain of links between invention and ultimately gains in productivity, and because the counterfactual against which the world with the invention is being compared is unknown. So, while it seems intuitive that inventions such as printing, steam power, rail travel or transistors have had revolutionary economic and social effects, and there is vast historical evidence, it is challenging to draw the causal line from spending on basic research to positive economic outcomes in standard econometric approaches. A further complication is isolating the role of national research spending on domestic economic outcomes when it is possible to import research findings from elsewhere, either through the flow of ideas in journals and patents, or embodied in products, such as cheap photovoltaic cells imported from China. Not everything has to be or can be invented everywhere. A key question for a country like the UK is linking national economic returns to national investment in research at the frontier, and how to identify comparative advantage in certain research areas. The UK has invested considerably less in R&D than other G7 countries (except Italy and for some periods Canada) for years, and less than the OECD average, as a share of GDP (Figure 2). The UK share has also trended down since the early 1980s. The Government has recently pledged that the figure should increase to 2.4% by 2027, a proportion not attained for nearly half a century. How will it affect productivity, if achieved?

One immediate impact will be on the regions where the money is spent. For example, Hausman (2012) finds that in the US university innovation stimulates economic activity which increases with geographic proximity to the university and initial city size. Valero and van Reenen (2019), drawing on location data for 15,000 universities globally, find that expanding the number of universities is strongly positively associated with future per capita GDP growth in their own region, and with evidence of spillover effects to neighbouring regions. They argue that the evidence points to the effect operating not just through direct expansion of expenditure but also through human capital accumulation and increased innovation in the region. The geography of research spending in the UK is uneven. Forth and Jones (2020) highlight the imbalance: the three regions including London, Cambridge, and Oxford account for 46% of public and charitable foundation R&D spending and have above average research intensity. Three other English regions (East, West Midlands, and the North West) have business research spending at or above the UK average but low public R&D spending. They argue that in addition to the national average research expenditure share being too low, the geographic imbalance and the remoteness of basic research from business R&D spending contribute to national research spending having an impact on productivity and growth that is less than it could otherwise be.

Figure 2 Total R&D expenditure as a share of GDP, G7 countries



Source: OECD (2021), Gross domestic spending on R&D (indicator). doi: 10.1787/d8b068b4-en (Accessed on 15 March 2021)

The UK context

When it comes to national impacts through frontier research, the UK has global strengths in some important areas of science and technology, such as AI, advanced materials, or biomedical research, despite the decades of under-funding. These are desirable economic activities, highly productive, export intensive, and employing a skilled workforce. The UK generally fares well in international comparisons on measures such as share of highly cited publications (BEIS 2019). The questions for research, policy and practice therefore concern the translation of areas of excellence in basic research into productivity impacts, both in terms of the national and regional impact, and in extending the range of research with economic impact potential being undertaken. Research is carried out in institutions which vary a good deal between countries, as does the structure of funding mechanisms (Janger et al 2019). The UK is above the OECD and EU averages in the proportion of basic research carried out in universities rather than other types of institution; the new Advanced Research and Invention Agency (ARIA) is intended to enable riskier research as it differs in its remit, although the details are as yet unclear – in particular the extent to which it will focus on basic or blue sky research or on translational research. Government policy has previously focused research funding on the 'golden triangle' of Cambridge, London and Oxford, such as for example locating the Crick Institute for biomedical research in London despite research strength in this field in the North West of England.

The UK is considered to be relatively weaker at translational research, which is closer to commercialisation, despite efforts such as the government-funded 'catapults' for areas ranging from satellite technology to cell and gene therapy. These are broadly considered success stories (BEIS 2021) but other opportunities to improve translation remain. For example, the combination of the NHS as a customer and excellence in both medical research and the pharma industry should make research translation in biomedicine straightforward; but even here translational weakness was identified as long ago as the Cooksey review (2006). Scientists continue to report barriers in the shape of factors such as culture gaps between universities and industry, the requirements of academic research processes, and institutional difficulties in interdisciplinary collaboration among researchers (Fudge et al 2016). This may reflect the bias toward funding universities, despite a history of government efforts to encourage universities to commercialise research (RSM 2018). But the incentive issues are complex. Just as with basic research, knowledge transfer practices vary widely across countries (Barjak et al 2015). In the UK, relatively few universities have intensive knowledge transfer relationships with industry, while the policy framework relies more heavily than in comparator countries on financial incentives for universities and researchers. The consequence appears to be that academics able to reap commercial success subsequently have reduced scientific productivity (Rossi & Athreye 2021). This is perhaps not surprising: if basic research is a public good, introducing market incentives into a market failure context should be expected to lead to under-production.

Other research questions

Therefore, there remain many open questions for UK policy with regard to the institutional landscape for research, including the scope for comparative studies. In addition to other G7 or OECD nations, the recent experience of rapidly-growing Asian economies may hold relevant lessons for institutional design. Given that there are many examples of UK basic inventions being successfully commercialised in other nations (graphene would be a recent one, AI may be becoming another), other areas to explore include:

- the supporting financial, institutional, and policy environment for basic research: are universities too dominant; is it possible to do inter-disciplinary research; do financial structures limit impact; are there adequate links with industry;
- the supporting institutional and policy environment for translational research and commercialisation: similar issues; in addition, the location of research and knowledge transfer in the context of supply chains and local economic structure;
- the regional impact of funding and institutions for research: can and should public sector funding achieve a more even regional distribution and what are the trade-offs;
- the financing of early-stage R&D. Although the UK venture capital sector is the largest in Europe, its pattern of investment (favouring management buyouts) differs from the iconic Silicon Valley focus on growing start-ups to the stage of a public market listing. The pathway to exit for founders in the UK is typically sale to an overseas buyer rather than an IPO. Why does British business invest relatively little in research by international standards? Is the UK state comparatively absent in these translation processes? If so, what kinds of intervention might exert the most leverage? If not, what explains the UK's relative weakness, such as regulatory or other barriers?

A more general set of questions concern the recent trope that ideas are not what they used to be: either they are becoming ‘harder to find’ (Bloom et al 2020), or they are inherently less transformative and productive than a previous wave of innovations (Gordon 2016). This is largely a US-focused literature, taking for granted that the US is the country closest to the frontier of knowledge. However, what happens at the frontier affects everyone else. Gordon argued that none of today’s digital technologies can compare with the impact of indoor plumbing or electricity, so productivity and importantly welfare gains will be inherently slower now than in the past – although he may have recently tempered his pessimistic view (2021 interview). Nordhaus (2021) debunks the idea of a future ‘singularity’ whereby computers and AI become so effective at innovating that a tipping point is reached beyond which knowledge and productivity snowball; he concludes from US macro data that there is evidence the famous Baumol effect (1966) leading to stagnating productivity is spreading through the economy.

On the other hand, it is hard to measure technological progress definitively, and the pessimistic takes focus on specific examples, where the typical technology S curve can be expected to take hold, often due to either physical limits or market saturation being reached. While the aggregate pace of productivity growth has certainly been slow since the mid-2000s, optimists about potential growth would point to a range of influential technologies (such as messenger RNA biomedical discoveries, improvements in battery storage at scale, the incorporation of LED lighting in new construction, additive printing of artificial organs, and more) that are likely to have a big economic and social welfare impact, and the reasons why these impacts may be slow in arriving. In general, the presumption that novel ideas result from the combination of existing ideas, combinatorial arithmetic can be expected to apply to idea generation, although the impact of the new ideas depends on how far apart in some sense the original ideas were, and hence how surprising their combination (Jones 2021). The interesting questions concern the extent to which slower productivity growth is inevitable, as the stagnationists argue, if so whether this is something to be concerned about (Vollrath 2020); and if not what are the processes or aspects of the environment that are delaying the translation of ideas into productivity.

In the UK context, the question of interest is what parts of the frontier the country and its devolved nations and regions could realistically expect to occupy, and how the basic R&D advantage in these areas contributes to productivity. Given that the economic welfare benefits ultimately stem from diffusion and use of new technologies, through what mechanisms does any individual nation or region benefit from frontier capabilities? And to what extent do these depend on the specifics of the institutional landscape for research?

ICTs and AI

Digital technologies attract much of the attention in public debate about invention and innovation, partly because they are often consumer-facing. However, the attention is warranted because as a GPT they enable invention across the economy. For example, basic research underpinning sectors ranging from pharmaceuticals (molecular discovery, protein folding) to energy transition (smart metering and grid management, autonomous vehicle systems) to construction (digital twins, monitoring services) depends on computational scale and power, rapid and reliable communications, and increasingly on machine learning techniques using 'big' data. The generation and use of knowledge, crystallised as structured data, is at the heart of the digital transformation of the economy.

The UK context

The US and China dominate in digital technologies on a range of metrics from market capitalisation or user base of digital platforms to AI patents to share of the cloud computing market (UNCTAD 2019). Nevertheless, the UK has strengths in a number of areas such as AI, fintech and blockchain technologies, chip design, robotics, and cyber-security. In addition to London, Cambridge has a globally significant technology cluster, attributed in part to the creation of the Cambridge Science Park in 1970. The UK is also one of the biggest markets for e-commerce globally, with the highest per capita online spend. In general, UK consumers are swift to adopt new digital technologies.

Research questions

There are significant measurement challenges in understanding the impact of digitalisation and the spread of AI. The standard economic statistics do not currently enable measurement of phenomena such as the use of cloud computing, for example (Coyle & Nguyen 2018), do not include data as an intangible asset (Statistics Canada 2020), and do not incorporate all relevant quality adjustments in price indices (e.g. Abdirahman et al 2020). Nakamura (2020) argues that the scope of mismeasurement due to innovation is accelerating, although the consensus in the economic statistics community is that measurement problems do no explain much if any of the productivity slowdown. Still, the phenomena that have transformed business and daily life, such as the growth of digital platforms and use of apps for everything, are almost invisible statistically. Although statistical surveys are being updated, it will be some time before they provide a clear lens on new economic structures. Meanwhile, the use of new data sources such as web scraped data, search data, satellite data or data provided by digital companies themselves, will help paint a more detailed picture.

Although measurement issues alone are unlikely to account for the productivity puzzle, it is also becoming evident that the use of digital and AI technologies and the associated intangibles, data and software, helps account for the difference in productivity between firms. Digital markets have characteristic winner-take-all dynamics caused by network effects and positive feedback data effects, as well as standard scale economies, leading to a pattern of 'superstar' firms (Tambe et al 2020; Autor et al 2019). Gutierrez & Philippon (2019) argue that the superstars have become less productive over time due to the lack of competition in their markets. Yet outside these prominent markets (search, social media, mobile operating systems), the intensity of use of digital technologies seems to be linked to firm-level productivity. As discussed further below, the hypothesis is that the use of the technologies is combined with organisational change and other complementary investments, including in employee skills.

At the more aggregate level, however, in addition to measurement efforts, the way digital technology is transforming value chains will require research. One accelerating phenomenon is servitisation in manufacturing and construction (Baines et al 2009 for a review). When the supporting services are taken into account, a different picture of the UK's manufacturing landscape, including areas of unremarked strength, may emerge (Hauge and O'Sullivan 2020). The time horizon of productivity improvements may change, as for example with servitisation in construction when engineering design companies or major contractors may remain engaged with projects over many years through provision of digital monitoring and maintenance services, rather than ending the relationship on completion. This presents in part a practical measurement problem (about the distinction between intermediate and capital spending and the allocation of capital services to different time periods) rather than a conceptual problem; but it is also the case that the ongoing services will reduce maintenance spend or time lost from service stoppages, as compared with the non-servitised counterfactual. The increasing adoption of AI is likely to transform industry ecosystems in areas such as autos, energy and also, as 'govtech' matures, in public services such as health or potentially also adult social care and education. The ability to capture value from the use of data and AI is legally contested; manufacturers such as John Deere and GM are increasingly using US courts to claim that purchasers of vehicles are in fact only renting information services, and are therefore obliged to continue to pay a regular subscription if they want to use the product. The farmer's purchase, which s/he was free to repair or resell, is thus transformed into a contractual data service attached to a tractor.

The measurement issues are universal, and constitute a significant research task. In addition, there are specific questions, as with the broader R&D landscape, both about the identification of areas of UK strength, barriers to growth and productivity, and the channels through which strength in basic and translational research at the knowledge frontier will affect both regional and national economic outcomes.

Innovation: Knowledge inside the firm

Using any new technology requires new skills and also organisational change. Information technology is distinctive because the ability to process information is a core part of a firm's productive capacity. The ability to do so differentiates firms, and the divergence is growing. Hall et al (2000) characterise this as e-capital, the firm-specific know-how generated by skilled workers. Brynjolfsson and Hitt (2000) estimated that high productivity firms had spent about ten times as much on organisational change as on the information and communications technologies themselves. Holmes, Levine & Schmitz (2012) model the transition process when adopting a new technology or techniques increases costs in the short term because of disruptions such as the need for workers to learn new things or the delays as organisational reporting lines and procedures change. Stokey (2020) considers two types of costs potentially shaping firms' use of novel technologies: adoption costs (likely to be higher for early adopters) and relative factor prices. Both may matter empirically, especially as digital technologies are complements to highly-skilled human labour, with a high relative wage in many places. Looking at productivity differences between firms in an early wave of adoption of digital, Faggio et al (2010) link the observed upward trend in productivity dispersion among UK firms to use of ICTs. Himbertet al (2020) find that the dispersion of productivity in 10 OECD countries has increased the most among intangibles-intensive firms. Thus, although the empirics are not straightforward (because of the need to find measures of this intangible knowledge or organisational capital), there is quite a body of evidence about the importance of information at the firm level.

Historical examples also shed light on the sometimes lengthy adjustment process involved in adopting and using a new technology. How innovators access knowledge is one issue; Berkes & Nencka (2020) show that more patenting occurred between 1883 and 1919 in US towns that had a Carnegie Library opened. What is today's equivalent of a public library in terms of knowledge-transfer mechanisms?

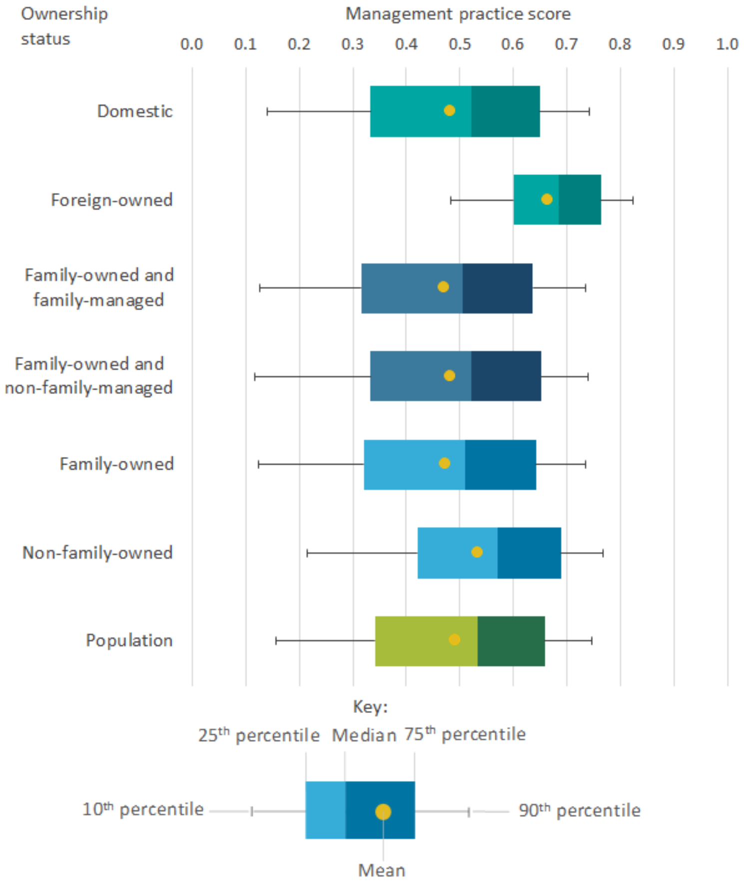
Bessen (2003, 2015) argues that early versions of spinning and weaving technologies required significant engineering skills to keep them operating smoothly but over time as the machinery became more standardised all workers acquired the skills to be able to operate their machines. Juhasz et al (2020) find that 19th century mechanisation involved significant organisational barriers in co-ordinating the workforce in a novel factory environment and with new division of labour into more specialised tasks. This both slowed the move to the factory system even when potential profitability made incurring organisational costs worthwhile, as employers learned what worked by trial and error, and meant the productivity impact showed later than the switch. Knowledge about complementary organisational innovations took a long time to diffuse across the economy. They argue that even if there are permanent productivity gains to be made from a post-pandemic pattern of working from home, there will similarly be a need for employers to learn how best to address the new co-ordination challenges.

In the management literature, a related debate concerns the absorptive capacity of organisations to use new ideas and technologies. This is defined as the processes using knowledge to achieve a 'dynamic organisational capability', and thus enhance productivity over time. While a longstanding concept (Nelson & Winter 1982, Cohen & Levinthal 1990), it has become a recent focus of attention due to digitalisation (eg Gebauer et al 2012, Grimshaw 2021).

The UK context

The extensive management literature has little overlap with economic analyses of productivity. One strand of research, however, focuses on several dimensions of management quality, including cross country comparisons (Bloom & Van Reenen 2007). The ongoing ONS survey of management quality based on this work in the UK is in its early days. Preliminary findings suggest higher quality practices in larger firms, foreign-owned firms, non-family-owned firms and the service sector (Figure 3). The ONS (2018: 39) reports: "Our conditional analysis found a statistically significant correlation between management practices and labour productivity, with an increase in management score of 0.1 associated with a 9.6% increase in productivity." (See also Awano et al 2018).

Figure 3 UK Management Practice Scores



Source: ONS: https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/labourproductivity/articles/experimentaldataonthemanagementpracticesofmanufacturingbusinessesingreatbritain/2018-04-06#deriving-management-practice-scores

Other research questions

The diffusion of knowledge capital among and within firms is therefore a key area where a richer understanding, integrating disciplinary insights, is needed. Research into management quality including through regular management surveys is just one aspect (Bloom et al 2016). The evidence of this work to date is that there are considerable differences in management even on some seemingly obvious dimensions of quality, where it seems surprising that certain practices have not spread more widely. These differences correlate with productivity differences between firms.

Beyond management quality, there is room to improve understanding about how firms acquire and use new ideas, whether these concern products and services or business process or business model innovations. Corrado (2021) points out that firms far more often create their own intangible assets rather than buying them in, in contrast to tangible assets. Many businesses undertake process changes without recording this as R&D spending; similarly if their internal changes involve hiring new categories of workers such as data scientists or software engineers. Astebro et al (2020) document a plunge in US start-ups led by scientists and engineers and argue that this is due to an increasing ‘burden of knowledge’ giving more established firms an advantage in establishing knowledge-management systems. One step in future research will therefore involve better measurement of a range of intangibles, including software and data – the development of sectoral statistics, and a range of methodological approaches to capture the use of intangibles and knowledge within the firm (Velu 2015). There has been considerable progress in measurement of intangibles at more aggregated levels – by sector or nationally. One recent example (Goodridge & Haskel 2020) measures the value of a firm’s data using employment of relevant skills, for instance. But more work will be needed to understand firm-level intangible investments. For instance, corporate accounting classes many intangible investment expenditures as expenses; Gu, Lev & Zhu (2021) show that highly innovative US firms that ultimately generate high productivity and profits report high accounting losses. These firms file for more patents and are granted more that turn out to be ‘blockbusters’.

Continuing inside the firm, in the economics literature there is relatively little work linking productivity outcomes to insights from either management studies of business model innovation or of the wider innovation system in which businesses are located. Business models are distinct from a firm’s organisation; they refer to the economic logic of production. A relevant example now is the choice of whether or not to operate as a digital platform; Coyle & Li (2021) show there is a large potential value to the platform approach by comparing different business models in the accommodation sector to estimate the value of data use. One approach using firms’ net asset turnover ratio as a measure of business model innovation finds it is significantly related to productivity differences among UK firms (Wannakrairoj & Velu 2021). There is a related question about the extent to which valued added that has become progressively more intangible in the ‘knowledge economy’ requires different social relations within firms (Coyle 1997, Haskel & Westlake 2017). One hypothesis is that high productivity is linked to high levels or trust or social capital within organisations, as this reduces the transactions costs involved in the spread of tacit knowledge (Adler 2001). Mayer (2020) argues that the adoption of an explicit corporate purpose has economic significance through enhancing trust, thus alleviating constraints on activity or reducing transactions costs, and enhancing productivity.

For firms do not operate in a vacuum but are located in economic and social networks, and are themselves social institutions comprising an important part of people’s lives. How does the structure of these relationships affects firms’ ability to learn and to implement new knowledge? Do their immediate geographic networks or their supply chain networks matter more? Supply chains have been described as ‘knowledge conveyor belts’ (Syverson 2011). Or is it instead common ownership that leads to knowledge transfers? One study (Griffith et al 2006) found that UK firms with a *US* R&D presence had higher productivity growth than other firms. And in general UK firms owned by multinationals have higher productivity (Griffith et al 2004, Haskel et al 2007). How does the observed shift from hierarchical organisations and vertical chains to flatter internal structures and broader ecosystems influence knowledge diffusion? How is the use of digital technology changing organisations and business processes, including any lasting shift to working remotely, and what is the link between levels of trust and delegation within firms and productivity? What accounts for the observed pattern of a strong link at regional (or national) level between measured economic complexity and productivity or earnings, and what policy interventions might influence the self-reinforcing dynamics involved, leading to growing divergence between successful and ‘left behind’ places (Mealy & Coyle 2021)? How does the UK’s ‘innovation system’ as a whole relate to productivity outcomes, either regionally or nationally or in different sectors of the economy, and how well will it enable businesses to adapt to the current and future technological transitions (Geels, 2005, 2021)? There are thus many open questions about knowledge flows at firm level, as well as how these firm-level productivity effects translate to sectoral or regional outcomes. Consideration of the acquisition and use of knowledge inside the firm leads naturally to consideration of the wider social context in which businesses are operating.

Knowledge in the economy

In a classic article, Mancur Olson (1996) observed that differences in average productivity levels between countries are simply too large to be explained by factor endowments and flows; the quality of policies and institutions between countries accounts for most of the observed differences. A firm with unchanged technology and inputs could thus be more productive if somehow transplanted to another environment. Although it is important to understand the sources of frontier ideas and the drivers of productivity differences between firms or within sectors of the economy, productivity performance cannot be reduced to these individual parts. The key insight of endogenous growth theory (Romer) is that knowledge spillovers are central to the path of the economy. These spillovers are often considered in the literature to be manifest either as human capital – embodied as people's measurable skills – or at least in part as patents or codified knowledge. But, while convenient in terms of measurement, these are a small part of the story. The flow of knowledge in the economy and society is complex. It is possible that even if ideas are plentiful, and not at all hard to find, they may have grown harder to *use*, for reasons relating to policy or institutional barriers or weaknesses (Coyle, in progress).

The UK context

The issues in this area are universal; it is institutional characteristics that differ between countries, and it is challenging to identify the particular parts of the institutional landscape that might particularly hinder UK productivity growth. For example, concentration has been on the increase across most OECD economies implying a general competition policy challenge. Nevertheless, the impact of competition policy and sector regulation are clearly important, both in growing digital markets (Furman et al 2019), formerly privatised utility sectors, and economically important sectors such as finance and pharmaceuticals. For example, the Financial Conduct Authority has been praised for its innovative use of 'regulatory sandbox' since 2016, with observers linking this to the number of fintech start-ups and their access to scale-up funding (Perry 2019). Might this model work for other sectors?

The absence of finance for growing companies has long been identified as a UK-specific problem. Although the UK has Europe's largest VC sector, the majority of funds go to larger established firms including through management buyouts [£16.9bn out of a total of £22.3bn in 2019 according to industry figures]. British commercial banks lend relatively little to business, and little of that to SMEs (Lloyds Banking Group 2020). In the technology sector, young firms and their investors will look to exit through sale to an overseas purchaser rather than through an IPO; although the productivity consequences may be favourable, the concern is that the core research capabilities will subsequently move abroad.

Corporate governance shortfalls have been identified, leading in particular to short-termism, given the UK's distinctly 'Anglo-Saxon' model. The Kay Review (2012:9) identified the "[D]ecline of trust and the misalignment of incentives throughout the equity investment chain" as principal contributory factors in short-termism and the failure of public equity markets to provide finance for investment, and in turn a policy and regulatory framework unduly based on efficient market theory and therefore over-reliant on information disclosure despite the asymmetries of information and thickets of principal-agent problems. Research into the effects of *corporate governance* on UK productivity has generally reflected preoccupations of the day, such as the stakeholder versus shareholder models debate in the 1990s. There are obvious empirical challenges in testing hypotheses, including simultaneity, sample bias, selection bias, interactions with other variables such as competition and measurement issues (Börsch-Supan & Köke, 2002). Nevertheless, there are many hypotheses concerning the shortfalls specific to the UK that would warrant investigation. Like an Agatha Christie novel, there are many possible culprits including:

- Executive pay practices encouraging share buybacks, discourage investment, and thus reduce productivity;
- Unitary board structures that exclude employee voices and thus discourage training and important HR practices;
- Short-termism when businesses depending heavily on intangibles (e.g., professional services, software) and relationships require long-term decision structures.

Other research questions

One set of influences is defined by the *policy environment*. Policies with respect to intellectual property (IP) are important: patents and copyrights, open standards, and – increasingly central – data access and open data policies. Data policies including their impact on innovation and growth are only now being shaped in the UK as elsewhere, as recognition of the role of data in productivity and market structure grows (Furman et al 2019, National Data Strategy 2020). With data, as with other forms of legally-defined IP, there is a trade-off between rewarding past invention to provide future incentives, and enabling wider invention or innovation through the use of non-rival ideas. Recent evidence suggests the cost of foreclosing further innovation through IP protection is higher for GPTs than for less pervasive technologies (Nagler et al 2021). The balance between costs and benefits is not yet well understood for data, where the legal ownership by default sits with companies that have collected data and there is no time limit on their ability to keep it proprietary (Coyle & Diepeveen 2021, Viljoen 2020). Yet part of the value of data as a knowledge asset is its potential to contribute to future innovation; as with any asset, future uses affect current values, and there is a considerable range of optionality due to the combinatorial arithmetic that applies to ideas.

A further set of policy questions concerns the role of corporate governance and the potentially adverse productivity impact of short-termism and common ownership (Gutierrez & Philippon 2017). Competition policy is also fundamental to the ability of and incentive for firms to apply new ideas (Syverson 2004). This is a period of considerable change in the application of competition policy to digital markets in the UK; the Competition and Markets Authority is establishing a new Digital Markets Unit that will combine traditional tools such as merger control, albeit updated for the specific characteristics of digital markets, and a new set of ex ante regulations including a code of conduct and requirements for data interoperability. These changes in the UK and other jurisdictions are, though, occurring in a context of a trend toward increasing concentration in many sectors, not just those with digital platforms (Philippon 2019). Concentration makes it harder to measure firm-level productivity, to the extent that revenues reflect market power rents – although, as Syverson (2011) notes, this measurement artefact is unlikely to account for the very large differences observed between firms. Competition policy (and trade policy, affecting competition from overseas) influences the Schumpeterian process of entry and particularly exit. The selection effect operating via the inability of low productivity firms to stay in business is an important driver of national productivity (Crafts 2004, Buccirossi et al 2013). It also affects the incentives of firms to undergo the disruption costs due to adopting new technologies, described above. Competition policy may also affect industry structure, for example, by affecting vertical integration and supply chain relationships. Backus (2020) finds that selection effects do not seem to account for rising observed average productivity in the industry he studies (ready mix concrete); rather, it is a treatment effect of more intense competition on managerial behaviour.

Stepping beyond these specific policy areas, there are wider questions about the *institutional environment*. Corrado (Brookings 2021) describes a range of investments in knowledge creation – education and training, public and private research, development and marketing research, organisational and management improvement – as “strategic investments in the long-run growth of individual companies and the economy.” Where these are provided by the public sector, they should be regarded as infrastructure when they produce a long-lived stream of returns in the form of a direct flow of ideas or knowledge. Public information assets (data or research) are collective intangibles, likely to be particularly important. For example, geospatial data is reference data on which many productive services can be built. Data policies to encourage data sharing and open data will create innovation opportunities (Coyle et al 2019).

There is an emerging literature on the role of social infrastructure in shaping economic outcomes (Kelsey & Kenny 2021). In a number of contexts, the urban environment seems to facilitate innovation, for example by making it easier to meet new people and exposing people to a wider range of ideas. Thus, amenities such as pubs and cafes or libraries can affect economic trajectories (Berkes & Gaetani 2020, Roche 2020). Going online makes it easier to access a wider range of ideas of course, but perhaps at the expense of tacit knowledge. Non-market sector productivity is of interest in itself as a component of aggregate productivity; for example, there has been a debate about how to measure and understand education and health service productivity during the pandemic, as this has affected economy-wide measures (Coyle et al 2021). Some public services are also increasingly understood to be components of social infrastructure, as important aspects of physical infrastructure and the built environment, including through shaping social capital and hence the flow of knowledge through social networks (Tóth et al 2021).

Social capital, social networks, and social norms will also shape ultimate demand for innovative products and services. A recent example is the role of attitudes to vaccines in influencing the take-up of Covid-19 vaccines, with enormous consequences for human capital (to put it only in dry economic terms). Although causality is never likely to be established – as the simultaneity is a feature not a bug – social capital is strongly associated with productivity, at least at the aggregate level (Coyle & Lu

2020). As Dasgupta (2009) notes, social capital can itself be interpreted as part of an economy's production technology, a shorthand for the ability to co-operate in the use of resources in production. Its impact can therefore be expected to be pervasive. For example, it could be linked to corporate governance in terms of the 'bridging capital' social networks of corporate boards (Booth-Bell 2018).

The percolation of knowledge around the economy, outside the boundaries of the firm and the research organisation, is therefore a broad terrain. Key research questions include the effectiveness of competition policy, in the light of increasing concentration in many sectors, and the role of weak competition (as opposed to differentiated firms-specific knowledge capital or intangibles) in explaining this; how to shape data policies to respect both privacy and commercial confidentiality while enabling competition and creating a stock of collective intangibles to enable innovation; how to measure and strengthen collective intangibles, encompassing productivity in the parts of the non-market sector that may contribute to a productive institutional landscape; and the social influences on the demand side of the end-to-end determination of knowledge capital flows.

Productivity for progress

A final set of considerations relate to some broader societal questions about productivity. Economists' understanding of productivity differs from an engineering perspective on the physical efficiency of relationship between inputs and output. It takes account of the value of output captured in the relationship between prices and preferences. Thus, although all bits of data are identical physically, consumers attach different values to different 1s and 0s of content. Although labour productivity is the easiest to measure, the gold standard is total factor productivity (TFP), ideally with all inputs (and their quality) accounted for, in the time period in which real output is produced. In this ideal world, TFP truly is the 'measure of our ignorance' (Abramowitz 1956), a reflection of pure gain in organising, which is something of a paradox in thinking about the link between knowledge capital and productivity. Knowledge fundamentally drives real output and welfare gains, but the better its roles are accounted for, the lower a measure of 'true' TFP would be.

Needless to say, the ideal has not been realised. Equally, the interest of policymakers is in the growth in real output, the economic welfare gains associated with this, and their distribution. A serious omission from most macroeconomic accounts of productivity is the role of natural capital assets. Even purchased material inputs such as minerals or timber or crops are not always accounted for in empirical work, and unpriced natural capital is not. Baptist and Hepburn (2013) show that, like any omitted intermediate, this will bias upward productivity estimates. Brandt et al (2017) show that the necessary adjustment to productivity measures depends on the difference between the rate of depletion or extraction and the rate of change of other inputs. Førsund (2018) surveys the literature to date on incorporating nature into productivity measures. However, there are other aspects of natural capital assets, in addition to resource use and the impact on material balances, that are likely to have longer term adverse consequences on productivity. One example is the effect loss of biodiversity or deteriorating soil quality will have on agricultural productivity (Dasgupta 2021). Assuming that private insurance markets cannot enable organisations to purchase cover (as seems likely given the inability of many households already to purchase flood insurance), risk-adjusted productivity measures are needed to incorporate the potential impact of climate change effects such as flooding or drought. For example, changing weather patterns may reduce the productivity of existing infrastructure.

A related issue, also highlighted by the strains on global supply chains at various stages of the coronavirus pandemic, is the question of the relationship between resilience and productivity. Resilience might be defined in several ways, but one illustration would be the contrast between the impact of severe cold weather in early 2021 on Texas and on neighbouring Oklahoma and Arkansas, Texas losing power and closing roads while its neighbours did not experience long outages and were able to clear the roads. The difference lay both in precautionary investment by the latter (for example in rarely-used snow ploughs) and the institutional and policy framework (for example in the regulation of the electricity generating industry). Another example would be the investment and ongoing costs incurred by Crossrail in collecting and storing large numbers of soil core samples from exploratory drills, which enabled its tunnelling to occur without hitting unexpected geological obstacles by incorporating design changes thanks to the information gathered (Mansfield 2015). The samples are now also available for others who want to dig in the city to use, including London Underground, and utilities companies. Similar questions can be posed about a wide range of infrastructure and products: how should we think about how much physical redundancy or economic insurance would be optimal?

A final set of wider questions relates directly to the link between productivity and economic welfare. There are links between productivity and well-being within firms and also at more aggregated levels. A recent survey (Isham et al 2021) concludes that there is evidence at firm level that worker well-being contributes to firm productivity, although the channel of causality may require considerable resources for the effect to manifest itself. They also conclude there is evidence that single minded pursuit of productivity growth harms workers' well-being and may therefore be counterproductive even in terms or productivity outcomes. The firm-level evidence is generally experimental. Di Maria et al (2020) argue for a causal link from subjective well-being to productivity among 20 European countries on the basis of production function estimation with well-being as an input. However, this evidence base is not large, particularly when it comes to the channels through which effects operate in either direction. Nor is enough known about the distributional aspects or the geography of the productivity-wellbeing link. For example, is the impact of a change in well-being on productivity larger for certain groups of workers (such as those with lower-than-average productivity)?

Conclusion

The common-sense view that productivity means getting more output for the same inputs obscures the complexities of the concept, particularly in an economy where services rather than products dominate expenditure, and where products themselves are increasingly differentiated. The list of inputs that are taken into account has gradually expanded, in addition to the increasingly sophisticated quality-adjustment of labour and capital. The range of measured intangibles has increased, yet there is a strong case for including others, not least data – although, like ideas, data is also an output. Another set of omitted inputs comprise natural capital services, and some of these are hard to measure too, such as preserving biodiversity or mitigating or averting climate change impacts. Similarly, the role of social capital in production should also be considered explicitly, not least as a key vector for the transfer of tacit knowledge and determinant of the innovation system. A final omitted input is time, rarely if ever explicitly accounted for in the analysis of productivity and growth. Yet for an economy largely consisting of services, both production and consumption require an accounting for time as well as money, and particularly in the case of digital services where consumers' time use is at the heart of the business model. Turning to the concept and measurement of output, its definition could be similarly expanded. Economics welfare depends on outcomes rather than directly on outputs. Questions of risk-adjustment and resilience turn attention to (potential) output over time rather than in one time period. Outcomes may be thought of in terms of well-being (and its distribution), although well-being may also be an input.

The vast economic literature on productivity has focused for the most part on a narrower set of questions. The availability of data means there is far more empirical evidence on manufacturing than on services, and very little on the non-market sector – little on government and almost none on non-profits, despite the scale of their activity and its potential contribution to economic welfare outcomes. There are insights from management studies, innovation studies, and systems or complexity science, that can contribute to the economic debate about productivity. This essay has considered the role of knowledge (in what is often referred to as the 'knowledge economy') in a broad scope, setting out some possible avenues for research to understand the scope for improving productivity, and consequently living standards and broader outcomes.

References

Abdirahman, M., and Coyle, D. and Heys, R. and Stewart, W. (2020). "Telecoms Deflators: A Story of Volume and Revenue Weights," Economic Statistics Centre of Excellence (ESCoE) Discussion Papers ESCoE DP-2020-11, Economic Statistics Centre of Excellence (ESCoE).

Abramovitz, M. (1956). “Resource and Output Trends in the United States since 1870,” *American Economic Review*, V. 46: 5-23.

Adler, P.S. (2001). “Market, Hierarchy, and Trust: The Knowledge Economy and the Future of Capitalism”, *Organization Science*, 12(2):215-234. https://doi.org/10.1287/orsc.12.2.215.10117

Agrawal, A., McHale, J. and Oettl, A. (2018) “Finding Needles in Haystacks: Artificial Intelligence and Recombinant Growth”, in The Economics of Artificial Intelligence: An Agenda, edited by Ajay Agrawal, Joshua Gans, and Avi Goldfarb, 149–74. Chicago: University of Chicago Press.

Allen, R.C. (2009). *The British Industrial Revolution in Global Perspective*. Cambridge: Cambridge University Press.

Andrews, D., Criscuolo, C., and Gal, P.N. (2015). “Frontier Firms, Technology Diffusion, and Public Policy: Micro Evidence from OECD Countries.” OECD The Future of Productivity: Main Background Paper 2.

Arrow, K. (1962). “The Economic Implications of Learning by Doing”, *The Review of Economic Studies, 29*(3), 155-173. Retrieved March 21, 2021, from http://www.jstor.org/stable/2295952

Astebro, T.B.,Braguinsky, S., and Ding, Y. (2020). Declining Business Dynamism Among Our Best Opportunities: The Role of the Burden of Knowledge (August 31). ISER DP No. 1099, 2020, HEC Paris Research Paper No. ECO/SCD-2020-1397, Available at http://dx.doi.org/10.2139/ssrn.3684945

Autor, D., Dorn, D., Katz, L.F., Patterson, C., and Van Reenen, J. (2019). “The Fall of the Labor Share and the Rise of Superstar Firms.” NBER Working Paper 23396.

A firm-level perspective on micro- and macro-level uncertainty An analysis of business expectations and uncertainty from the UK Management and Expectations SurveyGaganan Awano, et al ESCOE DP 2018-10

Backus, M. (2019). “Why is Productivity Correlated with Competition?”, *Econometrica, 88*(6), 2415-2444.

Baines, T.S., Lightfoot, H.W., Benedettini, O. and Kay, J.M. (2009), "The servitization of manufacturing: A review of literature and reflection on future challenges", *Journal of Manufacturing Technology Management*, Vol. 20 No. 5, pp. 547-567.

Baptist, S. and Hepburn, C. (2013). Intermediate inputs and economic productivity. *Philosophical Transactions of the Royal Society A*, 371(1986). 20110565.

Barjak, F, Es-Sadki, N, & Arundel, A. (2015). The effectiveness of policies for formal knowledge transfer from European universities and public research institutes to firms. *Research Evaluation,24*(1), 4-18.

Baumol, W.J. (1966). *Performing Arts, The Economic Dilemma: a study of problems common to theater, opera, music, and dance*. Cambridge, Mass.: M.I.T. Press.

BEIS (2019) International comparison of the UK research base, 2019. Available at: https://www.gov.uk/government/publications/international-comparison-of-the-uk-research-base-2019. Accompanying note available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/815400/International_comparison_of_the_UK_research_base__2019._Accompanying_note.pdf

BEIS (2021) Catapult Network Review https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/975595/catapult-network-review-april-2021.pdf

Berkes, E. and Gaetani, R. (2020) The Geography of Unconventional Innovation, *The Economic Journal*, ueaa111, https://doi.org/10.1093/ej/ueaa111

Berkes, E. and Nencka, P. (2020).Knowledge Access: The Effects of Carnegie Libraries on Innovation. Available at SSRN: https://ssrn.com/abstract=3629299 or http://dx.doi.org/10.2139/ssrn.3629299

Bessen, J. (2003). "Technology and Learning by Factory Workers: The Stretch-out at Lowell, 1842", *The Journal of Economic History, 63*(1), 33-64. Retrieved April 26, 2021, from http://www.jstor.org/stable/3132494

Bessen, J. (2015). *Learning by doing: The Real Connection Between Innovation, Wages, and Wealth.* London: Yale University Press.

Best, M. (2018*). How Growth Really Happens*. Princeton University Press.

Bloom, N. and Van Reenen, J. (2007). "Measuring and Explaining Management Practices across Firms and Nations", *Quarterly Journal of Economics,* 122 (4): 1351–1408.

Booth-Bell, D. (2018). "Social capital as a new board diversity rationale for enhanced corporate governance", *Corporate Governance*, Vol. 18 No. 3, pp. 425-439. https://doi.org/10.1108/CG-02-2017-0035

Brandt, N., Schreyer, P. and Zipperer, V. (2017). Productivity Measurement with Natural Capital. Review of Income and Wealth, 63: S7-S21. https://doi.org/10.1111/roiw.12247

Bresnahan, T. F., and Trajtenberg, M. (1995). "General Purpose Technologies 'Engines of Growth'?", *Journal of Econometrics* 65 (1): 83–108.

Brynjolfsson, E., and Hitt, L.M. (2000). "Beyond Computation: Information Technology, Organizational Transformation and Business Performance." *Journal of Economic Perspectives,* 14 (4): 23–48.

Brynjolfsson, E. Rock, D. and Syverson, C. (2021) The Productivity J-Curve: How Intangibles Complement General Purpose Technologies, *American Economic Journal: Macroeconomics*, 13(1): 333–372 https://doi.org/10.1257/mac.20180386333

Buccirossi, P., Ciari, L., Duso, L., Spagnolo, G., and Vitale, C. (2013). Compeittion policy and productivity growth: an empirical assessment. *The Review of Economics and Statistics, 95*(4), 1324-1336.

Buera, F.J., Kaboski, J.P., and Townsend, R.M. (2021). From Micro to Macro Development. NBER Working Paper No. w28423. Available at SSRN: https://ssrn.com/abstract=3781310

M. Cohen, D.A. Levinthal (1990). Absorptive capacity: A new perspective on learning and innovation *Administrative Science Quarterly*, 35 (1), pp. 128-152

Corrado, C, (2021). Intangible Capital, in eds Dynan & Sheiner, Brookings Institute forthcoming.

Coyle, D. (1997). *The Weightless World: strategies for managing the digital economy*. MIT Press.

Coyle, D., Dreesbeimdieck, K., and Manley, A. (2021). *Productivity in UK healthcare during and after the Covid-19 pandemic*. The Productivity Institute working paper No.002.

Coyle, D., Diepeveen, S., and Wdowin, J. (2020). The Value of Data. Cambridge: Bennett Institute for Public Policy (in partnership with the Open Data Institute). Available at: https://www.bennettinstitute.cam.ac.uk/media/uploads/files/Value_of_data_Policy_Implications_Report_26_Feb_ok4noWn.pdf

Coyle, D. and Diepeveen, S. (2021). *Creating and Governing Social Value from Data*. (Under submission)

Coyle, D. and Li, W. (2020). The Data Economy: Market Size and Global Trade. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjmqvLqg57wAhUJfMAKHckIDbgQFjADegQIEBAD&url=https%3A%2F%2Fwww.aeaweb.org%2Fconference%2F2021%2Fpreliminary%2Fpaper%2FZiDK3zHb&usg=AOvVaw2WSs1SloJaWuSIiWDck9_S

Coyle, D. and Lu, S. (2020). Trust and productivity growth – an empirical analysis. Bennett Institute working paper. Bennett Institute for Public Policy, Cambridge.

Coyle, D. and Nguyen, D. (2018). "Cloud Computing and National Accounting," Economic Statistics Centre of Excellence (ESCoE) Discussion Papers ESCoE DP-2018-19, Economic Statistics Centre of Excellence (ESCoE).

Crafts, N. (2004). “Steam as a General Purpose Technology: A Growth Accounting Perspective.” *Economic Journal* 114 (495): 338–51.

Crafts, N., and Mulatu, A. (2006). “How Did the Location of Industry Respond to Falling Transport Costs in Britain Before World War I?”, *The Journal of Economic History, 66*(3), 575-607.

Dasgupta , P. (2009). A matter of trust: social capital and economic development. SCI Discussion Paper Series. Manchester: Sustainable Consumption, Working Paper No. 1. Available at: https://www.escholar.manchester.ac.uk/uk-ac-man-scw:77434

David, P.A. (1990). “The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox.” *American Economic Review,* 80 (2): 355–61.

DiMaria, C.H.,Peroni, C., andSarracino, F. (2020). "Happiness Matters: Productivity Gains from Subjective Well-Being," Journal of Happiness Studies, Springer, vol. 21(1), pages 139-160, January.

Driffield, N. (2021). Understanding productivity: Organisational Capital perspectives, The Productivity Institute, working paper (forthcoming).

Faggio, G., Salvanes, K.G., and Van Reenen, J. (2010). "The Evolution of Inequality in Productivity and Wages: Panel Data Evidence." Industrial and Corporate Change, Oxford University Press, vol. 19(6), pp 1919-1951.

Fogel, R. W. (1962). "A Quantitative Approach to the Study of Railroads in American Economic Growth: A Report of Some Preliminary Findings", *The Journal of Economic History, 22*(2), 163-197. doi:10.1017/S0022050700062719

Fogel, R.W. (1964). *Railroads and American Economic Growth.* Baltimore: John Hopkins University Press.

Førsund, F.R. (2018) Productivity measurement and the environment, chapter in Grifell-Tatjé, Emili, Lovell, C. A. Knox, & Sickles, Robin C. (2018) The Oxford Handbook of Productivity Analysis. Oxford: Oxford University Press.

Fudge, N., Sadler, E., Fisher, H.R., Maher, J., Wolfe, C.D.A., McKevitt, C. (2016). Optimising Translational Research Opportunities: A Systematic Review and Narrative Synthesis of Basic and Clinician Scientists' Perspectives of Factors Which Enable or Hinder Translational Research. PLoS ONE 11(8): e0160475. https://doi.org/10.1371/journal.pone.0160475

Furman, J., Coyle, D., Fletcher, A., McAuley, D. and Marsden, P. (2019). Unlocking digital competition: report of the digital competition expert panel, March. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/785547/unlocking_digital_competition_furman_review_web.pdf

H. Gebauer, H. Worch, B. Truffer (2012). Absorptive capacity, learning processes and combinative capabilities as determinants of strategic innovation *European Management Journal*, 30 (1) pp. 57-73

Geels, F (2005), *Technological Transitions and System Innovations: A Co-evolutionary and Socio-technical Analysis*. Edward Elgar.

Geels, F., J. Pinkse and D. Zenghelis (2021), Productivity opportunities and risks in a transformative low-carbon and digital age, The Productivity Institute, working paper (forthcoming).

Goodridge, P. and Haskel, J. (2020). We see data everywhere except in the productivity statistics (unpublished working paper).

Gordon , R. (2016). *The rise and fall of American growth: the U.S. standard of living since the Civil War.* Princeton University.

Gordon, R. (2021). A conversation with Professor Robert Gordon on the rise and fall of American growth (interview with UCLA Anderson). Available at:https://www.anderson.ucla.edu/centers/ucla-anderson-forecast/forecast-direct/february-2021

Griffith, Rachel, Stephen Redding and Helen Simpson (2004). Foreign Ownership And Productivity: New Evidence From The Service Sector And The R&D Lab, IFS Working Paper. https://ifs.org.uk/wps/wp0422.pdf

Griffith, R., Huergo, E, Mairesse, J. and Peters, B. (2006). Innovation and productivity across four European countries. *Oxford Review of Economic Policy, 22*(4), 483-498.

Griliches, Z. (1957). "Hybrid Corn: An Exploration in the Economics of Technological Change", *Econometrica, 25*(4), 501-522.

Grimshaw, D. and M. Miozzo (2021). Human capital and productivity: a call for new interdisciplinary research, The Productivity Institute, working paper (forthcoming).

Gu, Feng and Lev, Baruch Itamar and Zhu, Chenqi, All Losses Are Not Alike: Real versus Accounting-Driven Reported Losses (May 16, 2021). Available at SSRN: https://ssrn.com/abstract=3847359 or http://dx.doi.org/10.2139/ssrn.3847359

Gutiérrez, G. and Philippon, T. (2017). Declining Competition and Investment in the U.S. NBER, working paper 23583 DOI 10.3386/w23583. Available at: https://www.nber.org/papers/w23583

Gutiérrez, G. Philippon, T. (2019). Fading stars. NBER, working paper 25529 DOI 10.3386/w25529. Available at: https://www.nber.org/papers/w25529

Hauge, J. and O'Sullivan, E. (2020). Inside the black box of manufacturing. Policy series: an industrial strategy for tomorrow. Bennett Institute for Public Policy, University of Cambridge. Available at: https://www.bennettinstitute.cam.ac.uk/media/uploads/files/Inside_the_black_box_of_manufacturing_FINAL.pdf

Hall, R.E., Cummins, J.G., and Lamont, O.A. (2000). E-Capital: The Link between the Stock Market and the Labor Market in the 1990s. Brookings Papers on Economic Activity, 2000, Vol. 2000, No. 2 (2000), pp. 73-118.

Haskel, J. and M Slaughter (2007) Does Inward Foreign Direct Investment Boost the Productivity of Domestic Firms? *The Review of Economics and Statistics*, 2007, vol. 89, issue 3, 482-496

Helpman, E., and Trajtenberg, M. (1994). "A Time to Sow and a Time to Reap: Growth Based on General Purpose Technologies." NBER working paper 4854, DOI 10.3386/w4854.

Himbert, A., Corrado, C., Criscuolo, C., Haskel, J., and Jonalasinio, C. (2020). The role of intangibles for productivity dispersion (presentation). OECD. Available at: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwj_5YS5lJ7wAhWvhf0HHXjDCokQFjABegQIBBAD&url=https%3A%2F%2Fscholar.harvard.edu%2Ffiles%2Fjorgenson%2Ffiles%2Fworldklems_corrado_et_al.pptx&usg=AOvVaw3YUYgKMRvYe_Y3HIARbsCS

Holmes, T.J, Levine, D.K., Schmitz, J.A.. (2012) Monopoly and the Incentive to Innovate When Adoption Involves Switchover Disruptions. *American Economic Journal. Microeconomics, 4*(3), 1-33. –

Hornbeck, R. and Rotemberg, M. (2019). Railroads, Reallocation, and the Rise of American Manufacturing. National Bureau of Economic Research. WORKING PAPER 26594, DOI 10.3386/w26594, issue date December. Available at: https://www.nber.org/papers/w26594

Isham, A., Mair, S., and Jackson, T. (2021). Worker wellbeing and productivity in advanced economies: Re-examining the link. *Ecological Economics, 184*, 106989.

Janger, J., Schmidt, N. and Strauss, A. (2019). "International differences in basic research grant funding - a systematic comparison," Studien zum deutschen Innovationssystem 9-2019, Expertenkommission Forschung und Innovation (EFI) - Commission of Experts for Research and Innovation, Berlin.

Jones, B.F. and Summers, L.H. (2020). A Calculation of the Social Returns to Innovation Summers. NBER Working Paper No. 27863, September 2020. Available at: https://www.nber.org/system/files/working_papers/w27863/w27863.pdf

Jones, C.I. (2021). Recipes and economic growth:A combinatorial march down an exponential tail, NBER Working paper 28340. Available at: http://www.nber.org/papers/w28340

Juhász, R., Squicciarini, M.P., and Voigtländer, N. (2020). Away From Home And Back: Coordinating (Remote) Workers In 1800 And 2020. NBER Working Paper 28251, DOI 10.3386/w28251. Available at:http://www.nber.org/papers/w28251 December 2020

Kay, J. (2012). The Kay Review of UK equality markets and long-term decision making, final report, July 2012. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/253454/bis-12-917-kay-review-of-equity-markets-final-report.pdf

Kelsey, T & M. Kenny, (2021). *The Value of Social Infrastructure,* Bennett Institute for Public Policy, https://www.bennettinstitute.cam.ac.uk/media/uploads/files/Townscapes_The_value_of_infrastructure.pdf

Krugman, P. (1991). "History versus Expectations", *Quarterly Journal of Economics*. Vol 106, pp651-667.

Lam, A. and Marsden, D. (2017) Employment systems, skills and knowledge. *The Oxford handbook of skills and training*, 466.

Landes, D,S. (2003). *The Unbound Prometheus: Technological change and industrial development in western Europe from 1750 to the present*. West Nyack: Cambridge University Press.

Lloyds Banking Group (2020) Environmental, Social and Governance Report. Available at: https://www.lloydsbankinggroup.com/assets/pdfs/who-we-are/responsible-business/downloads/lbg-esg-interactive-210223.pdf

Mansfield, I. (2015). The bit of Crossrail that is 3-times deeper than a tube train. 28 August. Available at:https://www.ianvisits.co.uk/blog/2015/08/28/the-bit-of-crossrail-that-goes-3-times-deeper-than-a-tube-train/

Matsuyama, K. (1991). Increasing Returns, Industrialization, and Indeterminacy of Equilibrium. *The Quarterly Journal of Economics, 106*(2), 617-650. doi:10.2307/2937949.

Mayer, C. (2021). The Future of the Corporation and the Economics of Purpose (November 16, 2020). European Corporate Governance Institute – Finance Working Paper No. 710/2020, Forthcoming in the Journal of Management Studies. http://dx.doi.org/10.2139/ssrn.3731539

McCloskey, D. (2011). *Bourgeois Dignity: Why Economics Can't Explain the Modern World*. University Chicago Press.

Mealy, P.A. and Coyle, D. (2021). "To them that hath: economic complexity and local industrial strategy in the UK", *International Tax and Public Finance*. https://doi.org/10.1007/s10797-021-09667-0

Mokyr, J. (2009). *The Enlightened Economy: an economic history of Britain 1700-1850*. Yale University Press.

Mokyr, J. (2005). The Intellectual Origins of Modern Economic Growth*. Journal of Economic History* 65:2, 285-351.

Nagler, M., Schnitzer, M. and Watzinger, M. (2021). "Patents on General Purpose Technologies: Evidence from the Diffusion of the Transistor", CEPR Discussion Paper No. 15713.

Nakamura, L.I. (2020)."Evidence of Accelerating Mismeasurement of Growth and Inflation in the U.S. in the 21st Century," Economic Statistics Centre of Excellence (ESCoE) Discussion Papers ESCoE DP-2020-15, Economic Statistics Centre of Excellence (ESCoE).

National Data Strategy. (2020). Department for Digital, Culture, Media & Sport, updated 9 December 2020. Available at: https://www.gov.uk/government/publications/uk-national-data-strategy/national-data-strategy

Nelson, R. R. and Winter, S. G. (1982) *An Evolutionary Theory of Economic Change*, Cambridge MA.: Harvard University Press.

Nordhaus, W.D. (2021). "Are We Approaching an Economic Singularity? Information Technology and the Future of Economic Growth", American Economic Journal: Macroeconomics, 13(1): 299–332 https://doi.org/10.1257/mac.20170105299

North, D (1990). *Understanding the Process of Economic Growth*. Princeton University Press.

Olson, M. (1996). "Distinguished Lecture on Economics in Government: Big Bills Left on the Sidewalk: Why Some Nations Are Rich, and Others Poor." *Journal of Economic Perspectives,* 10 (2): 3-24.

O'Sullivan, E. (2020). *A technology management and innovation systems perspective on the ARPA model*. Written evidence RFA0094, House of Commons Science & Technology Committee inquiry into 'A new UK research funding agency'. Available at: https://committees.parliament.uk/writtenevidence/9584/pdf/

Perez, C. (2002). *Technological Revolutions and Financial Capital*. Edward Elgar.

Perry, P. (2019). 'Taking the next step in sandbox evolution', *Raconteur*, 29 September. Available at: https://www.raconteur.net/finance/fintech/fca-sandbox-fintech/

Philippon, T. (2019). *The Great Reversal*. Cambridge: Harvard University Press.

Roche, M. (2020). Taking Innovation to the Streets: Microgeography, Physical Structure, and Innovation. *The Review of Economics and Statistics*, December 2020, 102(5): 912–928.

Rossi, F., and Athreye, S. (2021). United Kingdom, Chapter 4 in Arundel, A., Athreye, S., and Wunsch-Vincent, S. (Eds.). (2021). *Harnessing Public Research for Innovation in the 21st Century: An International Assessment of Knowledge Transfer Policies* (Intellectual Property, Innovation and Economic Development). Cambridge: Cambridge University Press.

Stiglitz, J., & Greenwald, B. (2014). *Creating a Learning Society: A New Approach to Growth, Development, and Social Progress*. New York: Columbia University Press.

Stokey, N.(2020). Technology Diffusion. NBER working paper 27466. DOI 10.3386/w27466. Available at: https://www.nber.org/papers/w27466

Syverson, C. (2004). "Market Structure and Productivity: A Concrete Example." Journal of Political Economy, 112(6): 1181–1222.

Syverson, C. (2011). "What Determines Productivity?" *Journal of Economic Literature*, 49 (2): 326-65. DOI: 10.1257/jel.49.2.326.

Tambe, P., Hitt, L., Rock, D. and Brynjolfsson, E. (2020). Digital Capital and Superstar Firms. NBER Working Paper No. 28285, **DOI** 10.3386/w28285.

Tóth, G., Wachs, J., Di Clemente, R., Jakobi, A., Ságvári, B., Kertész, J., and Lengyel, B. (2021). Inequality is rising where social network segregation interacts with urban topology. *Nature Communications, 12*(1), 1143.
Velu, C. (2015). Knowledge management capabilities of lead firms in innovation ecosystems. *AMS Review, 5*(3), 123-141.

Viljoen, S. (2020). Democratic Data: A Relational Theory For Data Governance. Yale Law Journal, forthcoming. Available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3727562

Vollrath, D. (2020). Fully Grown: Why a Stagnant Economy Is a Sign of Success. Chicago: University of Chicago.

Wannakrairoj, W. and Velu, C. (2021). Productivity growth and business model innovation. Economics Letters, 199109679.

Whelan, K. (2002). "A Guide To U.S. Chain Aggregated Nipa Data," *Review of Income and Wealth*, Vol. 48, pp. 217-233.

UNCTAD. (2019). Digital Economy Report. Value creation and capture: implications for developing countries. Available at: https://unctad.org/system/files/official-document/der2019_overview_en.pdf