Economic Impact of Significant New Deployment of Infrastructure

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Abstract

This paper aims to examine quantitatively and qualitatively the impact of five key general purpose technologies in order to gain insights into what factors may arise in relation to 5G as a potential example. We first attempt a definition of what constitutes a general purpose technology, providing a potential framework for analysis of impact mechanisms then take this to the five case studies. It is difficult to capture the impacts of such technologies because their scope is broad and commonly a suitable base case from which to measure impact is missing. In addition, there are in each case antecedents and complementary developments which influence their impact. However, our analysis points to a range of factors that must be considered in relation to potential new candidate technologies, including a range of potential governmental interventions.

1 Introduction

In examining this topic, we cover five broad areas. We first discuss the significance of GPTs as a distinct defining concept. Then we propose a logical framework for organising the mechanisms behind a range of impacts, with a template for identifying the key characteristics of high-impact general-purpose technologies (GPTs). This is followed by five case studies covering a range of areas. These lead, in turn to a framework for measurement and prospective analysis focusing on technological diffusion. Throughout, the focus is deliberately on the highest impacts.

2 Definition and Significance of GPTs

It is useful to start with some reflections on the (various) definitions of GPTs and their potential significance. In essence, the current paper arose out of a sense that assessing (*ex-ante*) or evaluating (*ex post*) why a technology is a GPT is important because it looks initially narrow and specialised but turns out to be fundamental and pervasively transforming. Moreover, the potential innovation feedbacks between a GPT and many connected sectors raises the possibility that its development may be constrained or distorted by its origins in a single sector.

The term GPT seems to have been introduced by Bresnahan and Trajtenberg (1995), who identified two key features: generality of purpose (essentially tautological, given the name) and ‘innovation complementarity’. GPTs are “enabling technologies”, opening new opportunities rather than offering complete and final solutions. Lipsey et al. (1998), after discussing several technologies briefly and considering what a GPT is not, characterise them via four "necessary and sufficient" characteristics: scope for improvement, wide variety of uses, strong technological complementarities with existing or potential new technologies; and Hicksian (by which they mean gross) complementarity with other inputs[1]. More controversially, the same authors (Bekar et al., 2018) later extend and refine this to six characteristics:

- Technological complementarities with technologies that
  - support it
  - it enables and/or
  - are in some sense transformative more broadly;
- Absence of substitutes;
- A wide array of applications; and
- Initially crude but evolving in complexity.

Clearly, using any of these definitions, the effects are wide-ranging and cannot necessarily be captured through simple or summative measures.

In our view, Bekar's second set at least is no longer either necessary or sufficient. There are substitutes for almost any technology that most people would consider a GPT. They may not provide equally effective for all the features, but they are substitutes, nevertheless. For example, electricity is universally accepted as a GPT. But, as Scott and Walker (2011) document, "[t]he 1930s witnessed an intense struggle between the gas and electricity industries for the household market …".

We therefore prefer to use a synthesis of the Lipsey and Bekar et. al. formulations:

- scope for improvement;
- a wide variety of uses;
- strong technological complementarities with existing or potential new technologies;
- innovation complementarities; and
- Hicksian complementarity with other inputs in application sectors.

As a further introductory observation, it is worth reflecting on why one would want to characterise something as a GPT. The reasons are particularly important in relation to other technologies that may turn out to be more 'GPT-like', have greater impact or need GPT-specific interventions (including regulation). It is also important to consider the extent to which the economics of GPTs are distinct from those of other technologies, especially in relation to infrastructures. For example, if we refer to technology as soft when it is knowledge-based or virtual, a GPT can be considered a soft infrastructure supporting others. 'Generality' refers to its infrastructural or horizontal nature with the added special feature (hence the above lists

[1] Note that the reference to inputs limits the generality and usefulness of this definition, especially when the input-output distinction is unclear or changing.

of characteristics) of two-way complementarity and influences between the infrastructure and the things it supports.

Finally, the fact that competing proto-GPTs may be imperfect substitutes has three striking implications.

The first concerns competition between proto-GPTs at the same 'level' of the production chain. Like any other 'platform competition', the struggle may end in tipping, possibly to an inferior standard (David, 1985). Those features best served by the winner will prosper; those for which a defeated rival is best will suffer.

The second involves competition between GPT and non-GPT alternatives, as seen in the alternating waves of general-purpose and specialised technological approaches in the computing case discussed below. The GPT reshapes other levels (typically downstream or application levels). Downstream competition may become so strong that small advantages in providing a specific feature become existential. This may result in the rise (upstream) of LPTs (limited-purpose technologies), enabling new downstream uses and (possibly) transformation of the original GPT.

The third is 'double generalisation' (an abuse of the term 'double marginalisation'), i.e. GPTs in a vertical relationship. This analysis is not yet mature in the literature, but its broad outlines are clear and so are examples (ICT is a prime example of the fusion of Information and Communications GPTs). One direction for development might be to define a GPT by accretion.

3 Logical Framework

Ideally, a logical framework would be built around a timeline showing the evolutionary stages of GPT development, deployment and impacts. The examples show the order in which these occurred in the past. But we would urge caution in applying this kind of logic or process map. Historical sequences do not imply causality for the cases we examine, let alone that they would necessarily follow the same sequence in the 5G setting[2]. In addition, the timing of these developments may be as significant as their order[3].

Important developments associated with GPT evolution can be identified and classified as discussed below. This defines broad categories; different elements have been significant in the historical cases, and it is difficult to establish causal relations linking them to each other and to the emergence of the GPT. As a result, it is not easy to separate necessary, sufficient or alternative factors favouring a GPT or to assess policies aimed at facilitating a GPT and

[2] For example, the computer case shows alternative periods of generalisation and specialisation in the GPT layer triggered by developments in application layers or significant use cases.

[3] For technologies with significant positive network externalities (Katz and Shapiro 1984), speed of uptake determines whether a technology will lead to 'crowding-in' and substantial downstream innovation or will generate 'excess inertia' and remain low-impact or die out. Even rapid deployment is no guarantee of success; Katz and Shapiro also identify the possibility of "excess volatility" whereby upstream innovations succeed each other before downstream (application) innovations can produce the GPT effect. Speed and scale also stimulate or suppress the availability of necessary finance. Both excess inertia and excess volatility have been described by the literature on the 3G/4G/5G/6G progression.

optimising its impacts. However, it is potentially useful to identify characteristics that may shape the development of a GPT, distinguish exogenous from endogenous drivers of change and list some general types of policy option.

GPTs develop along various trajectories. These can be influenced by the nature of the innovation behind the GPT. Some historical cases start with a single radical innovation[4] or a tightly-defined cluster of such innovations; others arise through a slow process of repurposing and accretion. The recognition and embrace[5] of a GPT will be far more abrupt in the former case. This has important implications for the efficiency[6] of GPT dynamics, especially when interpreting historical cases. The initial direction and its consolidation tend to be less reversible under conditions of radical innovation, and the risk of (commercial and technological) tipping or lock-in is greater. The rewards for innovation are stronger, but competition may be less effective in optimising the technological infrastructure.

Another characteristic is the balance of 'push' or 'pull' factors in driving the GPT transition. This may be a matter of the extent to which a GPT: i) meets a currently-unmet[7] need in application sectors; ii) improves on existing methods and services; or iii) supports a wholly-new vision of what might be possible (generally coming from the upstream or GPT layer)[8].

Related to this is the nature and ownership of the *knowledge* on which the GPT is based[9] and the timing of any investment[10] needed to use the GPT and initiate positive innovation feedback loops. These can be regarded as framework conditions to the extent that industrial and market structures and IPR regimes favour particular trajectories. These conditions are more susceptible to policy intervention.

3.1 Exogenous drivers of change

Some identifiable features associated with GPTs are framework conditions or triggering events exogenous to the GPT and its associated sectors. The framework conditions include, amongst

[4] Dewar and Dutton (1986) distinguish radical innovation based on tacit knowledge (on which there may be no consensus), disruptive to incumbent organisations and associated with discontinuous change. Incremental innovation, in contrast, is based on codified information and leads to incremental change.

[5] In this case, considering the GPT as a paradigm shift, which changes the way other innovations are perceived.

[6] For example, how soon the advantages accrue and whether the best GPT wins in a contested race.

[7]This is not the same as the framework relationship of the GPT to a fundamental constraint limiting socioeconomic progress (see below); it refers to *perceived* needs, which may be more transitory and limited than, say, excess demand for power, communication or mobility.

[8] It may be thought that a 5G GPT falls into categories i) or iii) given the ambitious marketing of 5G as a transformational technology rather than a mere quantitative improvement on 4G. Computers and NCMs seem to reflect improvements in existing methods, and electricity expanded to meet unmet needs. Clearly, the distinction between unmet needs and incremental improvements is vague.

[9] disembodied knowledge, e.g. mass production, or embodied in a good or service; open to all or tightly controlled by patents, etc. (Bresnahan (2010).

[10] For example, whether large sunk investments must be made before a GPT can begin to generate value (railroad tracks or distribution infrastructures for electricity or communications) or afterwards and incrementally, e.g. NCMs, computers. These differences in the structure and timing of investment can have major implications for both long-term growth and societal impacts.

others, the relation between a GPT and fundamental constraints limiting economic growth. As Bresnahan (2010) observes:

"Many observers today believe that long-run growth of the economy can only be sustainable if it involves a transition away from the carbon fuel sources used for steam and electricity. What this reflects is a deep economic observation: what sustains a growth path depends on the underlying economic conditions. When a fundamental constraint facing the economy was the limits of muscle power and the limits, given the technology of the day, of steam and water power, successful exploitation of fossil fuels was central to sustaining long-run growth."

This suggests that potential GPT impacts can be related to the degree to which they relax critical binding constraints affecting the economy at a given moment in time.

It is, therefore, worth considering in detail what critical constraints 5G can relax and how uniquely and effectively it can do so.

3.1.1 Triggering events

There is a range of shocks historically associated with the emergence of GPTs. These are difficult to anticipate, unreliable and often beyond the reach of (industrial) policy, so we just list a few.

- Macroeconomic and contextual shocks (e.g. wars), including supply chain disruptions and strategic material scarcities.
- Trade developments and the inclusion of technology-sensitive conditions among the non-tariff barriers recognised in trade agreements.
- Exogenous scientific developments and discoveries (especially those associated with radical innovation (see above).
- Changes in capital markets that influence the timing and availability of investment capital.
- Policy initiatives not linked to technology or industrial policy or those that are generic in nature, such as support for curiosity-led R&D.

3.2 Endogenous developments

Other developments are endogenously related to the emergence and nature of a GPT and can therefore be used to monitor and influence its evolution. These are not abstract but relate to the defining characteristics of a GPT.

3.2.1 Technological (including private and public funding, patents) developments

A range of technological developments may be associated with the emergence of an impactful GPT. These include the generation, spread and application of useful knowledge and thus the scope for improvement offered by the technology and indirectly to its technological and innovation complementarities. In this respect, a radical innovation may trigger subsequent innovations in its own field, substituting for prior technologies. In application areas, it may complement or substitute for existing technologies. In either case, it may trigger new innovations, but this is not guaranteed because it changes the productivity of existing application technologies and affects perceived returns to innovation. Also, it is important to distinguish technological changes related to the GPT itself from those occurring upstream (in enabling sectors) or downstream (in application sectors). GPTs have, in the past, shaken loose innovation and technological development in up- or down-stream sectors but have also captured those sectors (e.g. computerisation of a wide range of business activities that has resulted in the reframing of activities in application sectors as versions of IT).

3.2.2 Commercial

Other endogenous developments influencing the impacts of GPTs come from the commercial environment. Many of these involve complementary innovations in:

- Products – (extensive competition) new goods and services enabled by the GPT[11];
- IPR (licensing) – the extent to which development can be controlled and returns appropriated by different players (with different innovation potential and incentives);
- Intensive – changes in the nature and intensity of competition within existing markets and the associated patterns of cost reduction and consumer and producer surplus;
- Business models and market structures – especially changes in market concentration, vertical structures and even changes in sectoral layering~~ing~~[12]; and
- Adoption the extent to which a GPT is taken up in application sectors (including the public and private sectors and the knock-on or 'leading customer' links between them)

The implications are that the commercial environment may be the main channel for GPT development and impacts, industrial policy in application sectors may influence GPT impacts and also that GPTs may trigger changes in the economy in other sectors[13]. We should also recall that profit-motivated product development itself leads to biases compared with social preferences (Spence, 1976).

3.2.3 Policy

A range of potential policy tools has, in the past, affected GPT development. This does not mean that they should automatically be used in the 5G case, but they may be worth considering depending on the policy objectives. Since they are all well-known, we simply list them without comment:

- Policy domains:
  - R&D support
  - Technology uptake stimulus

[11] Both qualitative innovations and those made possible by a GPT-induced change in input productivity, such as the way cloud computing moved computerisation from the Capex to the Opex element of small firms' balance sheets and lowered the barriers to entry and growth.
[12] For example, separation like the emergence of data intermediaries and 'fintech' providers in financial services or vertical integration like content provision and platform services in media sectors.
[13] The electricity, rail and computer (cloud) cases show how this can happen for better or worse. For example, the bottleneck nature of rail transport led to a powerful collusive trust (a negative impact) and thence to the first effective antitrust laws and associated economic analysis (a positive impact).

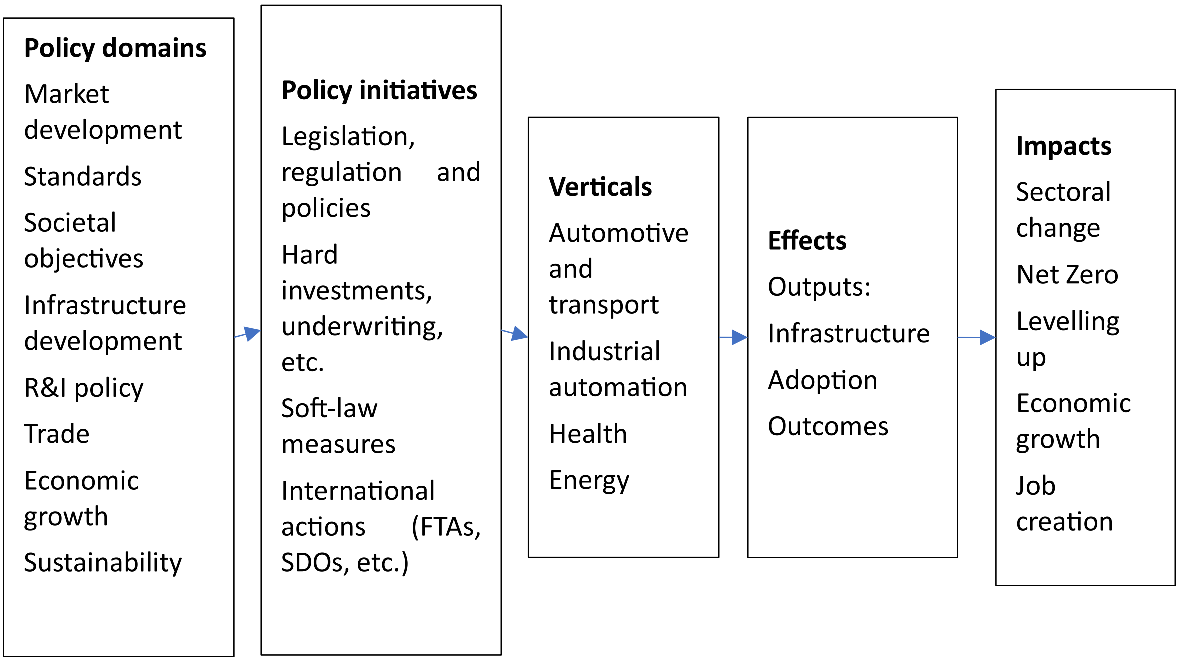
- Microeconomic development (Innovation, sectoral growth)
  - Regional development
  - Macroeconomic growth and trade
  - Standards
  - Inclusion, sustainability
  - Infrastructure development and deepening

- Policy Instruments
  - different modalities of R&D support
  - Innovation and deployment support, including procurement and 'launching customer'
  - Standards
  - Regulatory forbearance
    - Hard- and soft-law regulation

This list is intentionally inclusive or even over-inclusive: Not all of these were used to any visible effect in all cases.

3.3 The impact mechanism framework

The following diagram gives a linear view of how the logical framework elements can be organised for policy development purposes. Note that the essence of a GPT includes feedback loops, even from separated stages (e.g. when specific sectoral impacts trigger new policy initiatives), so the linear perspective should be used with caution.



This framework should be used in conjunction with the GPT characteristics. A GPT can be assessed against its:

- Potential for future development (innovation in its own domain) – does it represent a new paradigm or one that is in its mature or concluding phase?
- Variety of uses – are there barriers to valuable new applications or adoption, or is there a rich and sustainable set of application sectors to ensure its continued development as a GPT?
- Technological complementarities – does it enhance or reduce the productivity and development of existing or potential new technologies?
- Innovation complementarities (in other domains) – has it spawned innovation in vertically-related sectors?[14]
- Hicksian complementarity with other inputs in application sectors – does it raise the marginal productivity of other inputs (including human capital) and thereby diffuse benefits to the other parts of the economy from which those inputs come?

4 Case Studies

The cases we have selected for study deliberately cover different time periods and a range of industries, including some that have received less direct attention from historians of technical change. There is also some emphasis on Britain. Each is developed through a swift journey through the key points, then a brief link to the framework in the figure above. The more recent cases receive a more detailed treatment since they relate more closely to the case of 5G.

4.1 The Development of Railways in Britain

The internal movement of bulk goods such as coal was problematic in 18th century Britain, given the dreadful state of most of the road network. In many parts, a solution was found in the development of canals to feed into the river systems. The first major canal constructed to take coal to industry was the Bridgewater Canal, completed in 1776, which took coal from the Duke of Bridgewater's mines at Worsley directly into Manchester, halving coal prices there and making the Duke even richer by outmanoeuvring competition. James Brindley, its engineer, went on to build several other canals in the last part of the 18th century to serve the heavy industry of the north and midlands, as well as to transport fragile goods such as pottery (Wikipedia).

However, canals were not a solution in the northeast of England since the steep banks of the Tyne made it problematic to move coal to the river (from which it could be transported by ship to locations such as London). There, wagonways had been used to move coal, involving crude, mostly wooden rails, pulled by men or horses. This is where George Stephenson, a colliery engineman, encountered stationary steam engines in the early years of the 19th century. Meanwhile, at the opposite end of the country, Richard Trevithick was engaged in solving the problem of improving steam engines used to pump out water from the tin mines of Cornwall and put the steam engine on L-shaped rails at Coalbrookdale near Ironbridge (Wolmar, 2007). Subsequently, except for early experiments, the steam engine was a key

[14] A failed GPT may stimulate innovations that transcend it either in the form of superior GPTs or as non-GPT alternatives. Whether that justifies public intervention is a policy decision.

element in the development of rail transport. However, in Surrey the first public wagonway conveyed horse-drawn wagons for a toll. The first public passenger railway was the Swansea and Mumbles, a short horse-drawn ride on a colliery line. George Stephenson designed a locomotive in 1814 that was the first flange-wheeled adhesion locomotive, reducing the problem of weak L-shaped rails. Locomotives had the potential to transport far greater loads than horses could manage and quickly came to dominate.

These things, together with the use of wrought-iron rails (a big improvement on the brittle cast-iron ones), were introduced successfully on the Stockton and Darlington railway in 1825, built after it had promoted (against considerable opposition) an enabling parliamentary bill passed in 1821 (Bradley, 2016). The key feature was the compulsory purchase of the land along the route, so avoiding heavy wayleave costs imposed at various stages by landowners (Wolmar, 2007, p.9).

It was at George Stephenson's insistence that the railway was constructed to allow locomotives (constructed by Robert Stephenson's company), enabling greater loads of coal to be hauled. From the start, passengers were carried. Yet, many of the trains were horse-drawn. The gauge of the track was set at what became standard across most of the world, 4ft 8.5 in. The opening event attracted worldwide interest. Coal prices dropped by a half as a result of the increased loads trains could carry. However, the charging model adopted was taken from that used on canals and on turnpike roads, third-party carriage for a toll, thus militating against the standardisation of rolling stock (much more critical for railways than for canals) and causing endless disputes. Hence the directors of the railway abandoned open access in 1833 and ran all the trains themselves, enabling greater standardisation, and the railway soon became profitable. An extension to Middlesborough set the place on course to change from a hamlet to a major port and industrial hub (Wolmar, 2007).

The real start came in 1830 with the opening of the double-tracked Liverpool and Manchester railway. Although conceived initially as solely for the carriage of goods, the promoters perceived the importance of passenger travel, something that the canals between the cities could not compete with on speed and much superior to the road transport that was available. Clearly, there was significant latent demand for passenger travel once timing and convenience were improved. Stagecoach travel, which had reached its peak, soon declined. Despite opposition, the bill enabling the line was passed, construction took place according to the principles of George Stephenson and as construction was becoming complete, the Rainhill trials took place to determine the winning locomotive design. The way was clear and, given the high perceived returns, the finance forthcoming for an intensive period of further lines to be built and, gradually, a network to be developed, albeit in a much more haphazard way than seen, for example, in Belgium (Wolmar, 2007). There were still important developments and standardisation to come- improved braking, signalling (the early safety record was poor), the "battle of the gauges" against Brunel's broad gauge, and so on.

For several years, canals and railways coexisted. Clearly, canals were slow, but for goods that were not particularly time-sensitive, they had their place (and, possibly, lower marginal costs). Some were bought out by railway companies to reduce competition or to use for routes. But eventually, railways, with a more extensive network and greater all-weather reliability, won an increasing amount of the business. Passenger and freight carriage by rail increased enormously, contributing significantly to the economy. For example, from a start of near zero in 1830 to a peak in 1920 of 1.5 billion passenger journeys (only surpassed, after several falls in the intervening years, by 2012), there was almost continuous growth in passenger numbers- see figure 1 below.

Mitchell et al. (2011) estimate that the return on capital employed "fell from an average of 5.6 per cent in the early 1870s to around 4.5 per cent in the early 1900s, after which (until the Great War) it stabilised." Thus, the earnings were for many years lower than the cost of capital on average. Nevertheless, the external benefits to passengers and goods were considerable.

In sum, railway development in Britain is clearly seen as a GPT. It took many years before a network was formed, some lines were built that never produced a return and there was wasteful duplication. The development required simultaneously or relied upon many complementary technologies, including efficient steam power, wrought iron rails taking flanged wheels and advances in surveying, as well as considerable manpower. This development depended on huge amounts of private capital put into risky sunk cost investments, parliamentary bills authorising compulsory purchase, the outfacing of considerable opposition and a small number of individuals of quite remarkable ability and powers of persuasion.

In terms of our framework, railways in Britain were developed without *direct* state sponsorship, but benefitted from market, standards and infrastructure development and the policy initiative of Private Acts of Parliament. Vertical factors, including steam power, wrought iron and coal as inputs, industrial development and increased trade as outputs, were also clearly important. Connecting this with Lipsey et al.'s (1998) four characteristics, clearly, there was tremendous scope for improvement over the early experiments. Usage was developed much beyond the original roles of carrying a few passengers (what are now seen as) short distances and carrying coal to cities. Strong technological complementarities became apparent with the development of high pressure steam power, the Edmonson ticket machine and the telegraph. Railway employment showed significant growth (Foreman-Peck, 1991 table 3.5). Standard prices were regulated and set in terms of pence per mile until 1968 (Timperley, 2014), so comparisons with the UK Inflation Rate Calculator can be made. This implies that fares were very slightly reducing in real terms until 1914, then declining more rapidly until 1921, after which they fluctuated somewhat, sometimes rising in real terms, sometimes falling. The effects on life were transformative in terms of the development of cities, (limited) commuting and wider employment and social opportunities.

Attempts have been made to calculate the "social saving" due to the development of railways in Great Britain. This requires the identification of a counterfactual, in other words, what would have happened/ been used in the absence of the railways. The obvious alternative to passenger travel by rail is travel by coach (initially, stagecoach, much later motor coach). The alternative to freight transport is transport by canal and/or inland shipping. These are the alternatives chosen by Hawke (1970), who estimates the social saving relative to the national income of passenger traffic as 2.1% or 5.8% in 1865, depending on how comfort is weighted, and as 3% to 3.5% for freight traffic in the same year. McCloskey (1971), however, is strongly critical of these estimates and considers them too high. Foreman-Peck (1991) generates new estimates of railways' impact in Britain. Whilst accepting that railways have important consequences apart from savings in national income, he focuses on social saving through the lens of total factor productivity. He suggests the social saving in 1865 is no more than Hawke's upper bound. To move beyond 1865, counterfactual prices must be generated. Here the difficulty is what might have happened. For one thing, coastal steamship travel would have become more important. Another factor, harder to evaluate, is the benefit of increased speeds, which cannot be captured through estimates of passenger and freight train miles. Foreman-Peck estimates total factor productivity growth at around 1% per annum after 1865, so that by 1910, social saving reaches at most 27% of GDP. Note that efficiency growth in US railroads over a comparable period was far greater. Nevertheless, despite the obvious caveats, this is a significant social saving.

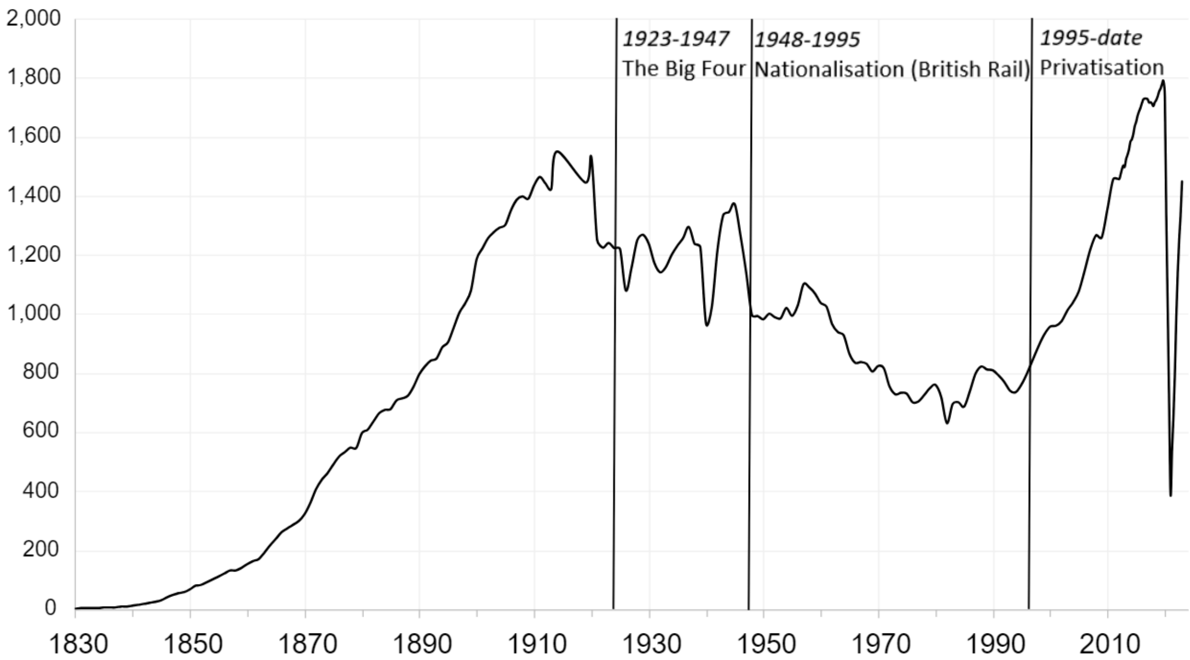


Figure 1: GBR rail passengers by year 1830-2016[15]

4.2 The Penny Post

The penny post of 1840 can be seen as a GPT in communications technology. Posts, including penny posts, existed long before Roland Hill's reforms. But it was the innovations brought about by him and his family, including his wife Caroline, his brother Edwin and his father Thomas, among others, which became the GPT (Hey, 1989).

As early as 1657 various local and, to a small extent, distance postal services from London were set up. London's penny post started in 1680. Various other penny posts were enabled by a 1765 Act, with the first in Manchester and Bristol starting in 1793, followed after the turn of the century by similar services in, for example, Liverpool and Birmingham (Oxley, 1973). However, there were many senses in which this pre-existing postal service differs from Hill's

[15] Source: https://en.wikipedia.org/wiki/File:GBR_rail_passengers_by_year_1830-2015.png

version. First, post needed to be taken to a receiving office (initially there were four in Manchester). There it was hand-stamped as postage paid or unpaid. It was then delivered by calling at the recipient's property and, if necessary, demanding the payment. Longer distance postage was still less ordered (Oxley, 1973).

The charges were various and determined by distance and number of sheets and carried on a mail coach. It must be remembered that by 1840 the telegraph was not in general use; the railways were scarce and disconnected (though they swiftly became employed for postal service); and, of course, the telephone was a distant prospect. Therefore, someone in London wishing to purchase goods from a manufacturer in Birmingham would need to use a slow, costly (9d for a single sheet letter, paid by the recipient and collected from a local office; Daunton, 2015) and unreliable system compared with purchasing the same goods from a London manufacturer. Although private posts had been in existence, the legal monopoly of the crown had been established in the 17th century. In sum, there were no significant (legal) substitutes for the postal service for letters, but this was by statute.[16]

Roland Hill's reforms were many. He estimated that the transport cost was a very small component of the total, 1/36th of a penny on average (Hey, 1989). Therefore, he proposed a uniform postage rate across the country between the main cities, towns and, to some extent, villages. More remote areas often had a central point for collection rather than household delivery. Hill was not, in fact, an advocate of general cross-subsidisation (Coase, 1939). He essentially abolished the idea that post could be paid on receipt (or rather, since the rate for post paid by recipient was double that for prepaid post, the strong incentive was to prepay). All became paid for before putting it into the mail. Hill was convinced that demand was very elastic and that there were strong economies of scale in the service. Both these were true, but not to the extent predicted or assumed by Hill. By 1850, there were 4.6 times as many letters posted as in 1839, but the cost of management had less than doubled (Daunton, 2015, table 1.1). Post unpaid letters shrank rapidly as a proportion of the total; even by 1841, they amounted to no more than 10% of the total in the London area.

These reforms paved the way for the famous Penny Black, an adhesive stamp that could be affixed to the envelope. These were produced by Hill's brother on machines he had devised by May 1840. In turn, this meant that starting in 1853, letters could be posted in the now familiar pillar boxes rather than only at receiving offices.[17] Insisting that houses had letterboxes meant that postmen need not call at houses but only drop the post through the door, greatly reducing unit costs of delivery.

Yet Hill faced multiple barriers put into his way in implementing his reforms and is described as an abrasive and somewhat divisive character with little administrative experience. Members of Parliament had enjoyed the right to send communications free and frequently abused this privilege, so many were antipathetic to his proposal to abolish self-franking. Post office officials, particularly the Secretary to the Post Office, Maberly, who saw the reforms as

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[16] The Post Office estimated that between one quarter and one half of the country's correspondence was conveyed illegally in the 1830s. (Daunton, 2015, p.22)

[17] An innovation of Anthony Trollope, who was by then a senior post office official (Daunton, 2015).

removing sinecures and reducing manpower, were particularly obstructive. Nevertheless, merchants, traders and bankers, together with some influential politicians of a free trade persuasion, viewed the existing system as corrupt and a restraint of trade (Hey, 1989). There were also challenges from existing private operators of local posts.

A more fundamental objection was whether a uniform penny post (for letters up to ½ oz.) would mean losses for the Post Office. Of course, Hill had no empirical observations to guide him but was convinced that growth in letter traffic would be sufficient to cover the fixed and variable costs. Initially, it was a financial disaster, with net profits falling almost to zero. However, because letters posted more than doubled in the year 1840 and doubled again in the next 10 years, initial problems were short-lived, and profits had recovered by the 1870s (Hey, 1989). As literacy increased, so did personal letter posting, in addition to the greatly increased commercial letter traffic. The number of items posted in 1900 was 22 times the number in 1840 (Daunton, 2015). The basic price remained at 1d until 1918.

Moreover, the service increased and expanded in many ways. Whilst "post towns" enjoyed local delivery, other locations used a variety of methods to obtain mail. Under the Treasury's 1840 ruling, delivery was established anywhere where it cost less than ½d. It is also important to recognise the vast scale of deliveries; by 1908, London had up to 12 deliveries per day, and the largest provincial towns outside London enjoyed six or more (Daunton, 2015). The service was also extended in character- Hill approved of the sending of books through the mail (introduced in 1848) and reduced that postage price in 1855 to one penny for 4oz. Printed papers were also distributed in the mail under a new system from this date (Daunton, 2015). Another interesting service developed following pressure from Chambers of Commerce- a sample or pattern post introduced in 1863 to consist of items of no intrinsic value (e.g. swatches of cloth) at the cheap rate of 3d for 4 oz. Because this was above the rate for books, it was later reduced to bring it into line. Clearly, the postal system benefitted commerce significantly, although the effects are diffuse and very difficult to estimate. All this eventually led to the introduction of a parcel post in 1883, something which was never a monopoly of the Royal Mail; the railways had their own service, although it was more complex in nature.

Given that inflation was essentially non-existent over the Victorian period, we can compare rates across the years in money terms. The penny post remained in place until the first world war but, by 1897, covered items of up to 4oz. Reductions in the cost of sending heavier "letters" were dramatic- a parcel of 1lb (16 oz) would have cost 2s 8d to send in 1840 (i.e. 32d), but by 1897, this cost only 4d; a parcel of 10lb could be sent for a shilling (12d) (Daunton, 2015, charts 1-4).

Viewed in context, the penny post, together with its later developments, was a GPT that had widespread external benefits for trade and for individuals. The growth in mail traffic, particularly in the 19th century, was massive. The post office also was a major employer, with almost 250,000 employees by the start of World War 1. It, like the railways, needed to initiate and develop techniques for controlling vast numbers of men (almost all were men prior to the war) in widely dispersed locations. Its development was facilitated by early subsidies, the monopoly right, and, initially, the absence of substitutes in the form of telegraph and telephone communication (although these later came within its orbit). It was a development of earlier systems, but these were partial and inferior in most respects. It required a range of complementary reforms and developments however, perhaps the most important being fast, accurate printing of stamps and improvements in intra-country transport. Railways and improved road transport were clear complements. It did require some financial sacrifice for some years. It also, crucially, required significant Government involvement in the imposition of a monopoly provider. The original use case, since broadened, remained largely intact and lasted for around 150 years until email use became common.

In terms of the Lipsey et al. (1998) characteristics, there was clear scope for improvement in the postal service. It had a wide variety of uses, particularly in the mid-Victorian era, in terms of facilitating trade and even (in the absence of alternatives such as telephone and, of course, email) for brief notes regarding changed commitments and engagements. There were strong technological complementarities with the printing of stamps and with improved transport, particularly with the development of railways, and these complementary services themselves gained from the growth of the postal service.[18]

4.3 The development of electricity

Almost simultaneously, Swan in Britain and Edison in the US developed the incandescent lamp in the late 1870s. This was not the first means of electrical lighting (precedence goes to arc lighting) but the first suited to a range of settings. Edison started his supply business in New York in 1882, almost certainly the first public supply in the world. Swan was initially hampered by Edison's decision to patent the lamp. Electricity was initially seen as a substitute for gas or oil in lighting homes and, to a lesser extent, businesses. It required either a domestic generator or public supply (Cunningham, 2013).

There were several barriers to public supply. One was the need to obtain wayleaves to string wires along streets or underground. Another was the attenuation that takes place at low voltages, in particular, a clear problem with the direct current (DC) electricity produced by dynamos, limiting distribution to a small area. In the later 1880s, alternating current (AC) was developed, using alternators and later three-phase generators together with step-up and step-down transformers; the much higher transmission voltages available greatly attenuated line losses due to resistance, enabling more extensive networks. American, German Italian and Hungarian engineers were primarily responsible for this development and the mathematics to understand it. By 1900, three-phase AC was becoming the standard. However, in other respects, no national or even regional standard had emerged- supply voltages differed somewhat and, more significantly, the frequency of alternation (hertz i.e., cycles per second) differed across systems.

Use of electricity solely for lighting led to extremely low load factors, particularly in summer; generation companies gradually recognised the need for more balanced loads to reduce unit costs. It was not until around the turn of the century that industrial and traction (largely tram) usage became important, taking over from horse or steam power in Britain. The expansion

[18] The railways were a substitute, as well as a complement, for the carriage of parcels, of course.

was then rapid, with unit charges falling significantly. Although the figures are rough, estimates in Hannah (1979) suggest that as average prices dropped by 25% between 1898 and 1912, usage grew by 5.7 times, meaning an extraordinarily high crude arc elasticity of demand. There was clear price differentiation reflected in the need for more balanced loads, a well-recognised factor affecting costs (Parsons, 1939). More reliable figures for the years 1921 and 1931 reveal a 193% increase in quantity accompanied by a 45% reduction in average price, an arc elasticity of 4.29. But they also show domestic consumers paying over three times as much per kWh as industrial and traction customers due to price differentiation in tariffs.

The Northeast of England and its dominant supplier, NESCo, was a forerunner of an integrated system of generation and distribution driven by consultants Merz and his associate McLellan. This involved several innovations, including steam-driven turbines in power stations of then unprecedented size, three-phase AC electricity ultimately standardised on 40 hertz (acceptable for lighting and not too high for industrial use), a distribution system at the then-record 20,000 volts, all developed at the turn of the 19th and 20th centuries. NESCo rapidly expanded in the region, although not without competitors.

In the rest of Britain, a mixture of municipal (developing out of a municipal gas system) and private generation and distribution systems prevailed. There was clearly a good deal of information sharing amongst electrical engineers through journal and statistical publications and consultancies, but local pride and a variety of voltages and hertz (which latter had significant sunk cost implications) militated against wider networking, despite the large variations in coal prices across the country which made some areas naturally expensive for electricity generation. Ultimately, a growing recognition that Britain was falling behind not only the US but, more significantly, Germany made a gradual push towards (almost) national networking essential.

It was in the 1920s that moves towards the National Grid commenced in earnest, culminating in the creation of the Central Electricity Board in 1926/27. Although push factors, including price, were strong, so was the resistance. The resistance came from four angles- local pride, generator conversion cost, control of the system and disfigurement of the landscape. Local pride was damaged by the proposals that only a proportion of existing generation stations would be required under a national system. Generator conversion costs arose from the need to consolidate 17 different frequencies into a single frequency (including a decision to move to 50 hertz rather than NESCo's 40 hertz). National policy was a major consideration as it became clear that only a publicly appointed board could coordinate and control the transmission and dispatch system, and there were objections to lines of pylons across the countryside. The inception of the National Grid with its merit order generation system came in 1933, although, in fact, it operated as a series of broad regional grids; national interconnection came in 1935.

Foreman-Peck and Waterson (1985) show that the selection of power stations for participation in the Grid led to a substantial reduction, in excess of 20%, in working costs relative to the costs of municipal firms not selected, and thus to a significant gain in efficiency in the system as a whole. This also eliminated the generation cost differences between selected company-owned and selected municipal power stations.

Although average prices rose slightly and then more rapidly in the war years from their 1936 low point, demand continued unabated so that by 1948, total usage was over twice as much as in 1936 (and is now almost 6 times that in 1948) (BEIS, 2022).

In sum, the history of the electricity industry in Britain, one of the most significant GPTs, demonstrates the roles (in no particular order) of (long) time to maturity, substitutes and complements, standardisation, prices and price discrimination, economies of scale, planning issues, political will and intransigency, political skill, domestic and international competition and cooperation and, it must be said, a small number of strong-willed and expert men.

Viewed in context, electricity as a GPT might best be seen by analogy as a combination of 2G to 5G telecommunications rather than just 5G, with the early stage being more akin to 2G. Its original use case was limited, and its context was local, not national. It showed continual expansion of demand and long periods of declining prices as technological change took place and efficiencies were enhanced, particularly in the amount of coal required per MWh. There is little doubt that it fits the Lipsey et al. (1998) set of GPT characteristics - there were huge opportunities for improvement over the early experiments, an enormous range of uses (most initially unperceived), strong complementarities with steam generation and associated boiler technology amongst others, and as its costs fell, complements such as electric motors, household appliances etc. grew in usage. Taking a growth accounting perspective on the US economy, Bekkar et al. (2019) consider that the intensive growth contribution of electricity to TFP growth was highest in the period 1909-1919, at 11%, significant but not as great as the contribution of the internal combustion engine. However, the activity is so wide-ranging and impacts so many sectors that evaluating its impact more broadly (for example, its impact on consumers) would be an impossible task- for example, the night-time economy would be a fraction of what it is, had electricity not been developed.

4.4 Computerised Numerically Controlled (CNC) machines

Computerised Numerically Controlled (CNC) machining is a manufacturing process that uses programming codes and operator control to instruct tools to make a product. CNC is a highly versatile GPT with extensive industrial applications in aerospace, health, automotive and consumer electronics, among several others.

The first CNC machine was attributed to John T. Parsons in 1949, who, as part of an Air Force research project at MIT, calculated the coordinates of a helicopter airfoil and transferred them onto a punched card used for manufacturing the helicopter blades and aircraft skins (Heinrich, 2001). The widespread adoption of CNC has since had a significant impact on the economy, thanks to its continuous improvement, the variety of its applications and the strong complementarities. The Society of Manufacturing Engineers defined Parsons as the father of the second industrial revolution.

During the 1950s, the non-computerised numerically controlled process (NC) controlled machine tools using punch cards that were programmed offline and relied on the hand-controlled feed of the machining head. During the 1960s and 1970s, in some instances, the process used rewinding tape readers and was controlled remotely by large mainframe computers or minicomputers, further reducing the price of the computer cycle.

In the 1970s, implementation costs fell even further with the introduction of microprocessors. This, coupled with the sluggish economic growth/economic downturn and rising employment costs in Western societies, greatly increased the demand for more efficient and cost-reducing 'lower-cost' affordable NC systems. However, the US was too slow to meet that demand. Many companies remained largely concerned with the generation of further ideas and inventions for manufacturing complex and high-precision components for their high-end applications of the high-profit aerospace industry and defence rather than the domestic tool target market. The vacuum was promptly filled by other countries such as Germany -with Siemens Sinumerik- and Japan (Heinrich, 2001), whose core policies focused on knowledge transfer and commercialisation aimed at the low-end target market and cost containment, a strategy that led to the creation of a large user market.[19] Germany's lead in the global market of CNC machining has been maintained to the present.

Despite a change of strategy, it was difficult and took decades for the US to recover lost ground in the NC commercial market. The UK was in a similar position despite the development of machine tools since the industrial revolution and the minimal destruction of manufacturing infrastructure by the war.[20] The British share of the world market fell from 8% in 1971 to 5% in 1977, and to 3% in 1981, with machine tool imports growing between 1971 and 1982 from 30% to 61% of domestic consumption (Heinrich, 2001).

With the rapid evolution of PCs, its main technological complement, and the associated drop in price, the adoption rate of computer numerical control (CNC) increased from 25 percent in 1976 to 41 percent in 1982 (Chudnovsky, 1989).[21] By the mid-80s, the computer control unit was located directly on the machine (Åstebro, 1992). Since then, several improvements have been introduced. As a result, the manufacturing process has continued to increase accuracy, reduce waste and production costs, lead times, and increase quality whilst further increasing efficiency. The significant profitability gains from its use have brought valuable improvements in manufacturing productivity and competitiveness (Stoneman and Kwan, 1996, King and Ramamurthy, 1992, Åstebro et al. 2003).

Despite its favourable properties, however, it took several decades for the majority of the eligible companies to adopt them.

Figure 2 shows the uptake of NC, CNC and two of its technological complements, Coated carbide Tools and Microprocessors, by firms operating in the UK engineering and metalworking sector. Their diffusion patterns follow the typical S-shape starting at the

[19] Adapting the technology to new use and new customers simplified usability, adaptability, and affordability is a strategy demonstrated to be successfully employed in the evolution of technologies such as PCs and home printers.

[20] Following the arguments of, e.g., Gerschenkron (1955), this relatively intact legacy may, in fact, have slowed the UK's embrace of the new approach.

[21] In Japan, the share of NC was 76% in 1986, while it was 55% in Italy in 1982, 40% in the United States and West Germany in 1983 (Chudnovsky, 1989) and 58% in the UK (Battisti, 2000).

beginning of the diffusion process, when the technology first entered the market, accelerating up to the inflexion point before reaching the saturation point, when 100% of the potential user have adopted the technology.

Typical of many diffusion processes (Rosenberg,1976, p. 191), they show the slow rate of adoption and also that there are variations in the rates of acceptance.

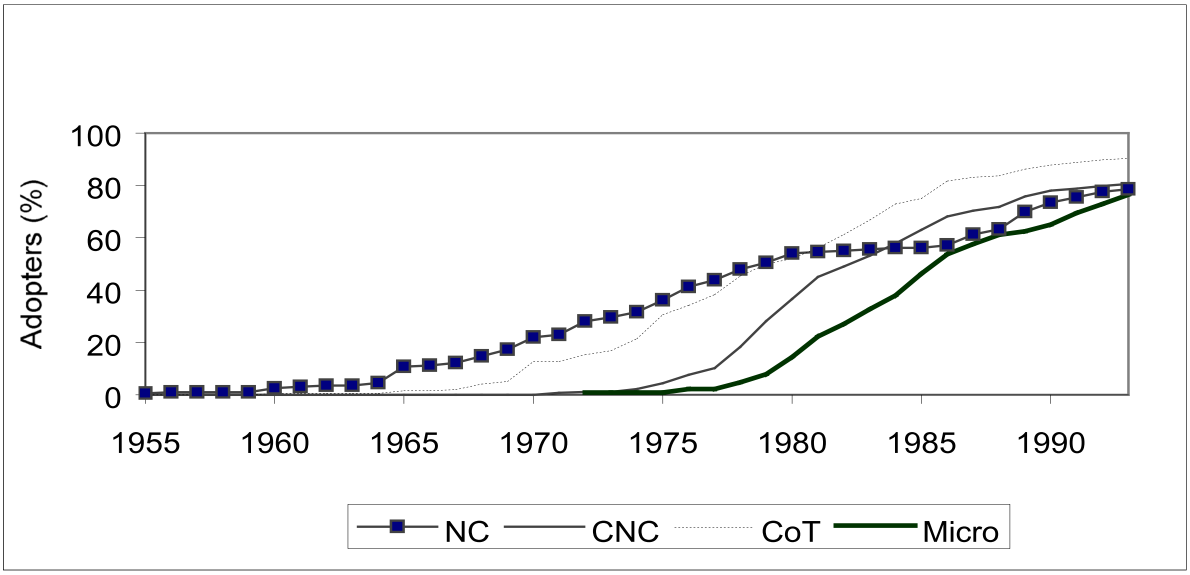

Figure 2: The Inter-firm diffusion of NC, CNC, CoT and Microprocessors[22]

As in many cases of an advanced generation of a GPT, the spread of NC coexisted for some years with that of CNC, its advanced variant, despite the latter being more productive. Battisti (2000), taking a vintage approach to the technological content of the capital stock of the adopting firms, showed that the speed of replacement (intra-firm diffusion) was driven by profitability considerations of their productivity, the scrapping/sunk cost of NC and the acquisition costs (including any necessary staff re-training and re-organisational changes) of CNC. In addition, as shown in Figure 2, from the mid-eighties, due to their long life-cycle, the replacement of NC created a second-hand market that attracted further users of NC based on affordability considerations, e.g. whether the reduction in labour and other operational costs could have compensated for the possible increase in capital costs per unit of output. The increased use of the older variant of CNC slowed down the uptake of the most advanced and productive computerised variant with implications for overall industrial performance. Some experts predict that a similar surge in the demand for second-hand CNC is likely to happen soon due to an expected rise in the average unit prices of new CNC machines fuelled by the recent rising raw material prices and the looming shortage of semiconductors used in CNC machines.

[22] Source: Personal elaboration of CURDS data- Centre for Urban and Regional Development Studies (CURDS), University of Newcastle upon Tyne (see also Battisti, 2000; Battisti and Stoneman, 2003)

A second familiar feature of CNC's increasing popularity and profitability is the development of a range of applications and associated complementary tools used in the production process. They can be classified as ‘hard tools’ such as Coated and Carbide Tools machines and Microprocessors that first appeared in the sixties (see Figure 2) or more recent developments such as 3D printers, and ‘programming’ tools, such as Computer-Aided Design (CAD)/ CADCAM that appeared in the seventies (see figure 3). Both technologies have been extremely influential in the realisation of the benefits of CNC adoption (Åstebro et al., 2010, Ewers et al., 1990, Stoneman and Kwon, 1996, 1994, Battisti et al, 2010). The advantage of CAD over other hard technologies was the additional cost reduction brought about by the electronic transfer of information between CAD and CNC. Their computerised integration eliminated the labour previously required for transferring information to the design and manufacturing functions, reducing operational costs whilst increasing labour productivity. The success of their joint adoption is visible by the spread of uptake as stand-alone technologies and, in particular, by the rate of joint adoption, as illustrated in figure 3.

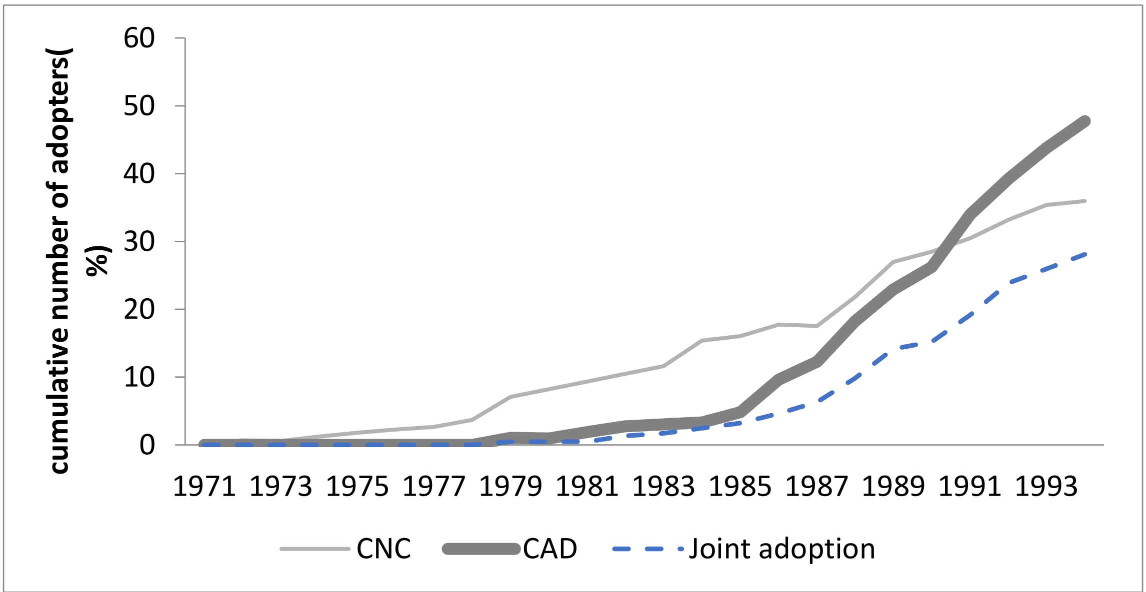

Figure 3: The adoption of CNC and CAD (historical data)[23]

CNC and CAD can be programmed by a Windows-based PC/CNC machine, requiring only basic programming skills to operationalise the process, significantly eliminating the cost of professional training in CNC machines and design. These properties have further increased the extent of use and, with it, the growth and global competitiveness of manufacturing. Of course, many of these developments required developments in computers and computing capacity (next study).

Besides CADCAM, the latest complementarities emerging in the CNC domain are generated by digital technologies such as Artificial Intelligence (AI) and the Internet of Things (IoT). AI, for example, is deployed for automated inspection equipment, including image processing technology to replace manual inspection. The Internet of Things is increasingly incorporated

[23] Source: Åstebro et al 2012; see Åstebro 2002 for details about the survey.

into production processes, driven by the demand for real-time information access. Manufacturers are increasingly focusing on the adoption of smart devices such as cloud-based CNC machine remote monitoring, allowing them to overcome geographical boundaries. The availability of sensors, cloud computing capacity, advanced internet access and speed are paving the way for further growth of CNC with important spillovers into the economy. The development and the impact of CNC is clearly not over, and continues to develop advancements and applications.

CNC is used in automotive, general machinery, precision engineering, and transport machinery, amongst others, and its multipurpose nature is reflected in the broad areas of application in various sectors of the economy, from general machinery manufacturing to automotive, energy, electronics, healthcare, and aerospace and defence. Its global CNC market was valued at USD 86 billion in 2022 and it is predicted to continue to grow, driven by the demand for semiconductor production equipment, medical devices and electric vehicles, and telecom communication devices (Fortune Business Insight, 2021).

To conclude, several lessons can be learnt from the uptake of a GPT such as CNC.

Even though the speed of adoption of new technologies has been significantly increasing over time (Comin and Hobijn, 2010), the uptake of new technology can be a very slow process.

The inter-firm diffusion rate measured by the speed of uptake and the number of adopters is a good proxy for the impact of new technology on an economy. However, the realisation of its benefits at the industry level depends on the depth of its use (proportion of output produced using the new technology) by the adopting firms. This takes longer and is slower than inter-firm data (number of firms) might suggest.

To fully assess the impact of a new technology, and crucially a GTP, assessing the extent of use and the dynamics of the adoption and of the replacement process of the old with the new technology by the adopting firms (the intra-firm diffusion) is as important as observing the number of users (inter-firm diffusion), with the former being the main driver of the realisation of the benefits from adoption (Battisti and Stoneman (2003).

In terms of our framework, CNC was initially developed with direct US state sponsorship (Airforce and MIT). It has since relied on private/business R&D for its advancements worldwide. Sometimes, its advancement has been propelled by exogenous shocks, as in the rapid adaptation of CNC to make ventilator components that led to a significant increase in CNC demand in the healthcare and pharma sector during the pandemic. Its uptake has not required specific direct government intervention or market regulation, but it has been aided by government-led advancement in telecommunication infrastructure and internet provision, as well as the STEM education level of the workforce that enabled its advancements and sustained growth.

CNC benefited from vertical factors. PC's, including fast processors and programming advancements, were clearly important inputs. The outputs have been widespread, spanning across all manufacturing sectors, with a significant impact on their competitiveness and stimulating further CNC development.

The increased demand for efficiency, mass production, customisation and precision has financed further improvement in its applications and business model, starting a virtuous circle in CNC hardware and software innovations and developing crucial Hicksian complementarities that are difficult to disentangle.

4.5 The development of computers

4.5.1 Introduction

Probably the most significant GPT of the post-second World War is the development of computers. However, computing's antecedents can be traced back several centuries.

Computing was an arduous task that has been ripe for automation since the early days of commercial and economic quantification. The 'technology' involved was essentially computational mathematics (a conceptual or 'soft' technology) but spawned methodological advances and a wide range of mechanical and electronic technologies. These, in turn, led to rapid advances in the speed, scope and accuracy of computations and to new uses throughout society. Beyond this, the ability of computers to convert data between mathematical and other forms (from the digitisation of texts to today's Natural Language Processing, context-aware computing and other developments) has led to an enormous explosion of capabilities which in turn have driven technological advances. In this sense, computers form an ideal GPT. One additional feature not shared by all GPTs is the emergence of distinct domains (e.g. hardware and software) and the non-linearity of progress, which has involved retrograde evolution in both functional and technological terms.

The history of computing stretches back long before the emergence of what might be recognised as computers. Initially limited to addition and subtraction (which could be performed simply on an abacus), other arithmetic operations and mathematical concepts developed in step with new and further uses and new technologies (as the development of logarithms allowed multiplication and division to be performed by addition and subtraction, giving rise to the slide rule). This increase in the feasibility of more sophisticated computations also had economic consequences, both through the wider availability of computational capability (which tended to increase transparency and the efficiency of transactions and contracts) and through the emergence of new computational specialisms, e.g. accounting, that performed essential intermediation functions and allowed economic transactions of increasing complexity and scope.

A similar step change is currently in progress with the computerisation of texts and other data. As with the abacus, this began with the automation of very simple processes – printing presses, typewriters and word processors. The easy availability of faithful copies changed the nature of contracts – the specific fixation of a handwritten and signed physical document gave way to authentic records of its *contents*.

4.5.2 Timeline

Initially, computers took the form of specific devices developed to perform narrowly-defined tasks for pre-existing purposes. Gradually they were repurposed, which led, in turn to new, more flexible hardware. A rough timeline is as follows:

- Pascal's adder (the Pascaline 1600s). Pascal was led to develop a calculator by the laborious arithmetical calculations required by his father's work as the supervisor of taxes in Rouen (Pascal 1645). He designed the machine to add and subtract two numbers directly and to perform multiplication and division through repeated addition or subtraction.
- Leibnitz's multiplier (the Stepped Reckoner, about 1700) was the first calculator that could perform all four arithmetic operations; Leibniz developed it as a direct extension of Pascal's adder, though the fabrication technology of the time prevented it from operating reliably (Tweedale, 1993).
- the Jacquard loom (1804) used punch cards to represent weaving patterns that could be used by a retrofitted device to guide semi-automated looms. As a result, complex and detailed patterns could be manufactured by unskilled workers in a fraction of the time taken by master weavers and their assistants working manually. Widespread adoption caused the cost of highly sought-after patterned cloth to plummet. It could now be mass produced, becoming affordable to a wide market of consumers, not only the wealthiest in society, in the process, the 'status' aspect of such fabrics was also eroded.[24]
- the Babbage Difference Engines (Park, 1996) and the Babbage-Lovelace Analytical Engine -1820s-30s -(Hollings et al 2018). Difference engines are mechanical calculators based on the principle of finite differences – that is to say, like Pascal's and Leibniz's devices, they multiply by repeated addition. They were designed to perform a single function; tabulating logarithms and trigonometric functions. The Analytical Engine, in contrast, was a general-purpose programmable computing engine. It adopted the Jacquard Machine's use of programming by means of punched cards but added a 'Store' for numbers and intermediate results and a separate 'Mill' where arithmetic processing was performed. It could perform direct addition, subtraction, multiplication and division. It could also perform a range of modern computer programming functions.[25] It had a variety of outputs including hardcopy printout, punched cards, graph plotting and automatic production of stereotypes - trays of soft material into which results were impressed that could be used as moulds for making printing plates. Various partial prototypes were produced and upgraded as complementary technologies (electricity, electromagnetism and the telegraph) advanced. Significantly, however, neither type of machine was fully prototyped; the Difference Engines were stopped by internal conflicts (between Babbage and his chief engineer) and the withdrawal of British Government funding[26].

[24] See CUCH1 and Age of Revolution

[25] For example, conditional branching, looping (iteration), microprogramming, parallel processing, iteration, latching, polling and pulse-shaping,

[26] In 1878, a committee of the British Association for the Advancement of Science described the analytical engine as "a marvel of mechanical ingenuity" but recommended against constructing it. The committee acknowledged

- The Edmondson railway ticket (Evans and Elphick, 2013) and the Railway Clearing House (Healey, 1969) were a matched hardware and organisational development that sought to perform a different unction, driven by a railway use case. The former device (essentially an automated system for producing printed tickets reflecting changing data) was intended to automate the payment of fares and issuance of tickets and to account for the monies collected; the latter reflected the structure of the railway network, where passengers would use the services of multiple companies in making journeys, so that monies collected could be reallocated to the companies involved.
- the Hollerith tabulating machine (1890)[27], was driven by the inventor's experience in the US census, specifically the need to record (via punched cards, again) tally and sort the data. These designs won a government competition, reduced the time needed to complete processing census data from 10 years to a matter of months and were widely adopted by many nations. The company he formed merged with others to form IBM. The uptake and benefits of the technology were successively upgraded via relays, valves/vacuum tubes, core memory, transistors, lasers and integrated circuits. Each step resulted in products that stimulated applications, which in turn stimulated the demand for more and better products, and so on ad infinitum – including much of the grounding of 5G itself. Also note the connection of this GPT with the other examples (directly in the case of railways).

After this, the development of computers and their applications becomes too complex to summarise. However, there are some stylised facts that shed light on the extent to which the GPT description is appropriate and the sustainability of computing as a GPT (Thompson and Spanuth, 2021).

One of the basic GPT papers (Bresnahan and Trajtenberg 1992) cites the example of computing, starting with (in their account) expensive computers with a few high-value applications (military, space, etc.). This was accompanied, in the US, by a highly-concentrated industry skilled at obtaining public procurement and R&D contracts; the military applications essentially funded the development of mass-market chips, both through R&D subsidies and via the accretion of learning-by-doing cost reductions, which gave firms like Texas Instruments a strong first-mover advantage in the open market. The resulting combination of experience curve economies and sharply-improved performance led more industries to adopt computers. This increased demand financed further improvements (and novel developments in software as well as hardware), so the virtuous cycle flourished. On the hardware side, this has been sustained for decades (a phenomenon often referred to as Moore's Law) and has been transformative. Merely quantitative improvements have led in turn to qualitative transformations of hardware, software, products and business models.

Since the early days of the Intel 4004 processor, there has been enormous market expansion. Despite very recent slowing in the wake of the pandemic, and the takeover of many personal

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the usefulness and value of the machine, but could not estimate the cost of building it, and were unsure whether the machine would function correctly after being built. BAAS 1878.

[27] CUCH2

computer functions by a mixture of handheld devices (e.g. smartphones) and cloud-based servers, sales remain at a high and broadly stable level. The basic insight is that data on computers *per se* no longer give an accurate picture of the update and dissemination of computerisation.

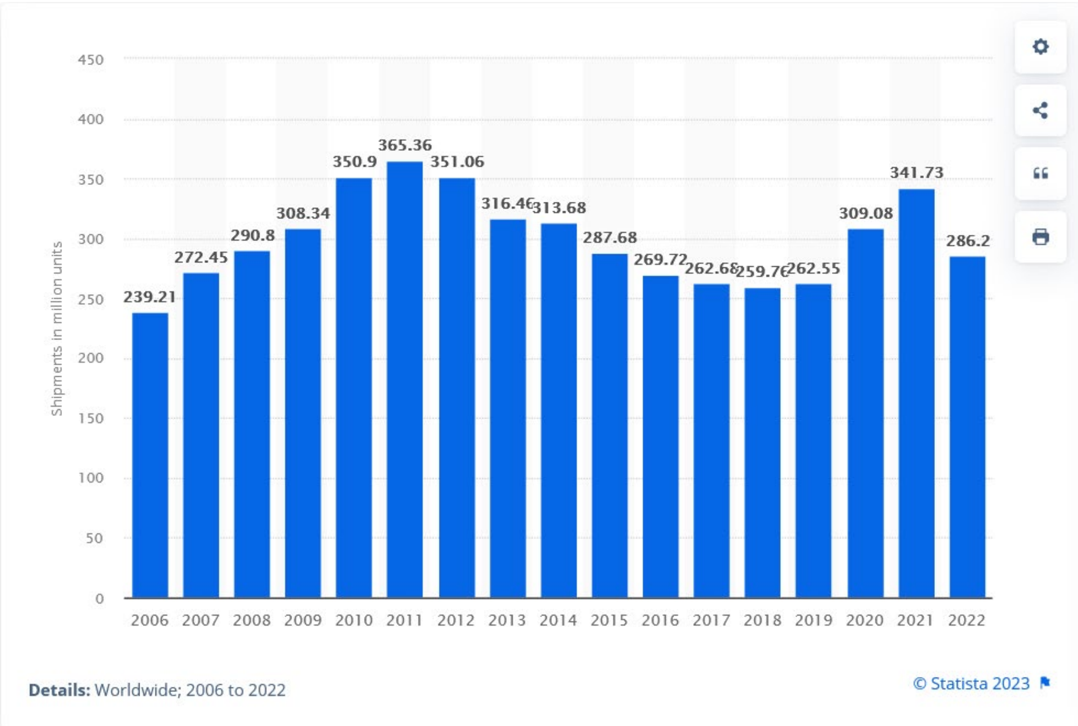


Figure 4: Worldwide shipments of personal computers[28]

A longer time perspective in figure 4 shows initial rapid growth in PC sales on a worldwide basis, which slowed and stabilised as saturation was reached (so many sales involved replacement of existing PCs with newer versions rather than further uptake, at least in developed regions) and the measurable market fragmented into desktop, laptop and tablet segments and the aforementioned migration of computational tasks to a spreading range of ‘smart’ devices. Moreover, it has been widely observed that many people have multiple ‘smart’ and connected devices, so hardware indicators greatly overstate the number of people participating in the ecosystem created by this GPT.

Finally, many of these devices are ‘converged’ in the sense that multiple devices are capable of performing overlapping functions. To some extent this simply demonstrates that the GPT is not the same as the devices. Indeed, in some parts of the world, where internet provision is inadequate to providing high-speed, affordable and reliable connections, work-arounds have been developed to provide equivalent services using ad-hoc networks[29] and to provide smartphone-equivalent payment, e-health/m-health and related services in areas such as African countries, where smartphones are far less prevalent but feature phones are ubiquitous.

[28] See https://www.statista.com/statistics/273495/global-shipments-of-personal-computers-since-2006/.
[29] Especially in mobile applications and resource-poor settings.

The following graphs (figures 5 to 9) give a quantitative sense of the growth of personal computers especially in relation to the UK.

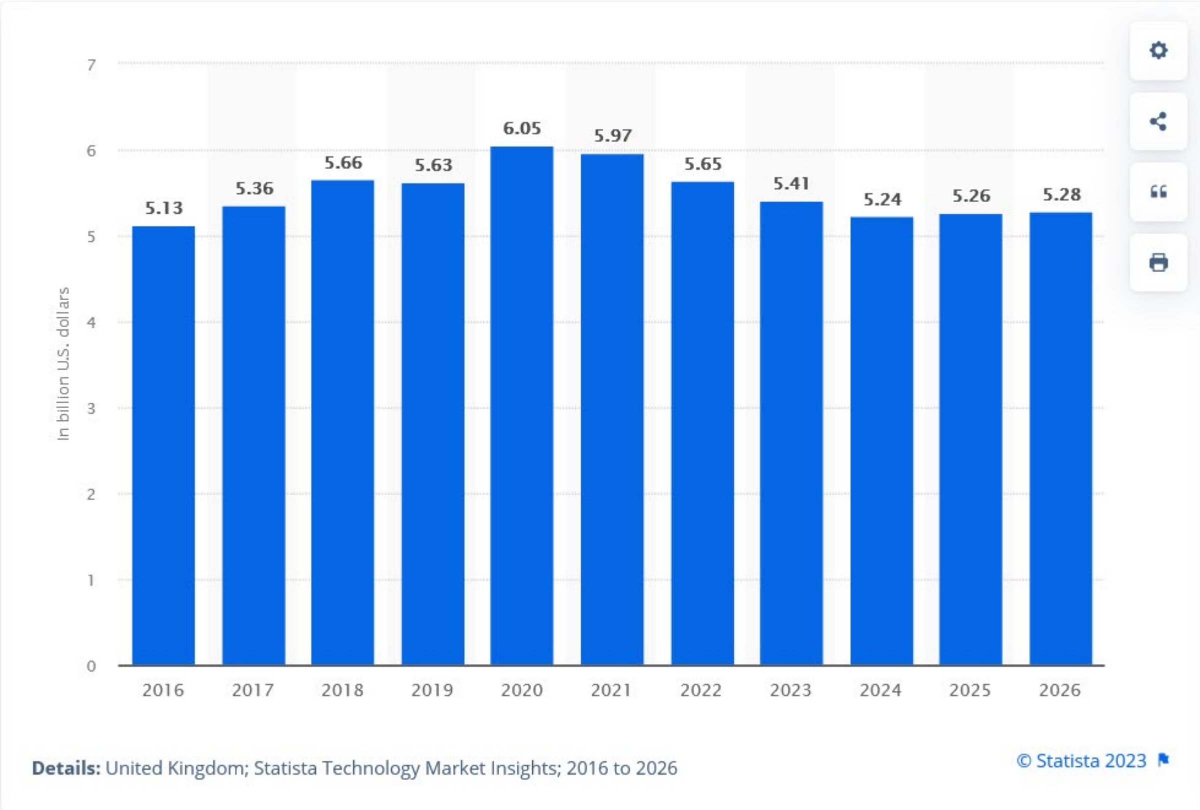


Figure 5: UK PC revenues[30]

[30] Source: Statista.com at: https://www.statista.com/forecasts/1180460/revenue-pc-market-united-kingdom

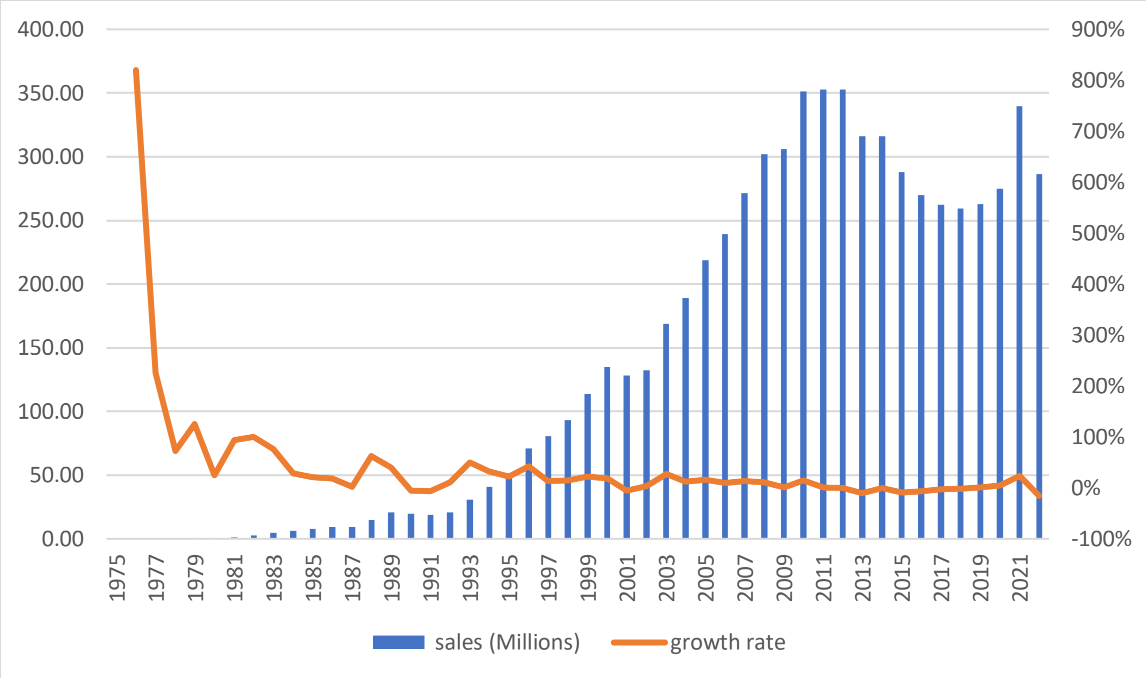


Figure 6: Worldwide PC sales[31]

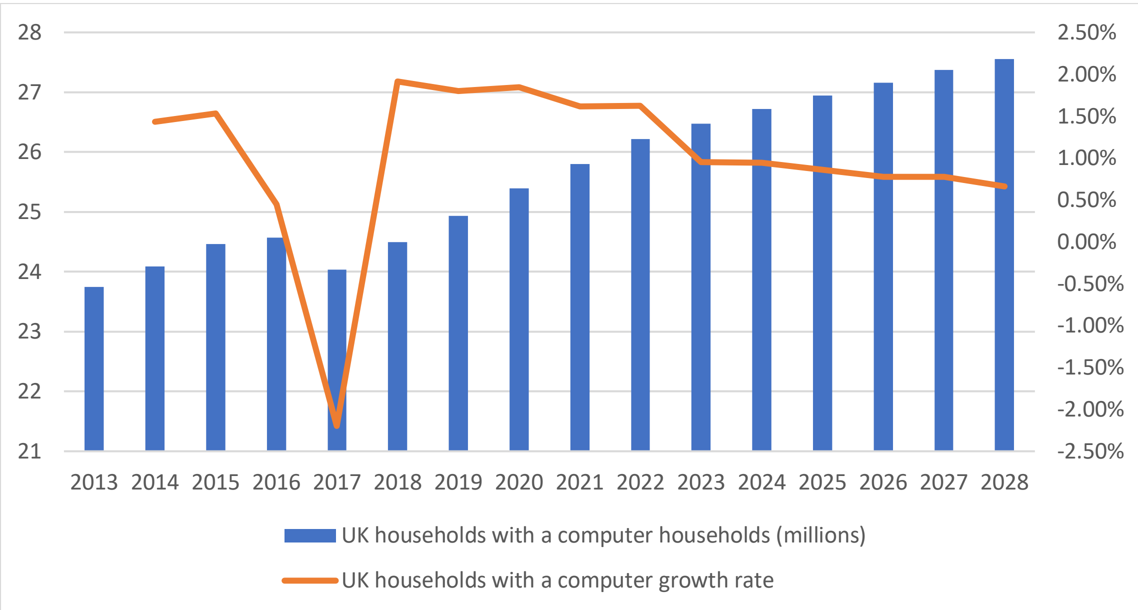


Figure 7: UK Households with a computer[32]

[31] Source: Author's presentation of data from Statista.com
[32] Source: Author's presentation of data from Statista.com

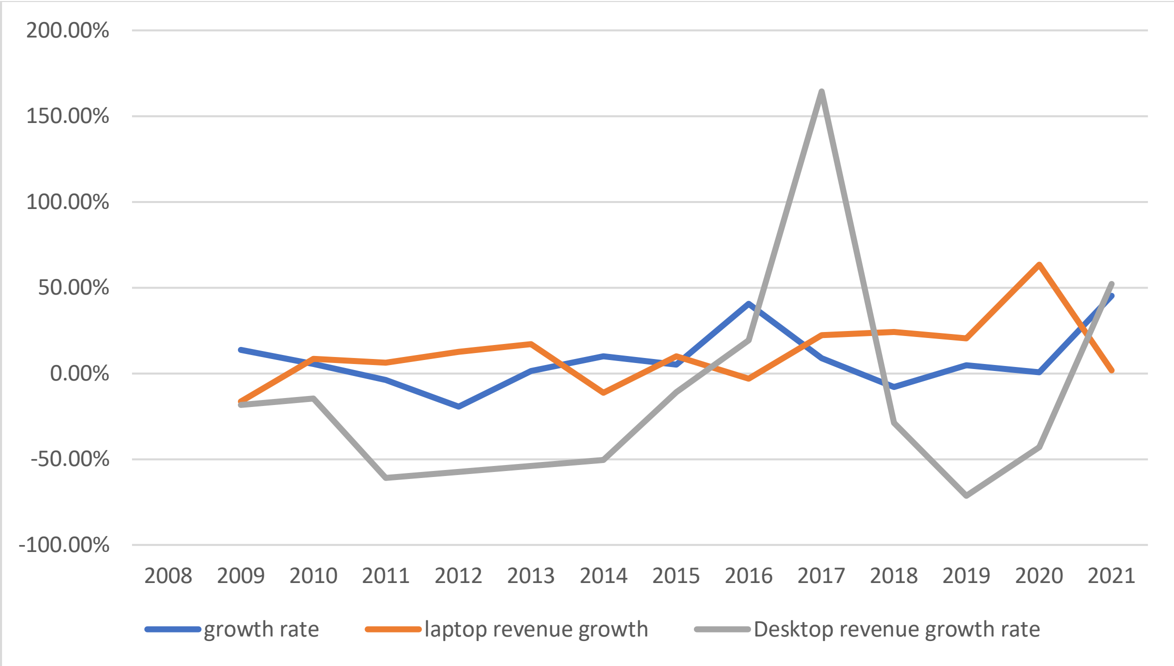


Figure 8: UK growth rate of PC sales and Laptop and Desktop Revenues[33]

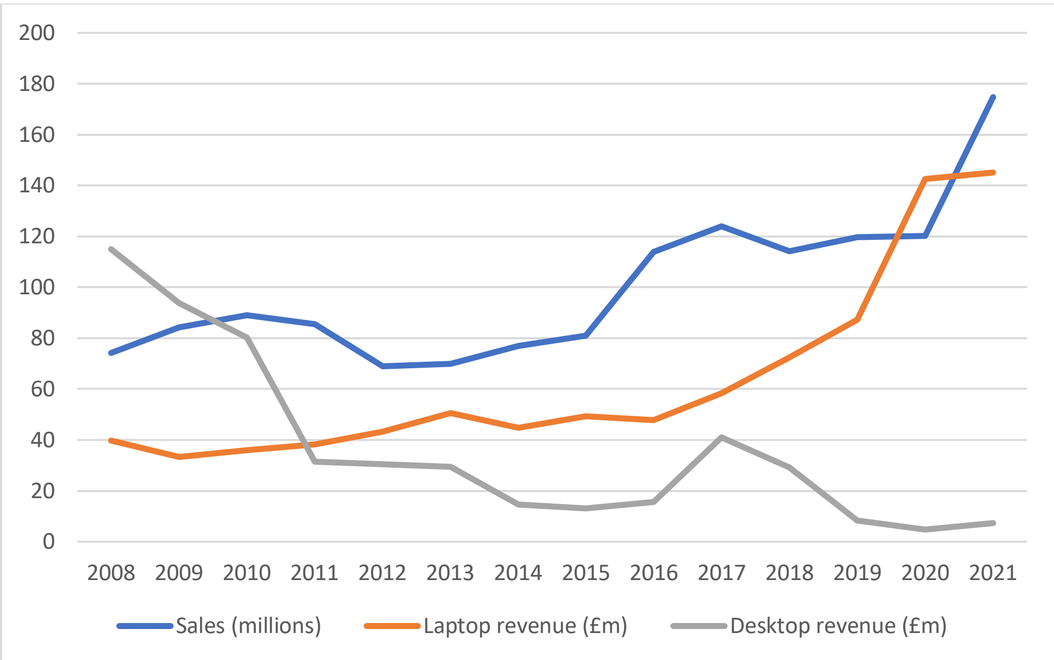


Figure 9: UK levels of PC sales and breakdown into Laptop and Desktop revenues[34]

This market growth has fuelled ever-greater investments to improve chips. By one estimate, processor performance has improved about 400,000 times since 1971 (The Economist, 2016).

[33] Source: Author's presentation of data from Statista.com
[34] Source: Author's presentation of data from Statista.com

Indeed, one popular description of Moore's Law phrases this growth as hardware performance doubling every two years at constant cost. Not surprisingly, the effect of computing on the economy has been substantial, too. Byrne, Oliner, and Sichel (2013) estimate that since 1974 information technology has been responsible for more than a third of the annual labour productivity growth in the US non-farm sector.

4.5.3 Evolution does not always run uphill

It is tempting to think, especially given the enormous transformations produced by the computerisation considered as a GPT and the seemingly-inexorable operation of Moore's Law, that any sufficiently generative technology can be relied on to continue in the direction it is headed, producing more and more derivative innovations, improvements in economic, societal and governance performance and an ever-greater 'deepening' of its GPT status and impacts. But a closer look at this case suggest that this is too simple. In this section, we consider some qualifications to this view.

The re-emergence of specialisation

First, we note that the development of computerisation, whether in the software or the hardware plane, has not always tended towards greater generality and wider functionality. Specialisation has re-emerged in response to competition and the demands of specific applications. This can be seen broadly in the way different challenges are met.

Some of the literature on GPTs addressed the question of substitutes, asserting that a GPT should have a wide range of technological complements, but no close substitutes (see for example Bekar et al. 2018). This depends on a 'killer application' that drives their evolution. For example, *cybersecurity challenges* can be addressed by technical, economic or regulatory means. Specifically, privacy and authentication functions have sometimes been pushed 'up the stack' (handled technologically with computer-intensive approaches), linked to identity tokens or reinforced at the behavioural or regulatory level. This is significant when the challenges have technical *and* behavioural aspects – subsequent evolution on both the 'good' and 'bad' sides may be driven more by psychological or societal factors than by technology, and inconsistencies may be magnified, and problems exacerbated by attempts to manage or evaluate these problems in technological terms. When these are discovered, the spread of the GPT effect may go into reverse.

There may also be a tendency for advances in the core or generating technology (the GPT itself) to crowd out complementary technologies and other developments. Continuing the cybersecurity case, this happens with e.g. privacy by design' and 'secure by design' proposals; they provide strong levels of general performance but may not be sensitive to weak signals of pending disruption or inappropriate placement of responsibility and liability in complex computer-enhanced systems.

Sometimes, *technology in use moves backwards*, as with the sudden re-uptake of SMS and related systems (e.g. WhatsApp), which closely followed the advent of 'smart' 3G telephony and its associated computational capability.

The *location* of computational resources may also evolve in ways that owe more to competitive performance incentives than to technical efficiency. This has dominated movement of computation into and back out of the cloud (Cave et al., 2015). Cloud servers tend to be general purpose, offering a wide range of ingress, access and curation functions as well as processing capabilities, and compensate for any loss of specificity by economies of scale and scope. However, they have recently been replaced for some applications by e.g. data centres in close physical proximity to major financial exchanges (despite crowding costs and scale pressures), hardware-based 'fast but dumb' methods for identifying trading opportunities and making trades to the partial exclusion of sophisticated financial economic modelling, and the substitution of 'unstructured' machine learning models for analytically-based alternatives for identifying and simulating complex relationships.

This operational re-specialisation has been matched on the hardware side as well. Specialised processors (GPUs) were originally developed to replace general-purpose CPUs for graphics calculations but are now used for data-intensive applications – especially so-called "embarrassingly parallel" tasks such as: Gaming ; Video encoding and editing; 3D graphics rendering (including AR and VR); Machine learning e.g., neural network training; Blockchains and cryptocurrency mining; and cybersecurity computations including some forms of encryption and password cracking.

This in turn eventually led back to a GPT approach by way of de-specialisation of the architecture. An example is provided by the NVIDIA Tesla line of General-purpose graphics processing units (GPGPUs); both AMD and NVIDIA partnered with Stanford University to create a GPU-based client for the Folding@home distributed computing project for protein folding calculations.

Another example is bespoke silicon for financial trading - chips designed to perform moving average computations at incredibly high speed that facilitate agile momentum trading and front-running strategies, which in turn change the nature off market liquidity and informational efficiency.

Finally, there are an increasing number of so-called 'planet-scale data centres' for extremely large applications including search engines and weather forecasting.

In summary, it is difficult to overstate the impact of computers, but at the same time difficult to untangle the complex picture of developers, developments, government involvement, companies pressing at the boundaries of what is legal and changes to life generally. It is a much more complex and confused picture that earlier developments facilitated by a few individuals.

In relation to the framework, significant phases and developments include: computers began as automated and specialised approaches to arduous and repetitive tasks but became general-purpose in response to emerging sectors and the interaction of academic and commercial communities. Their development was encouraged by public support, especially driven by the needs of large public services (e.g. rail transport) and (in the US) military consumption. This, in turn, produced scale economies and the emergence of large dominant players.[35] Significantly, it was also associated with the emergence of regional innovation hubs like Silicon Valley in which innovations in hardware, software, finance, business models applications and services became self-sustaining. This economic geography aspect (agglomeration and *filière* structures) of the computing GPT was not always seen in the other cases but carries over into cellular communications and the design of innovation and industrial policies e.g. Nanotech, Biotech and Synthetic Biology (SynBio).

The computing case also shows how the associated verticals can change; some (like transport, financial services and health) were transformed internally, with new layers (e.g. platform services) and changed structures of competition and innovation. Other verticals, like online services and software development, emerged *de novo* or split off from the original hardware-orientated computer sector. Other significant stages were the emergence of personal computing, mobile or converged devices, de-generalised devices and programmes and user-friendly programming tools, which served as vectors to accelerate the GPT process.

5 Measurement, Dynamics and evaluating impact of a GPT

It is not possible to collapse economic impact of a group of GPTs to any single measure such as GDP growth. This is in part because GPTs change the nature of society itself. Even a manufacturing industry such as CADCAM changes what can be done and therefore what is done. These issues have been much debated, for example, in the development of computers, where attempts to index productivity have been stymied by lack of a suitable base. Nevertheless, our examples can each be quantified as to impact along at least some dimension, as the descriptions and graphs have shown. But each of these brief studies also demonstrates that the spread of a particular innovation in each case takes time. However, broadening to a much wider range of industries (not necessarily qualifying as GPTs) shows an interesting and important characteristic. The speed of adoption of these various innovations appears to be increasing over time. Figures 10 and 11 below (11 uses a log scale) illustrate the point well. It is most apparent in the contrast between the early cases (In Britain, post, telegrams, railway lines, etc.; in the US telephone and electricity) and the latest cases such as mobile phones, social media and industrial robots, but it is also seen in the post-war cases such as air freight and colour tv versus mobile phones. Of course, in the longer term many of the developments, even the most major, decline. Rail and posts are obvious examples, but more recent cases include landline phones.

[35] For example, Texas Instruments used ‘experience curve’ cost reductions and performance improvements from large military contracts to establish a dominant position in the private market. This, in turn, led to an ecosystem of small innovative firms producing IP that was exploited by larger players.

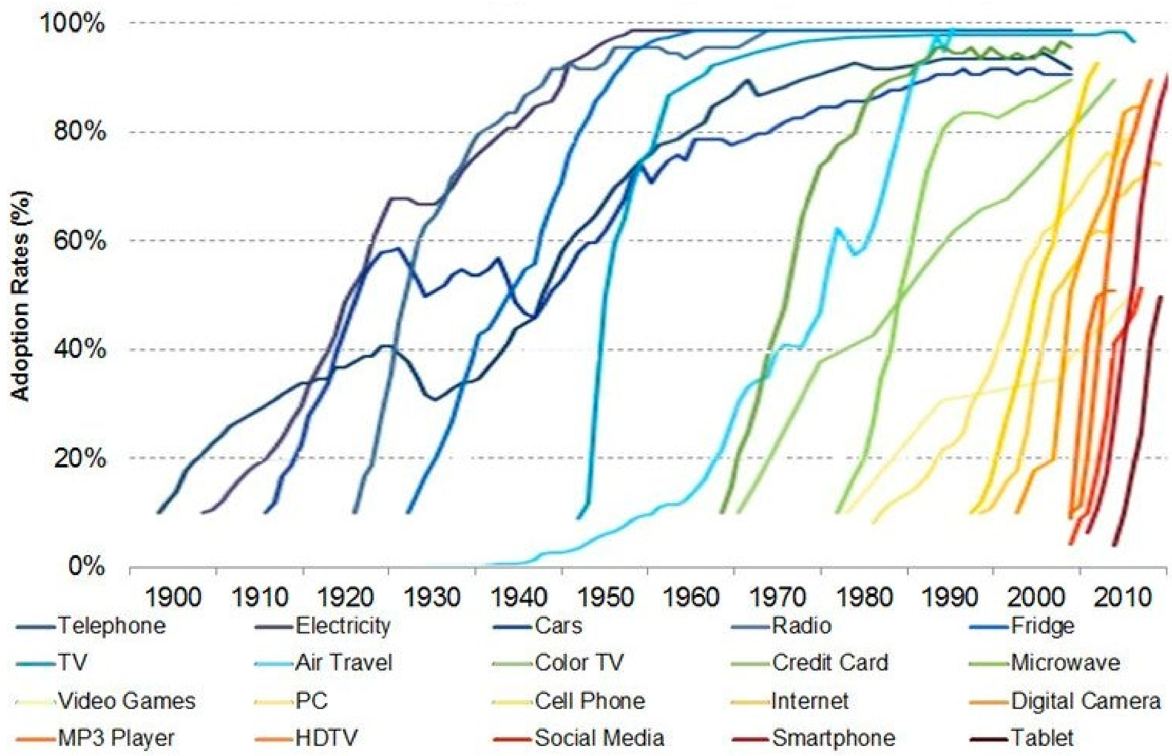
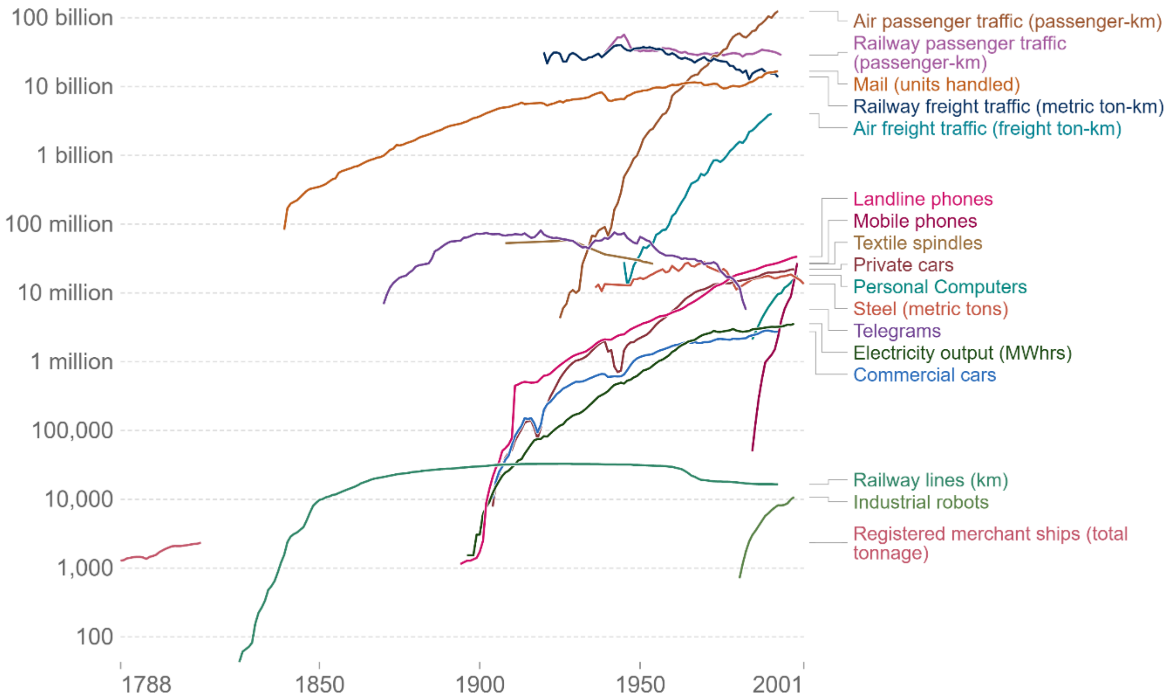


Figure 10: US technology adoption (1900 to the present)[36]



[36] Source: Black Rock – "Interpreting Innovation" see e.g., https://www.blackrock.com/hk/en/market-insights/article/hk-one/DEFAULT/investment-insight/interpreting-innovation

Figure 11: UK technology and infrastructure diffusion[37]

The impact of GPTs on the economy is apparent from the seismic technological waves they have generated since the beginning of the industrial revolution.

Over time the demand growth for new technologies has driven the process of technology substitution and technology exploitation with waves delivering their impact over shorter and shorter periods of time, confirming the Schumpeterian view of the economy evolving through an evolutionary process of continuous innovation and creative destruction in an economy supported by an intensive process of knowledge accumulation and exploitation.

In this process, the role of the GPTs in this study is evident. Whether large infrastructure -as in the case of railroads, electricity, and mail- or technologies that rely on communication infrastructure -as in the case of PCs and CNC-- they all had a major impact in stimulating further technological advancements and complementarities. They are milestones in the growth of an economy and in maintaining its competitiveness. There were additional significant impacts on the labour market and management, illustrated in the earlier cases. They also show the importance for development of a state-of-the-art infrastructure that enables the UK economy (for example) to timely ride the technological wave and sustain the global competitive pressure generated by their appearance. But in examining cases in the past, what are now seen as GPTs often had humbler origins and stumbling beginnings, as well as several stages of innovation Improvements and new generations.

Measuring the success and the dynamics of the uptake of GPTs has been the concern of the economic analysis of technological change and growth theory since the 1950s.[38] Studies have covered a broad range of GPTs, including electricity, railways, and technologies incorporated into capital goods such as PCs and CNC, and 5G.

Many of these studies have defined the success of a technology according to its extent and speed of uptake across the economy, illustrated by the S-shaped diffusion curves presented in this study.

Others have measured the success of a GPT with respect to the intrinsic technological characteristics and dynamics leading to their technology dominance, as in well-known case of QWERTY versus Dvorak's keyboard design (David, 1985) or in the evolutionary approach (Nelson and Winter, 1982). They have also explored the role of expectation of future technological changes in the technology itself or its substitute in determining their impact.

Other studies again have moved away from the technological aspects and have focused on the role of market characteristics in determining the speed of advancements and the returns

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[37] Source: One world data at: https://ourworldindata.org/grapher/technology-infrastructure-diffusion-uk

[38] See, for example, Griliches (1957) on hybrid corn or Fishlow (1965) on railroads or Hughes (1971) study on the importance of reaching latent scale economies as a form of technological progress in the utility industries such as electricity. Many of these studies were initially carried out mainly by economic historians and were later formalised into mathematical and econometric micro and macro-economic models to capture the dynamic of their development and impact. The majority of the early studies concerned US cases.

to a technology (see for example Bresnahan and Greenstein, 1999). They have looked at the degree of market concentration, whether an open or closed economy, the speed of the industry growth rate, inter-firm differences and networks and the impact of new entry and market dominance in generating benefits from their use. A stream of literature has also examined the institutional environment and the role of market regulation, standards, subsidies to R&D and other government interventions in shaping the returns and hence the diffusion pattern.

In analysing the dynamics of successful GPT uptake, a distinction has also been made between returns to the users - whether firms or consumers/households – and returns to technology suppliers. Such analyses consider learning, profitability and sociological considerations, information acquisition, uncertainty reduction, and behavioural and game theoretical considerations including tastes and preferences.

Whether supply or demand, such models identify a series of factors that influence the dynamics of the technology uptake (see, for example, Stoneman et al. (1995), Geroski (2000), Hall (2004), Thirtle and Ruttan (2002), for a review of such studies). However, the supply- and demand-based approaches have often been criticised on the grounds that the dynamic behind the success of new technology, especially a GPT, is when the forces of demand and supply start interacting in a virtuous circle (Rosenberg, 1982, David, 1991, Bresnahan, 2010). The existence of such a self-reinforcing feedback between producers' learning by doing and consumers' learning by using leads to embodied technological change (advancement in the technology) in response to the disembodied improvements in the use of the technology.

History shows that technological breakthroughs hardly ever happen in isolation and rely on the speed of advancement and development of complements, whether they are managerial/organisational (Brynjolfsson et al. 2002) or purely technological. The vertical and horizontal development of such complementarities determines the benefits of GTP. For example, the profitability of electricity or a railway depends on timely vertical advancements such as the metallurgical improvements of the materials used for the powerplant or the rail track. A power plant depends on horizontal improvements in the transmission network to reap the benefits of economies of scale and reduce the cost of transporting electricity. Similarly, PCs would have had limited impact without the support of a fast and reliable telecommunication network. Such complementarities make it difficult to identify the impacts of the GPT *per se*.

Moreover, the multipurpose nature of a GPT also implies that any single user interaction or application in isolation cannot capture its impact due to the breadth of complementarities it generates in the various applications and sectors of the economy. As stated by Bresnahan (2010), the success of a GTP rests in (i) its widespread use, (ii) the capability to undergo technological improvements but crucially also in (iii) the capability to enable innovations in application sectors, with (ii) and (iii), illustrating the loop of innovation complementarities.

It is now commonly accepted that it is the development of such complementarities, whether of managerial/organisational or technological nature, that determines the success and the generation of the benefits from using a GPT. It is also the timing of the appearance of the vertical and the horizontal complements that affects the performance (either profitability or productivity) and hence the diffusion of GPTs. The lag in developing such complementarities has been known in the literature as the productivity puzzle, whereby GTPs, such as ICT -and more recently AI- for many years 'have appeared everywhere but in productivity statistics' (Solow,1987).

Attempts have been made to capture the success of such user/producer dynamics via the number of patents generated whilst capturing the multipurpose nature of the technology via the breadth of the technological classes it spans across. However, the count of innovations is only an imprecise proxy of their impact. Moreover, it does not necessarily capture the impact of non-technological non-patentable innovations e.g., managerial and organisational changes or the technological trajectory of horizontal and vertical improvements, posing some limitations to the assessment of the full impact of a GPT.

For the same reason, the counting of the technology adopters (inter-firm diffusion), as in the S-shaped model, although useful to assess the speed of uptake, does not provide the extent of the benefits from the use of a technology over time, especially when the technology, such as a PC/ICT, or 5G is well established and widely used (and the number of adopters is close to the saturation level).

Other models have taken a different stance and have instead focused on the economic displacement in the labour market that the technological breakthrough of a GTP generates in an economy. Lipsey et al (2005) argue that this is the real cause of the delay in the emergence of the economic impact of a GPT (the paradox). They also argue that its intensity depends on the degree of compatibility of the GPT with existing technologies and/ or the GPT it is meant to disrupt. Several arguments have been put forward in the analysis of GPTs, as to whether the resulting up- and re-skilling is labour-reducing, the new jobs it creates are labour-enhancing, and the trade-offs between the two (See for examples Montobbio et al. 2021, or Nedelkoska and Quintini, 2018).

Some studies have moved away from the microeconomic approach to measuring the benefits from adoption and have focused on the impact of the GTP on the growth of an economy. Endogenous growth models, general equilibrium models, and growth accounting models have been challenged by the analytical complexity of modelling, estimating and predicting the impact over time of a GPT (see for example Helpman, 1998). The results have been mixed, and refinements are still ongoing. Some models have failed to detect their impact (the paradox), especially in the early stages of diffusion, or if they have, they produce a point estimate that is not representative of the dynamics of the adoption pattern over time and the decreasing benefits over time as new adopters enter the market or led by the technology lifecycle or the appearance of a competing technology. Another shortcoming is that the economic models often fail to account for the quality and speed improvements of the technology over time (technology generations) and fail to acknowledge that the impact of a GPT can last for over a century e.g., electricity. The technology's decline is difficult to predict, and its effect is potentially pervasive across GPTs. As provocatively argued by Lipsey et al (2005), we would not have had 5G without the internet, PC/ICT and similar complementarities generated by electricity. Hence, their impact should be included in the overall impact of the latter.

Too often, macro models assume that only one GPT is used at any point in time meaning prices are a poor estimate of value and fail to disentangle the contribution of the technology from that of its various complements.

Lastly and crucially for policy intervention, they often do not measure the broader social benefits of technological advancements.

In summary, the pervasive and multipurpose nature of GPT and the evolving nature of its impact makes it very difficult to isolate its contribution to the economy. Whilst the dynamics leading to the emergence of a GPT are fully understood, as well as the seismic impact they generate on the economy, their economic success is difficult to quantify and predict with any degree of accuracy. Comin & Hobijn (2004) have calculated that the cross-country differences in the timing of adoption of new technologies account for at least a quarter of per capita income disparities. Hence, in a competitive global market, the timely transition to a new technology or to its latest generation, e.g., from 4G to wireless 5G, is important to maintain a competitive advantage and to avoid costly locked-in effects into the limited capacity of previous variants. But in conclusion, attempting to capture the nature of a GPT by a single indicator (such as GDP) is doomed to fail.

6 Conclusion

This study aims to investigate the characteristics of a GPT (like 5G) that might influence the probability of it being high impact. To this end, we developed a template for identifying the key characteristics that would indicate that a GPT has a potential for high impacts. These are not just technological, but also include the wider economic and policy contexts. Of course, anticipated impacts remain uncertain even after the characteristics in the template are taken into account. Impact magnitudes for GPTs depend also on complementary developments (e.g., in application sectors) and may require policy interventions. To clarify the lessons of history and facilitate their application to new GPTs, our logical framework organises the analysis and alternative potential paths based on criteria, evidence, indicators and risk factors or critical uncertainties. These, we conjecture, include standards development, exogenous events and emergent complements or substitutes. The use of the framework also involves examining the roles of governmental or quasi-governmental bodies in facilitating or hindering this change, which can include the granting of licences, monopoly rights, self- and co-regulation and the like. The framework, besides being a template for the analysis of existing GTPs, allows us to delineate potential scenario spaces of new GTPs in order to identify relevant possible futures, take account of critical uncertainties, describe use cases and their current and near-term relevance to the UK, identify possible policy levers, and analyse relationships among these elements in order to construct and assess policy options.

We have developed and refined the framework by analysing five historical examples based on information collected from historical sources on the range of preconditions, inputs and outcomes involved. The GPTs are the development of railways in 18th century Britain; the Royal Mail national "penny post" in 1840; the development of electricity; computerised numerically controlled machine tools; and the development of computing. The analysis of their economic impacts incorporates the extent to which the technology development led to the widespread adoption, complementary innovation and technological dynamism that are the defining characteristics of a GPT. We note that some things are easier to measure than others, and that "GPT is as GPT does" - the best metrics are those measuring the state of the mechanisms underlying the performance of a GPT in terms of its widespread adoption, continuous improvement, variety of uses and capacity to stimulate complementarities.

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