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Does Economic History Need GPTs?

by

Alexander J. Field
Department of Economics
Santa Clara University
Santa Clara, CA 95053
email: afield@scu.edu

ABSTRACT

In the last decade one of the most successful memes in economic history has been the concept of a general purpose technology. The rapid multiplication of technologies accorded this designation has raised questions about whether the concept has gotten out of hand. My intent in this essay is to ask whether the concept has indeed gotten out of hand, and, more fundamentally, whether, when the concept of a GPT and the ways it has been used are critically examined, we may conclude that the discipline of economic history could do as well without it. I note that the GPT criteria are not always consistently applied, the technologies under discussion are often not clearly identified, and that the criteria ultimately do a haphazard job of separating the consequential from the inconsequential.

Does Economic History Need GPTs?

In the last decade or so one of the most successful memes in economic history has been the concept of a general purpose technology. Tim Bresnahan and Manuel Trachtenberg published the seminal article in 1995 and by now the list of notable publications building upon, amplifying, and drawing from the concept is lengthening. These include Helpman (1998), Rosenberg (1998), Caselli (1999), Crafts (2003, 2004), David and Wright (2003), Gordon (2004), Goldfarb (2005), Lipsey, Carlaw, and Bekar (2005), Jovanovic and Rousseau (2005), and Rousseau (2006, 2008). Bresnahan and Trachtenberg built on earlier work by David (1990, 1991), and one of the most widely cited of Wright's paper's is his joint work with David, "General Purpose Technologies and Surges in Productivity: Historical Reflections on the Future of the ICT Revolution" (2003). Wright has been sympathetic to the idea of GPTs, defining them in his 2000 review of Helpman (1998) as "deep new ideas or techniques that have the potential for important impacts on many sectors of the economy" (Wright, 2000, p. 161). Although the argument of the David and Wright paper – and its title – reflect an implied acceptance of the usefulness of what has become a widely used concept, the authors also had this to say, after noting the wide range of technical and organizational advances for which the GPT appellation has been proposed:

> One has only to consider the length of such proposed lists of GPTs to begin to worry that the concept may be getting out of hand. History may not have been long enough to contain this many separate and distinct revolutionary changes (2003, p. 145).

My intent in this essay is to ask whether, indeed, the concept had gotten out of hand, and, more fundamentally, whether, when the concept of a GPT and the ways it has been used are critically examined, we may conclude that the discipline of economic history could do as well without it. This is not to take issue with the historical analysis of David and Wright, or that of others such as Rosenberg (1998) or Crafts (2004), which have been influential and important contributors to our thinking about the impact of technical change and the sources of TFP growth. It is rather to question the extent to which these, and other papers within this tradition, depend in any essential way on the concept of a general purpose technology.

What GPTs Promise

The appeal of the GPT research program is twofold. First, it captures the essentially correct intuition that technological change is unbalanced – occurring at widely different speeds in different industries or sectors. Over the last century and a half, TFP in the United States has grown at roughly 1.5 percent per year. Across different shorter macrohistorical epochs, however, this rate has differed substantially, with the highest rates registered during the interwar period. Even more importantly from the standpoint of this paper, within any given epoch, TFP growth has not been the result of balanced advance across all sectors of the economy. Harberger emphasized this in 1998 when he argued that economic growth is typically driven by ‘mushrooms’, which grow very rapidly here and there in a pattern that is tough to predict, as opposed to by ‘yeast’, which causes different parts of the bread to rise at approximately the same rate.

David and Wright pointed at the yeast rather than mushroom-like character of TFP growth within manufacturing in the 1920s, the result of a broadly diffused replacement of mechanical means for distributing power within the factory by wires and electric motors. Their empirical claim about manufacturing is supported by data at the two digit level. But whereas it looks like yeast within manufacturing, if we step back and consider the economy as a whole, manufacturing sticks out in the 1920s like a giant mushroom on an otherwise placid and slow growing lawn. Almost all of the roughly 2 percent per year growth in TFP in the private nonfarm economy between 1919 and 1929 was due to the extraordinary 5 percent per year advance within manufacturing (David and Wright, 2003; Field, 2006).

Viewed from this broader perspective, the experience of the 1920s can be seen as similar to what we observe throughout history. Sectors (and often industries) experiencing high TFP growth and revolutionary cost reductions coexist with sectors experiencing evolutionary change or in some cases downright stagnation. The economic history of the 1920s – and the GPT concept itself, which draws on this history – can thus be interpreted as reinforcing Harberger's point about the mushroom-like nature of technological progress.

But GPTs and the criteria for identifying them have promised to do more than just remind us of the unbalanced nature of economic advance. They aspire to offer a means of identifying and characterizing the most important "engines of growth" that underlie the dynamic sectors or industries within an economy. From the standpoint of technological history, therefore, the idea of a GPT, a technology leading to revolutionary change, also resonates with the obvious reality that some innovations are more important than others. As economic historians or historians of technology one of our tasks is to develop narratives that identify and distinguish those that are consequential from those that are not. Does the concept of a GPT help us do this? To, answer, we need to apply GPT criteria consistently, and study the technologies thus identified. We can then try and see whether these screens deliver what they promise.

GPT Criteria

Much thought has gone into specifying GPT characteristics. Bresnahan and Trachtenberg (1995) and Lipsey, Bekar, and Carlaw (2003) identify several defining features of a GPT: 1) that it have potential for *rapid improvement* and elaboration, 2) that it have *broad applicability* across many sectors of the economy, and 3) that it foster *spillovers* by stimulating improvements in other products and processes, and in turn be stimulated by these complementary advances. Jovanovic and Rousseau (2005) use different words, but say essentially the same thing: a GPT should be 1) pervasive – spreading to most sectors, 2) improving over time, and 3) able to spawn new innovations. They also state that GPTs “transform both household life and the ways in which firms conduct business” (2005, pp. 1184-85). Gordon (2004) argues this as well. It’s not entirely clear whether this is a clarification of the pervasiveness criterion or is intended as a separate test.

Where do these criteria come from? They have been distilled from a few canonical histories, starting with ICT broadly defined. The criteria have subsequently been used to identify other technologies that might have similar features. The GPT concept has then, in the hands of theorists, taken on something of a life of its own. Theoretically minded economists have embraced the idea because it appears to be a powerful abstraction with interesting implications, for example, about the time pattern of productivity improvement associated with revolutionary technological change. In particular, because of the physical capital and complementary training and R and D requirements often associated with GPTs, one can argue that they might retard the rate of TFP growth before they advanced it, by diverting resources on the input side prior to the reaping of a bonus on the output side. Several of the more widely cited articles in the GPT tradition study relationships between upstream and downstream innovators, and identify externalities in the R and D process that may produce coordination problems or deficient or excessive levels of innovative effort. Based simply on a page count or a study of its reference list, the seminal Bresnahan and Trachtenberg contribution is in fact more theoretical than historical in its focus.

Nevertheless, the literature has always anchored itself and seen itself as building upon research in economic history, and the prospects for cross fertilization between history and theory partly explains the success of the meme. That cross fertilization, and the validity of the theoretical implications deduced, however, can only be as valid as the historical foundations upon which the basic category rests.

Problems with the GPT Concept

There are several difficulties with the derivation of the GPT concept from, and its application to, economic history. The first, already noted by David and Wright, is the expanding list of innovations to which various authors have attached this designation. Here are some key questions we must ask. In developing lists of GPTs, has a stable set of criteria been consistently applied? Have authors been clear about precisely what technologies they are discussing? Is it true that all of these are similarly revolutionary? And has the filter represented by these GPT criteria done a good job in separating innovations that were consequential from those that were not? That is, can we point to innovations that economic historians and historians of technology agree are important in terms of their contributions to what Harberger called real cost reductions that nevertheless do not appear on GPT lists because they do not satisfy one or more of the GPT criteria? If that is so, and if the main purpose of the GPT is to help us identify revolutionary innovations, are these criteria of any real value?

Too Many GPTs?

A number of economic historians have embraced the GPT as a useful way of framing studies of individual innovations, sectors, or industries (see, e.g. David and Wright 2003, or Crafts, 2004). But the most systematic effort to motivate the concept through examination of the historical record is to be found in Lipsey, Carlaw, and Bekar (2005), who have also worked hard to try and refine the criteria for a GPT.

Chapters 5 and 6 of their book survey the economic history of the world from the Neolithic revolution to the present, with lots of concrete discussion of specific advances, both technological and organizational. As Buchanan (1991) notes, the sources and uses of power is one of the central themes in the history of technology and this is reflected in the lists compiled by these authors. Prime movers, such as water wheels, windmills, steam (external combustion) engines and the internal combustion engine figure prominently, as do electric power systems, which enable prime movers to produce energy which can be moved across substantial distances, as well as applications of prime movers to transportation such as railroads and motor vehicles.   More recently of course, the GPT of note has been computer technology or the internet (IT or ICT). Organizational innovations such as the factory system are also mentioned.

Lipsey, Carlaw, and Becker identify roughly 20 innovations that can be divided into 6 general categories:

Agricultural/Biological Engineering: (Domestication of plants and animals)

Mechanical/Chemical Engineering (Bronze and Iron)

Power Generators (water wheel, steam engine, dynamo, internal combustion engine)

Transport Equipment (wheel, 3 masted sailing ship, iron steamship, railways)

Data Storage and Communication (writing, printing, computer, internet)

Organizational Technologies (factory system, mass production, lean manufacturing).

Other authors, though less liberal with the designation, have called attention to many of the same technologies. In his review of Helpman, Wright (2000) places a big emphasis on prime movers (waterwheel, steam engine, electricity, and the internal combustion engine), transport equipment that uses them (railways, motor vehicles) and data storage and communication (writing, printing, and ICT). He also mentions, in the materials category, bronze. Gordon (2004) mentions steam, electricity, and the internal combustion engine, as well as the internet. Rousseau (2008) limits attention to power generators (steam engine, “electricity”, internal combustion engine) and data storage and communication (writing, printing, and IT). Rosenberg (1998) sees the principles underlying chemical engineering as a GPT.

In their 1995 article, Bresnahan and Trachtenberg mention five technologies. In the category of agricultural or biological engineering, they reference Griliches’ work on hybrid corn (1958). Among power generators, they tag the steam engine as well as the

Table 1: General Purpose Technologies

	Lipsey, Carlaw, Bekar 2005	Bresnahan & Trachtenberg 1995	Rosenberg 1998	Caselli 1999	Wright 2000	Basu and Fernald 2003	Gordon 2004	Crafts 2004	Jovanovic and Rousseau 2005	Rousseau 2008	WIKIpedia (2008)	TOTALS
Agriculture/ Biological Engineering												
Domestication of Plants	1											1
Hybrid Corn		1										1
Domestication of Animals	1											1
Biotechnology												
Materials/Chemical Engineering												
Bronze	1				1							2
Iron	1											1
Chemical Engineering			1									1
Prime Movers: Mechanical/Electrical Engineering												
Waterwheel	1				1							2
Steam or Steam Engine	1	1		1	1		1	1	1	1	1	9
Electricity		1			1		1	1	1	1		6
Electric Motor		1										1
Dynamo	1			1								2
Electronics											1	1
Internal Combustion Engine	1				1		1		1	1		5
Transport Equipment/Mechanical Engineering												
Wheel	1											1
Three masted sailing ship	1											1
iron steamship	1											1
Railways or railroad	1				1	1					1	4
Motor Vehicles or Automobile					1						1	2
Data Storage and Communication												
Writing					1					1		2
Printing					1					1		2
IT or ICT				1	1	1		1	1	1		6
Semiconductors		1										1
Computer	1										1	2
Internet	1						1				1	3
Organizational Technologies												
Factory System	1	1		1								3
Mass Production	1											1
Lean Manufacturing	1											1

dynamo, although here the key innovation is alternatively described as electricity. They also mention the factory system. Finally, in ICT, the principal focus of their paper, they focus on semiconductors, rather than the computer or the internet per se.

Table 1 summarizes GPTs identified in these and other articles. Three conclusions can be drawn. First, a rather broad range of technologies have indeed been identified as GPTs. Second, there are three arenas: steam, electric power, and ICT, which appear on almost all lists. Third, even within the areas of greatest agreement, there are differences in exactly what is identified as the GPT. This is particularly so within the latter two. Sometimes “electricity” is simply referred to generically (Wright, 2000; Gordon, 2004; Crafts, 2004; Jovanovic and Rousseau, 2005; Rousseau, 2008). Sometimes the reference is to the dynamo (a direct current generator, also sometimes called a magneto) (Caselli, 1999; Lipsey, Carlaw and Bekar, 2005) or to the electric motor (Bresnahan and Trachtenberg, 1995). And sometimes what is described is the use of all three in factory electrification (David and Wright, 2003).

In fact the electrification of the factory, often described as replacing steam power, depended critically on advancements in the steam engine, in particular the steam turbine. The turbine used steam to produce direct rotary motion which in turn, using a magneto or dynamo mounted inline, produced electricity. It is true that the engines in Edison’s Pearl Street station in 1882 used steam engines with pistons generating reciprocating motion that was then converted to rotary. Parsons did not perfect the dynamo until two years later. But the latter, which directly produced steady, high speed rotary motion without the efficiency losses associated with the reciprocating to rotary conversion, was particularly well suited to making electricity, where loads are stable and uniform, lacking the variability common in other applications. The steam turbine was critical for the subsequent reductions in cost per kilowatt hour which helped make the electrification of the factory economically feasible.

The GPT literature sometimes presumes that the technologies it identifies as such are as distinctly revolutionary as for example was the cotton gin. If we are to evaluate this claim we must be clear and consistent about exactly what is the GPT. In part because the alleged impact of the GPT unfolds over what may be long periods of time, exactly what we are talking about can prove elusive, as the above discussion reveals.

Similarly with IT or ICT. It is sometimes referred to generically. Sometimes there are more specific references to semiconductors (Bresnahan and Trachtenberg, 1995), computers (David, 1990, 1991), or the internet (Gordon, 2004). Even these identifications, if one probes, can be problematic. When we speak of the “internet”, for example, what is paramount? Is it the hardware and software protocols such as TC/ICP, the http protocol, html markup language? Or is it the switches and routers, or the innovations that permitted multiplexing hundreds of bitstreams over a single fiber optic cable?

Have GPT Criteria been Consistently Applied?

If pervasiveness simply means that “a lot” of it is used, then most of the technologies on Table 1 appear to qualify. But if broad applicability means that the technology is used across many sectors, the situation becomes murkier. It’s hard to see, for example, how the design of a sailing ship with three masts measures up, unless we mean simply that vessels using this design carried many types of raw materials and manufactured goods. If we adopt such a broad interpretation, however, and say that technology A is used by sector B if sector B purchases a good or service whose production is enabled by technology A (in this case technology A is the sailing ship producing transport services) we will quickly get to a point where it is very difficult to distinguish between single use and general purpose technology, given the nature of input-output matrices. Even if we adopt the narrower approach, insisting on direct use of the technology in the sector or industry, the measure of pervasiveness is to a certain extent hostage to industrial organization, particularly the degree of vertical integration.

These ambiguities may help explain why only some authors refer to railways as a GPT, even though clearly “a lot” of them were used, they carried many different types of freight, and they led to spillovers, at least in the United States, by enabling, for example, Chandler’s modern business enterprise. The use of steam power by railways helps make the case that the steam engine was pervasive (used in many sectors). Should railways themselves be seen as pervasive in the same way?

Even with the “Big Three” (steam, electricity, ICT) one can ask how consistently the criteria have been applied, particularly if we include the Gordon/Jovanovic and Rousseau requirement that the technology “transform both household life and the ways in which firms conduct business.” Whereas “electricity” (or the electric motor) satisfies this, as does ICT (semiconductors, computers, the internet) it is questionable whether steam, or at least the steam engine, “transformed household life.” It is true that steam can be used to facilitate central heating, for ironing clothes, and for certain types of cooking , but households simply did not make direct use of steam *engines* in any significant way, with the exception of the limited experience in the first part of the twentieth century with steam powered automobiles, or the eighteenth century use of Savery engines to raise water for use in indoor plumbing.

Do the GPT Criteria Separate the Consequential from the Inconsequential?

Do all consequential innovations satisfy the GPT criteria? And does it matter if they do not? Imagine an innovation with limited impact on a larger number of sectors (perhaps the felt tipped pen). Should we necessarily pay more attention to it than an innovation that had a large and revolutionary direct impact on only one or a few?

Table 2 presents a list of innovations which have typically been absent from lists of GPTs. Most will be well known to those who have taught or taken a course on the industrial revolution or European or US economic history. To leaven the cake, I’ve thrown in a few developments from the twentieth century. For a few of these (perhaps modern business enterprise), enthusiasts might argue that they should be considered GPTs. But for most, it is hard to make the case, because the technologies are single as opposed to general purpose. Because they are single purpose, there is little ambiguity about how they might usefully be employed. They offered relatively complete, immediately usable solutions to a readily apparent problem. It is hard to imagine that it might take two or three decades for entrepreneurs to see how they could be used to most productive effect, or that it would take expensive R and D efforts to figure this out, or that they would require large complementary investments in training before their benefits could be realized. And in most cases it is quite implausible that the appearance of these blueprints would have caused a significant initial productivity slowdown. Consider for example the innovations typically associated with the industrial revolution. Standard texts emphasize the steam engine, which is on most lists of GPTs.

Table 2: Single or Limited Purpose Technologies

Agricultural/husbandry innovations:
- 3 field crop rotation

Textile Innovations
- cotton gin
- flying shuttle
- spinning jenny
- water frame
- mule
- power loom

Iron and Steel making innovations
- coke smelting
- puddling
- hot blast
- Gilchrist Thomas process
- Bessemer process
- Siemens-Martin open hearth process
- Basic Oxygen Furnace

Transport Innovations
- horse collar
- horse shoe
- pneumatic tire
- Jet Engine

Miscellaneous
- Haber - Bosch process
- gunpowder/explosives
- elevator
- containerization

Information Communication, Storage and Retrieval
- Reading Glasses
- vertical file cabinet
- carbon paper
- xerox machine
- telegraph
- telephone
- radio
- television

Organizational Technologies
- Modern Business Enterprise
- interchangeable parts

But the other oft-emphasized developments include complexes of innovations in textiles on the one hand and iron making on the other. Take textile inventions such as the cotton gin, the spinning jenny, the water frame, Crompton's mule or the power loom. These innovations were improvable and there was mutual interaction between the technical advances in downstream and upstream processes.

But they were not general purpose. They remained single or limited purpose. The cotton gin was used to clean short staple cotton. That's it. It was of no use in the preparation of wool, flax, silk, or even long staple cotton fibers. Was it important and consequential? Undoubtedly, since it resulted in a major positive supply shock to the cotton textile industry by shifting out the supply schedule for cleaned cotton. Many have argued that it gave a new lease to the peculiar institution –slavery -- and thus might be held indirectly responsible for the American Civil War and the 600,000 plus deaths associated with it. But there is no way we can call the cotton gin a GPT. And the same is true for the spinning jenny, water frame, mule, or many of the innovations underlying the advance of the British iron industry, such as Darby's coke smelting, Cort's puddling, or Nielsen's hot blast, or the steel innovations of the second half of the nineteenth century (Bessemer converter, Gilchrist-Thomas process, or Siemens-Martin open hearth furnace).

Bessemer and Siemens Martin processes, for example, were industry (and indeed material) specific, and would clearly not pass muster as GPTs. People grasped immediately how these innovations could simplify and cheapen a product that had been known for centuries. What was not so immediately obvious were the potential uses for cheap steel. Does that make steel a GPT? It took Carnegie and others time to persuade users they should make skyscrapers, plate ships, and replace iron rails with it. Cheap steel in turn encouraged complementary innovations such as, in the case of taller buildings, elevators. If bronze was a GPT, why not cheap steel? Again, my intent here is not to argue for an expansion of the list of GPTs, but rather to question the ultimate usefulness of the concept.

If one follows the impact of product and process innovations far enough through the input-output table, one will eventually find products or technological complexes used as inputs in many other sectors, with the potential to generate spillover effects in using sectors. These processes, products, or complexes are the consequence of many separate breakthroughs as well as learning by doing, much of which has been sector specific. Personal computers, for example, have required advances in software, sector specific semiconductor manufacturing, and the thin film technology and mechanical engineering that underlies mass storage technologies.

Finally, consider the Haber-Bosch process for synthesizing ammonia. This is a single purpose chemical process with wide reaching implications for agricultural production. Some (see Smil, 2001) believe it to have been one of the most significant innovations of all time, permitting huge increases in world agricultural production. Without careful calculations it is hard to say definitively that the social savings or contributions to TFP growth of Haber-Bosch are lower or higher than those of say the steam engine or the internet. The point here is that there is no necessary connection between pervasiveness, or use in both households and firms, and economic importance. A single purpose innovation can have a larger economic impact than an innovation, widely adopted in different sectors and thus pervasive, which results in a relatively small move forward. If the purpose of the GPT concept is to provide a filter that reliably identifies technologies with large economic impact, we must question how well it succeeds.

Crafts (2004) and Field (2006) have independently noted the relationship between social saving calculations and estimates of the contribution of a new technology to TFP growth. It is relatively easy to convert one to the other. Ultimately, in terms of distinguishing between important innovations and those which are relatively inconsequential, we want to differentiate between those that, counterfactually, add a lot to TFP growth and those that add only a little. The implications of Table 1 and Table 2 considered together is that GPT criteria don't really help us very much here, because, for example, there are many single purpose innovations (e.g., the cotton gin) with big implications for TFP (and all sorts of other outcomes) and there can be "general purpose" innovations which represent relatively marginal improvements over previously existing technology and have low social saving/contribution to TFP (e.g., the felt tipped pen).

We are not creating a straw man in suggesting that the aim of the GPT concept was, as it were, to help separate the wheat from the chaff. Evidence that the concept and its associated criteria were intended to catch "big", "important", "revolutionary" innovations abounds in the title, abstract, and text of Bresnahan and Trachtenberg. "Whole eras of technical progress and growth appear to be driven by a few 'General Purpose Technologies' (GPT's), such as the steam engine, the electric motor, and semiconductors," reads the abstract, and the title refers to GPTs as "Engines of Growth". The intent to provide a filter differentiating the important from the inconsequential is also reflected in the following passage:

> Anecdotal evidence aside, are there such things as 'technological prime movers'? Could it be that a handful of technologies had a dramatic impact on growth over

> extended periods of time? What is there in the nature of the steam engine, the electric motor, or the silicon wafer, that make them prime 'suspects' of having played such a role?" (1995, p. 84).

And in their concluding remarks, the authors speak of the interplay between ""key" technologies and the industrial organization and firms that spring up around them" (1995, p. 102).

Perhaps however the real value of the GPT concept is, among "engines of growth", to pick out a subset in which there is a substantial lag between initial innovation and the reaping of productivity benefits, due to the need to make complementary investments in training and R and D, and because of spillover interactions between downstream and upstream processes.

None of these dynamics, unfortunately, is unique to GPTs. Consider again the classic histories of the textile innovations, with bottlenecks created in weaving, then spinning, and then weaving again. Landes (1969) described these as sequences of challenge and response. Similarly in iron making, with breakthroughs first in smelting and then in refining. Is the need to make complementary investments something that only pertains to GPTs? Take containerization, arguably one of the most consequential innovations of the twentieth century. It is hard to argue that containerization is a GPT, but it most certainly required large complementary investments in ship, truck, and railroad design, as well as port and other transshipment facilities.

The question of whether GPTs are more likely than other engines of growth to exhibit long delays before their full productivity benefits are reaped, and arguably short term productivity downturns in the period when complementary investments are required, is difficult to assess because of the aforementioned lack of clarity in the literature about what the exact innovation is. If the steam engine is a GPT, is the railroad, which uses a steam engine to provide motive power, also a separate and distinguishable GPT? The muddiness of labeling makes it possible, using different choices about what is called the revolutionary technology, to claim that benefits were more or less immediately realized or that they were long delayed.

Much of Bresnahan and Trachtenberg is involved with modeling the interactions between GPT producing and using sectors and the ways in which industrial organization may provide appropriate incentives for R and D investments or result in too little of it. The article is motivated by the assumption that the history of semiconductors and their uses is an illustration of a more general phenomenon, and they speak of future research in which they will conduct historical inquiry to explore how slow to change institutions might have influenced the size and trajectory of the contributions of engines of growth (1995, p. 103). But the motivation of their paper begs the question of whether what they are studying is a one or possibly two trick pony.

Are the Big Three (IT, Electric Power, Steam) Really Isomorphic?

Sticking with the "Big Three" (steam, electricity, and ICT), and assuming we resolve ambiguities about exactly which technologies we are talking about, we must ask whether these arenas share enough isomorphisms to justify the distillation of their experiences into a common category with presumably broader applicability. In making this assessment, one must be cautious about the use of stylized facts, and once over lightly historical analysis.

Bresnahan and Trachtenberg's treatment of steam power and its uses is, to be blunt, superficial. Continuous rotary motion is not a "central defining feature" or "generic function" of a steam engine (p. 86). No steam engine (or internal combustion engine, with the exception of the Wankel) produces rotary motion directly. Only with Parsons' work on the steam turbine in the 1880s did this become possible. Until the turbine, the reciprocating motion of eighteenth century steam engines such as those of Newcomen or Watt, desirable in many applications (such as pumping water, fulling wool, or refining iron) could be converted to rotary motion only through such "downstream" innovations as the crankshaft or sun and planet gearing systems. Reciprocating engines remained the norm throughout the nineteenth century, even as fuel efficiency improved dramatically with high pressure and compound engines. They remain the norm today, except in electric power generation. Powered by external or internal combustion engines, most automobile and ship transport continues to be driven by reciprocating engines.. And again, contra Bresnahan and Trachtenberg, continuous rotary motion does not make sewing cheaper (p. 86) – sewing requires reciprocating motion, and few sewing machines were ever driven by steam power.

Calling attention to these mischaracterizations might be dismissed as carping if the history of steam power and its application indeed turned out to have strong analogies to what has been experienced in ICT. But the suggestion that its history is isomorphic, central to much of the GPT literature, turns out to questionable. Crafts (2004) has carefully reexamined steam and its application in Britain, and concludes first that its overall contribution to TFP growth was modest and second that its greatest impact was not until the last part of the nineteenth century – almost a century after Watt's innovations, and depended on the cost reductions and performance improvements associated with the development of high pressure engines.

Within manufacturing, there is little to suggest that entrepreneurs had difficulty understanding how steam might be valuable. It was another prime mover, providing more flexibility in location that water power, but the choice between steam and water was based on a comparison of costs and benefits. Unlike systems of electric power, which eventually comprised installations to generate and transmit power over long distances to drive what were often small electric motors, the minimum efficient scale of a steam engine was too large to permit any fundamental redesign of manufacturing facilities. And as far as the design or use of other equipment within steam powered factories, we find relatively little evidence of spillovers. Most of the fundamental textile innovations, for example, were designed to be driven by other types of power, in particular water (see Crafts, 2004, p. 348; von Tunzelmann, 1978).

At least within Britain the evidence of major spillovers as the result of steam powered transportation is also lacking. Railroads had relatively little impact on location decisions on an island covered with rivers, canals, and featuring a heavily indented coastline. And Britain did not rush to embrace the new organizational form known as the modern business enterprise (for the US, see Field, 1987). Over water, wind powered sailing ships remained effective competitors to steamships for decades. Steamships were not economic for longer journeys until coal consumption fell sufficiently such that the space and weight requirements of carrying fuel crowded out a smaller portion of payload capacity (Harley, 1988).

While Crafts works within the framework of the GPT tradition, and interprets his research as reinforcing the point that it may take a long time (40 years in the case of electricity, 80 years in the case of steam) for a GPT to have its full impact on TFP growth

(p. 348), his analysis of steam power in fact raises doubts that the history of ICT can be distilled and reified as an instantiation of a more general phenomenon. And indeed, his final comments reinforce this interpretation (2004, p. 349).

What about electric power? It was of course the analogies between the electrification of the manufacturing sector and the productivity trajectory of ICT that David had described in his 1990 article that Bresnahan and Trachtenberg built upon in developing their concept of a general purpose technology. The computer age is still very much upon us, and most of us are sympathetic to the idea that the diversity of uses to which these new devices might be put was not immediately apparent when they developed. This goes all the way back to Digital Equipment Corporation's head Kenneth Olsen's famous skepticism about the potential market for computers in homes. It clearly did take some time for both consumers and producers to figure out how most effectively to make use of what advances in semiconductor manufacture, mass storage technologies, and software had made possible; productivity improvements resulting from better supply chain management would be an example.

This is the analogy to which David (1990, 1991) and David and Wright (2003) appealed in looking back to electrification. But it is important to note their discussion of other developments that helped precipitate factory electrification:

> It did not acquire real momentum until after 1914-1917, when the rates charged consumers by state-regulated regional utilities fell substantially in real terms, and central station generating capacity came to predominate over generating capacity in *isolated* industrial plants. Rapid efficiency gains in electricity generation during 1910-1920 derived from major direct investments in large central power plants, but also from the scale economies realized through integration and extension of power transmission over expanded territories (David and Wright, 2003, p. 6).

This suggests that, to a greater degree than is often emphasized in the GPT literature, the timing of factory electrification was the consequence of this sharp fall of electric power rates, not simply the initial failure of imagination on the part of factory designers and operators, or the need to develop a skilled cadre of engineers and technicians who understood the potential for productivity gains in an electrified factory. While this is not an either/or choice, to the degree that the timing of electrification is attributed to a more mundane matter of costs, rather than imagination, the similarities to the narrative frequently told about ICT become weaker.

A second historical point emerging from this reconsideration is that whatever the key revolutionary technology we focus on here -- the GPT literature refers inconsistently to electricity, the electric motor, or the dynamo – the dynamo is the least appropriate candidate. The dynamo, or magneto, or direct current generator, had been around for decades. What was needed to make the commercial electric power industry truly viable was a steam engine that could directly produce rotary power. This Parsons supplied with the team turbine, patented in 1884.

The scale economies that the above passage refers to also depended on advances on high voltage transmission of electricity across long distances, including, most would argue, the switch to alternating current. And then, finally, there is the small electric motor. Perhaps this is what David meant by the dynamo, since the device in principle can convert electricity into rotary motion as well as the reverse. This is not however common usage: a dynamo refers usually to a device, using principles discovered by

Faraday in the 1820s, in which a magnetic enclosure induces a current within a rotating coil of wires.[1]

It matters that we get the history right. The critical innovation in making commercial electric power a possibility was therefore not the magneto or the dynamo, which had been under development for decades, but the steam turbine. In part because of the scale issues identified in the above passage, however, it took several decades for electric rates to fall sufficiently to warrant the wholesale reorganization and redesign of American factures that was such a distinctive feature of the productivity history of the 1920s.

In his earlier work David (1990, 1991) identified the steam engine and the electric motor as general purpose *engines*. By this he meant that these power sources were used in many sectors and industries (this is the origin of the pervasiveness criterion). The reciprocating steam engine, for example, pumped water out of deep mines. In manufacturing, it powered trip hammers to refine iron, drove bellows in blast furnaces, fulled cloth, or, converted to rotary motion, drove spindles and looms in textile factories. And in transportation, of course, steam engines powered both railroads and steamships (which most do not consider GPTs in their own right, although some do).

The electric motor, in turn, found wide application throughout transport (streetcars and urban subways; submarines), industry, and in the home. David also emphasized the long delay between the first commercial power installation (the Pearl Street Station in New York in 1882) and the electrification of factories in the 1920s, and suggested that

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[1] Then again, "The Computer and the Steam Turbine," or "The Computer and the Small Electric Motor" were probably less catchy as article titles, and could not play off the title of a chapter in Henry Adams' biography..

the productivity benefits of computers might be delayed, possibly for similar reasons. Even though computers are not themselves engines, they find a broad range of applications in various sectors of the economy and in the home and thus can legitimately be viewed as general purpose in the sense that they satisfy the pervasiveness test.

Bresnahan and Trachtenberg built on David's work and ideas, although they emphasized semiconductors rather than computers. Are the isomorphisms in fact sufficient to justify moving from two general purpose engines to three general purpose technologies and then beyond?

One can make a counter case that the history of ICT should be treated sui generis. It involved not just different means of producing, for example, rotary motion in a factory, but products that were sufficiently distinct from their antecedents that they can be considered genuinely new. The isomorphisms between ICT and electricity are not exact, and this is even less the case with steam. When one goes beyond this, it's not clear that one has anything much at all.

Conclusion

In his August 2006 Eh.Net review of Lipsey, Carlaw, and Bekar, Joel Mokyr spoke of the GPT concept in the past tense, as a "a theme that briefly rose to prominence a decade ago in the literature of the economics of technological change." But, with apologies to Mark Twain, the rumors of the death of the GPT concept are exaggerated. It continues to crop up in new working papers, and many of the original papers exploiting the concept have only found their way into print in the last four or five years. Since the usefulness of the concept stands or falls on how well it is grounded in and in turn illuminates the record of economic history, it is important that economic historians participate actively in discussions of its merits. It is important that we ascertain if as, Gertrude Stein described Oakland California, there is no there there.

The GPT concept originated during the first half of the 1990s, a time when, as Solow put it, investments in IT were showing up everywhere except in the productivity statistics. Building on David's prior work, Bresnahan and Trachtenberg formalized the analogies between the diffusion of ICT and the electrification of the factory, drew implications from them, and suggested that these two instances might be examples of a more general phenomenon. The seminal article was published in 1995, the year U.S. productivity growth finally began to accelerate. The promise of delayed productivity benefits seemed to provide a rationale for the rising stock valuations associated with the tech bubble that peaked in March 2001. This historical context may help account for the success of the meme.

Why be critical of the GPT enterprise, if it generates useful collaboration between economic historians and theorists and if the models developed lead to interesting implications? The problem is that if the empirical referents of the GPT are shaky or inconsistently identified, then the use of models derived from it can lead to conclusions which are, for want of a better word, simply implausible. An example would be Jovanovic and Rousseau's suggestion that the productivity slowdown beginning in 1973 could be attributed to the need to make complementary training and R and D investments associated with the first stage of computerization, which they date from Intel's invention of the 4004 single chip microprocessor in 1971.

The authors are careful not actually to say that computers caused the slowdown.[2] But they imply it. The abstract of the article states that "The productivity slowdown is stronger in the IT era…." and it is easy for readers to draw that conclusion. If ICT is a GPT (and if it's not, what is?) and if GPTs require complementary investments with sometimes long gestation periods before returns are enjoyed, then productivity growth rates might decline before they increase. No one has a completely satisfactory explanation for the deceleration of TFP advance during the dark ages of US productivity growth (1973-89).

But ICT capital is such a small fraction of the fixed asset stock in the 1970s that it requires a considerable stretch of the imagination to believe that computers had anything to do with this slowdown. In 1971 the current cost net stock of computers and peripheral equipment ($5.3 billion) and software ($4.6 billion) was together less than half of one percent of a total fixed asset stock of over $2.3 trillion.[3] Moreover, the data on R and D spending are simply not consistent with the hypothesis that the initial era of computerization stimulated a surge of complementary spending in this area. Research and development spending as a share of GDP peaked in 1964 at 2.88 percent, fell gradually to the end of the decade (2.53 percent), and then plummeted in the 1970s, reaching a nadir in 1978 at 2.12 percent.[4]

The last two decades of the nineteenth century witnessed a remarkable series of innovations in the areas of power generation These included Parsons' and Laval's work on the steam turbine in the 1880s, Edison, Siemens, and Ferranti's advances in the

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[2] Choosing their words carefully, they write that "the arrival of IT…did not reverse the decline in productivity growth that had begun more than a decade earlier" (2005, p. 1184).

[3] http://www.bea.gov, Fixed Asset Table 2.1, accessed July 23, 2008.

[4] http://www.nsf.gov/statistics/nsf07331/tables/tab13.xls, accessed July 24, 2008.

production and transmission of electricity, and Daimler, Benz and Diesel on the internal combustion engine (see Buchanan 1992; Smil 2005). Although these technologies have been subject to evolutionary improvement, the twentieth century produced few new advances in inanimate power generation. Nuclear power could be viewed as an exception, but from the standpoint of the technology of power generation, it simply represents the development of an alternate fuel to generate the heat to produce the steam for a steam turbine. Most of our electricity is still produced by steam turbines and most of our vehicles and ships are still striven by reciprocating internal combustion engines. These innovations date from the late nineteenth century (Buchanan, 1991, p 76). The productivity history of the twentieth century, particularly the very strong performance in the second quarter of the century, can be understood partially as the working out of the implications of the steam turbine and the internal combustion engine.

A parallel line of development drove advance in the area of information transmission, storage, and retrieval. We can trace this thread from the telegraph and telephone through tabulating machines and radio and television to the modern computer and internet.

These themes and the histories of the Big Three are intertwined. Just as the development of the commercial electricity industry depended critically on advances in steam power, advances in computing depended on moves forward in electrical engineering and semiconductors. It is not useful to retreat to describing technological advance as a smooth continuous flow, but we should also acknowledge that some violence is being done to the historical record when we speak of “steam,” “electricity” or “ICT” as separate and distinguishable “engines of growth.”

In each of these cases, a detailed understanding of technological history is a critical ingredient in deciphering the causes of the fluctuations in TFP growth rates over time. Whether the GPT concept adds anything essential to these explorations remains open to question. Why? Because too many technologies have been labeled with this designation. Because which technologies are being discussed is often unclear. Because the GPT criteria are not always consistently applied. And finally, because these criteria do a haphazard job of separating the consequential from the inconsequential.

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