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Technology, Growth Theory, and the First Industrial Revolution

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Abstract

In the 21st century, growth theorists have ambitiously extended the limits of what need to be understood into preindustrial times without renouncing sound microeconomic foundations, and growth theory has become irreversibly historical. This paper argues that much progress could be achieved if the frontier of growth theory is extended with a richer understanding of ideas, knowledge, and technology. The paper first defends the strong relevance of second-generation Schumpeterian models to the first Industrial Revolution. It then presents an evaluation of Mokyr's (2002) non-mathematical theory of useful knowledge by identifying the main postulates of this theory that may illuminate Schumpeterian models of the first Industrial Revolution. The paper concludes with a discussion of three methodological obstacles that prevent immediate progress in this trajectory of inquiry.

JEL Codes: B41, N13, O30

Keywords: Unified growth theory, economic history, Schumpeterian growth, useful knowledge, endogenous technology.

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Teknoloji, Büyüme Kuramı ve Birinci Sanayi Devrimi

Öz

21. yüzyılda büyüme kuramcıları, anlaşılması gerekenlerin sınırlarını iddialı biçimde ve sağlam mikroekonomik temellerden feragat etmeksizin, sanayi-öncesi zamanlara doğru genişlettiler ve büyüme kuramı geri dönülmez biçimde tarihselleşti. Bu makale, eğer büyüme kuramının sınırı, düşünce, bilgi ve teknolojinin daha zengin bir anlayışı ile genişletilirse çok daha fazla ilerlemenin sağlanabileceğini öne sürüyor. Makale, önce, ikinci-nesil Schumpeter-gil modellerin Birinci Sanayi Devrimi için olan uygunluğunu savunuyor. Ardından, Mokyr'ın (2002) matematiksel olmayan faydalı bilgi kuramının bir değerlendirmesini, bu kuramın Birinci Sanayi Devrimi'nin Schumpeter-gil modellerini aydınlatabilecek önermelerini belirleyerek sunuyor. Makale, bu araştırma çizgisindeki hızlı ilerlemenin önüne geçen üç yöntembilimsel engele ilişkin bir tartışmayla son buluyor.

JEL Kodları. B41, N13, O30

Anahtar Kelimeler: Birleştirilmiş büyüme kuramı, iktisadi tarih, Schumpeter-gil büyüme, faydalı bilgi, içsel teknoloji

1. Introduction

The first Industrial Revolution has been a typical subject matter in economic history, and the "Revolution remains one of history's great mysteries" as recently emphasized by Clark (2016, p. 232). Understanding the first Industrial Revolution within a unified framework that has sound microeconomic foundations is also an imperative for the growth theorist in the 21st century. From a methodological point of view, the key issue is the nexus between history and theory. From the theorists' side, the notion that a marriage between the two is essential has been taken to the center stage first by Schumpeter (1947) and reevaluated, among others, by Romer (1996). From the historians' side, the advances in cliometric research have clearly demonstrated that economic theory illuminates the analyses of historical phenomena and *vice versa* (De Meulemeester and Diebolt, 2007; Diebolt, 2012; Diebolt and Haupert, 2016).

The debate known as the Convergence Controversy has emerged in the mid-1980s when large datasets of population and output, *i.e.*, the Maddison Database and the Penn World Tables, have first become available at that time. A consensus has been established despite the mixed evidence; convergence to common long-run growth rates and to common long-run levels of living standards, in the global context, does not exist (Durlauf and Quah, 1999; Islam, 2003). Instead, comparative development is characterized by an increasing gap of living standards between the rich and the poor, the existence of (local) convergence clubs, and the polarization as well as the persistence of world income distribution. Understanding this Great Divergence necessitates a longer run view to the past basically because today's polarized world is a by-product of diverse cross-country patterns of industrial revolutions. Takeoffs to sustained growth occurred in different areas of the world at different times and not yet occurred in a majority of countries (Galor, 2005, 2011; Lucas, 2009).

The Unified Growth Theory (UGT) developed by Galor and Weil (2000) and Galor (2005, 2011) has directed several theorists to explore these issues. As described by Galor (2005, p. 174), this theory "is designed to capture the complexity of the process of growth and development over the entire course of human history." Motivated by existing evidence on the very long-run evolution of population and output, the UGT categorizes human history into three eras, *i.e.*, the Malthusian stagnation, the Post-Malthusian transition, and the Modern Growth. Central to the theory is the following observation by Galor and Weil (2000, p. 809):

> "[...] historical evidence suggests that the key event that separates the Malthusian and Post-Malthusian Regimes is the acceleration in the pace of technological progress, whereas the event that separates the Post-Malthusian and Modern Growth eras is the demographic transition that followed the industrial revolution."

Economic history shows us that industrial revolutions are usually followed by demographic transitions. For this reason, a demographic transition should be an essential feature of theories aiming at explaining industrial revolutions. That is, unified growth models must incorporate the necessary elements that generate the inverted U-shaped dynamics of population growth from preindustrial times to the present.

What differentiates Galor and Weil (2000) and Galor's (2005, 2011) UGT from earlier work is not solely its success in predicting demographic transitions. Instead, the main advance of the theory is the analysis of Malthusian stagnation as a pseudo steady-state equilibrium which endogenously and gradually vanishes throughout the process of economic development. Thus, the task of the unified growth theorist is not only to develop a growth model that simply predicts multiple equilibria which represent different phases of economic development but also to develop this model in such a way that the model is truly unified in the sense that the emergence of transition from stagnation to growth is endogenous and gradual—unlike, for example, the separated steady-states in Lucas's (2002) model. From a technical point of view, the dynamical system defined by equations that characterize the equilibrium at any date must include some latent (state) variables whose evolution throughout the stagnant equilibrium trajectory eventually alters the qualitative properties of this equilibrium and triggers a takeoff. This represents a fundamentally different view of dynamical systems since the steady-state characterized by the constancy of some certain variables of interest, which is locally stable conditional on the latent variables, is not ultimately stable in the sense that the state of the economy endogenously hits some thresholds. The transition from one equilibrium to another—the transition from stagnation to growth to be exact—should not necessitate an exogenous shock which is extensive in size. Instead, a gradual escape from stagnation to growth—a phase transition in more technical terms—is the desired feature. As Perrin (2011, p. 362) emphasizes in the title of her article, the UGT truly provides "an insight."

In addition to their empirical success in accounting for the Demographic Transition, the models of unified growth explain the differential takeoff dates that have caused the Great Divergence among nations. Besides, modelling long-run growth as a very long transition process away from steady-state trajectories is a promising strategy. As rigorously proved by Growiec (2007), any growth model with strictly positive (endogenous) long-run growth necessarily depends on some assumptions usually in the form of equality restrictions on structural parameters. Thus, the new agenda proposed by unified growth theorists is of prime significance in many respects.

This paper presents a discussion on why unified growth models could and should be extended with a richer understanding of knowledge and technology to explain the first Industrial Revolution in a truly satisfactory way. The starting point of this discussion is the following observation: Unified growth models do not generally analyze technological progress with an endogenous market structure where industrialization in general and firms' and entrepreneurs' activities in particular are explicitly defined. There surely are exceptions, models developed by Desmet and Parente (2012), Peretto (2015), and Attar (2015) for instance, but the convention in the literature is to represent technology as a single productivity term that is an endogenous state variable and that shifts the production frontier upwards.

Contrary to the simplistic view of technology in the unified growth literature, there has been much progress in 2000s and 2010s on how different types of innovative activity interact in dynamic general equilibrium models where economic growth is fully endogenous and the model has indeed industries, see, *e.g.*, Peretto (2018). A contribution to the unified growth literature would therefore be to enrich the analysis of unified growth issues with an endogenous market structure as in the second-generation Schumpeterian models (Peretto, 2015). But this raises the question of whether the microeconomic structure of second-generation Schumpeterian growth models is generally compatible with the historical specificities of Britain in the 18th century. As discussed in Section 2, the answer to this question is yes: A second-generation Schumpeterian model with process and product innovations fits quite well with the purpose of understanding the nature of technological progress during the first Industrial Revolution.

While it is fortunate that growth theorists have a formal framework rich enough to allow for analyzing the first Industrial Revolution, this does not solve all of our problems. The second-generation Schumpeterian models represent an intellectually transformative step for the next generation of growth theorists as these models extend our understanding of endogenous technology over the very long run into the past. Specifically, Peretto (2015) identifies the endogenous dates at which different phases of industrialization start as explicit functions of structural parameters and initial values of endogenous state variables. After Galor and Weil (2000) and Galor (2005, 2011), the analysis presented by Peretto (2015) is arguably the most critical advancement in growth theory that deals with the very long run. However, even this model does not illuminate the ways by which ideas and knowledge affect technology. Put differently, while Peretto's (2015) model beautifully identifies how and why independent entrepreneurs establish new firms and existing firms invest in new technologies, ideas and knowledge are portrayed, for simplification purposes, as if these two are functionally identical to technology.

Building upon the discussion in Section 2, the paper analyzes Mokyr's (2002) non-mathematical theory of ideas, knowledge, and technology in Section 3. Mokyr's (2002) is a theory that clearly distinguishes ideas, knowledge, and technology from one another, and its main purpose is to identify the intellectual origins of the first Industrial Revolution. While Mokyr (2002) defends his theory by building upon a bulk of convincing historical and anecdotal evidence, Section 3 of this paper introduces and exemplifies Mokyr's (2002) ideas by strictly adhering to the viewpoint and terminology of (modern) growth theory. The main message of this section is that, if growth theorists are to enter the black box of ideas, knowledge, and technology, Mokyr's (2002) theory is possibly the best shot among the available.

Growth theory has great potential to take further steps into *terra incognita* of ideas and knowledge by trying to make Mokyr's (2002) concepts operational in developing second-generation Schumpeterian models of the first Industrial Revolution. Some recently constructed (unified) growth models have already exploited some of Mokyr's (2002) hypotheses (Milionis and Klasing, 2009; O'Rourke, Rahman & Taylor, 2013; Strulik, 2014; Attar, 2015; de la Croix, Doepke & Mokyr, 2018). However, the set of what theorists can do within their dynamic general equilibrium environments is inherently limited. The remaining problems that prevent immediate progress are threefold: First, the degree of historical complexity surrounding the first Industrial Revolution is naturally overwhelming. Second, introducing new types of knowledge, while necessary to operationalize Mokyr's (2002) theory, serves as another constraint since a new type of knowledge is a new stock variable and, in most cases, a new 'endogenous' state variable. Finally, and this is perhaps the most daunting one of these problems, it is extremely difficult to measure knowledge and technology variables, especially for a past episode. Section 4 presents a concluding discussion of these three limitations.

2. Schumpeterian Growth and the First Industrial Revolution

The second-generation Schumpeterian models have been developed in the late 1990s to overcome Jones's (1995) scale effects critique; notable contributions are of Young (1998), Dinopoulos and Thompson (1998), Peretto (1998a, 1998b), and Howitt (1999). Technology, in these new models, has been redefined as a surface of two complementary dimensions of innovation: the creation of new products along the horizontal dimension of Entry, and the creation of new processes that induce better-quality or less-costly-produced products along the vertical dimension of R&D. As tested by Laincz and Peretto (2006), Madsen (2008), Madsen, Ang & Banerjee (2010), Ang and Madsen (2011), and Venturini (2012), the long-run growth patterns of today's industrialized economies in the postwar period can best be understood by the second-generation Schumpeterian models of endogenous growth if one takes the underlying microeconomics (of industrial organization) seriously. Since the principle of continuation and sound microeconomic foundations are fundamental premises of the UGT, we must then be able to develop unified growth models that explain the epochs of history not only from the lens of human capital accumulation and endogenous demographics (as extensively pursued by unified growth theorists) but also from the lens of the Schumpeterian understanding of endogenous technology.

Before proceeding further to argue that the first Industrial Revolution has strong Schumpeterian origins, it is necessary to clarify some issues. Perhaps the most important of all is what is meant by the term 'Schumpeterian.' This section utilizes the term in three regards: (i) to describe the nature of technological progress as defined by the second-generation Schumpeterian models of horizontal (Entry) and vertical (R&D) dimensions of technology, (ii) to qualify the origins of technological progress in both dimensions as governed by profit-seeking motives, and (iii) to differentiate the present analysis from semi-endogenous growth models.

Next, one must be explicit about the meanings of horizontal and vertical dimensions of technology. The existing Schumpeterian models with two-dimensional endogenous technology use either a continuum of intermediate investment goods or a continuum of consumption goods as the locus of industrial activity. That is, there exists either a continuum of intermediate investment goods used to produce one homogenous output to be consumed or a continuum of consumption goods aggregated to define the (homogenous) consumption good. The R&D accordingly enters the picture as the innovation of new process knowledge of each product, and the Entry is simply the innovation of new products each embodied with some level of process knowledge.

But, what actually is the process knowledge of vertical dimension? Interpretation varies on this as well. To some theorists, this is the quality of a good—either an investment or a consumption good—in the sense that goods produced in more sophisticated ways return higher satisfaction—either in final production or in utility terms. To some other theorists, this is simply a measure of productivity entering the production function of the good itself. This latter interpretation of process knowledge arguably fits better to an environment where some form of useful (technological) knowledge plays a very distinct role in the invention of new products.

The emerging questions regarding the Schumpeterian connection are

- whether the two dimensions of technology would accurately represent the dynamics of technological progress in the 18th century Britain, and
- whether the notion of Schumpeterian innovation as an incentive-compatible occupation of searching for new technological knowledge in a purposeful way would apply, again, to the 18th century Britain.

The dichotomy here is not trivial since these two questions ask fundamentally different things. Regardless of its nature, technological progress could have originated from Marshallian externalities, for example. Similarly, regardless of its origin, it could be unidimensional such that only the Entry is active, and the R&D is not, or *vice versa*. The rest of this section presents answers to these questions.

For the first question, the relevance of the creation of new products in the horizontal dimension of technology is self-evident by the very definition of industrialization. The Industrial Revolution in the 18^{th} century Britain and other industrial revolutions throughout the history were all characterized by the invention of the new. For the 18^{th} century Britain, historical/anecdotal evidence strongly indicate that certain macro-inventions in some industries, *e.g.*, textiles, metallurgy, and machinery in general, were of crucial importance. The rise of better-quality and less-costly-produced products in the vertical dimension—another solid fact of the first Industrial Revolution—was associated mainly with the emergence of machines, and the switch from manufactory to factory was first realized during the Industrial Revolution. As summarized by Landes (1969, p. 5), "The result has been an enormous increase in the output and variety of goods and services."

Regarding the second question, we should be more careful. Consider, first, the Entry. Dutton (1984) and Sullivan (1989, 1990), among others, emphasize the rapid increase in the number of patents after 1760. However, MacLeod (1988) presents evidence that rise doubts on the role of British patent system in the early stages of the Industrial Revolution. The propensity to patent was low in many leading industries partly due to the bureaucratic burden, and many scientists and inventors had non-profit motives such as fame and public service. Sufficient incentives for inventive activity, instead, were created by alternative mechanisms of awards, prizes, and compensations as argued, among others, by Mokyr (2002, 2008). The Royal Society for the Encouragement of Arts, Manufactures and Commerce based in London, for example, had granted 6,200 prizes to inventors between 1754 and 1784.

Regarding the process of Entry runs from invention to innovation, the conventional wisdom of economic historians and growth theorists credits the crucial role of inventor-entrepreneurs in creating and commercializing entirely new products or processes. As summarized by Solo (1951, p. 417),

> "During the early Industrial Revolution, both invention and innovation were usually carried out by the same person, *i.e., the inventor-entrepreneur,* who devised new techniques and applied them. The commonest type of technological change was the introduction of labor-saving *and cost-reducing* machinery. With the growth of the patent system, invention and innovation were more generally performed by separate persons. The inventor sold rights to his invention; the innovator introduced it." (*italics added*)

The demand and supply channels of innovation might be complementary, and whether one dominated the other during the first Industrial Revolution is far from being clear. This actually has been the subject of an early controversy between Schmookler (1966) and Rosenberg (1974). The former treats invention and innovation as demand-driven processes such that solutions to new technological problems are to be aimed only if there exist sufficiently large markets for the resulting products. The latter, on the other hand, argues that the knowledge bases from which inventions originate exhibit a diverse pattern across industries and that one should not simply ignore the different paces of progress in different knowledge bases. Regardless, what matters for the (Schumpeterian) growth theorist who is already familiar with—and confident in utilizing—the knowledge production function is the equilibrium behavior of optimizing agents. Demand, after all, is a central block of any economic (growth) theory that defines a utility function. In the light of this discussion, then, suffice it to conclude that some sort of an incentive mechanism for inventive/innovative activity for Entry existed in the 18th century Britain.

What complicates the answer to our second question is the vertical dimension of technological progress. The historical evidence suggests, as indicated above, that the labor-saving/cost-reducing improvements in technology during the Industrial Revolution originated mainly from the switch from manufactory to factory, *i.e.*, from the rise of machines. Put differently, the source of higher productivity was some sort of positive externality created by the invention, the innovation, and the employment of these specific forms of physical capital, *i.e.*, the general purpose technology (GPT) from which an increasing number of sectors of production utilized and benefited. This in turn would imply that, if productivity gains were solely due to the process knowledge originally embodied in the machines, the choice of process knowledge was external to the firm that produces the final good using the machine. Thus, for the firms along the horizontal dimension, there did not exist a separate incentive mechanism—other than that of the Entry—that directed them to invest in the vertical dimension of technological progress.

Why would a new firm that has just entered the market by bearing the (entry) cost of operating with a machine not invest in developing the initial (blueprint) mode of production into more productive modes? There is no good reason if process knowledge satisfies excludability and if the investment is profitable. More clearly, if a firm can successfully exclude its process knowledge (at least in the short run) and if the marginal return of developing better production processes meets its marginal cost, then the firm would certainly invest. This, however, raises at least one new question: Do we really believe that the process knowledge of a product was excludable if increasingly many sectors adopt a unique GPT? Reconsidering what process knowledge actually is leads us to the fact that, even if the machine as a GPT spills over the production process of many goods, the process knowledge must be product-specific to some degree. Consider, for example, an engine as the GPT that works for the unique purpose of generating the energy needed in a number of sectors of, say, consumption goods. However significantly it shifts the production frontier upwards in all sectors, the generation of energy is only a part of the process knowledge of production, and the essential differences of producing, say, railway transport service and cotton fiber may still leave some room for productivity gains other than creating the energy with a machine. Besides, and perhaps more importantly, there existed many different machines and other intangible procedures employed in different sectors of production for different purposes during the Industrial Revolution, and the combinatorial process due to the multiplicity of these GPTs supports the specificity of process knowledge. Consequently, then, some sort of incentive mechanism for R&D existed during the early stages of the Industrial Revolution even if the micro-techno-economic foundations of this incentive mechanism are more complicated than that of the Entry.

3. Useful Knowledge and Endogenous Technology

3.1. Industrial Enlightenment from Bacon to Mokyr

Central to Mokyr's (2002) theory are the intellectual origins of the Industrial Revolution. The relationship of *Homo sapiens* with knowledge and knowing exhibits a diverse pattern across time and space. In some particular epochs of history and in some particular places in the world, some intellectual enlightenment movements emerged and changed the nature of this relationship. In Mesopotamia circa 5000 B.C., the first settled societies developed an intellectual form of life with language, writing, logic, and mathematics; they invented one of the most important tools of all times—the wheel. 'Philosophy,' literally meaning 'the love of knowledge,' was born in Ancient Greece circa 600 B.C. The rise of Confucianism in China a little later and the Golden Age of Islam from 800 A.D. to 1300 A.D. were all alike. None of such intellectual movements, however, was followed by an industrial revolution. Mokyr (2002, p. 34) asks what would be special for 1800 A.D. Western Europe. His answer is twofold:

> "[...] the rate of technological progress depends on the way human useful knowledge is generated, processed, and disseminated. This is hardly a new idea. Two historical phenomena changed the parameters of how the societies of western Europe handled useful knowledge in the period before the Industrial Revolution. One was the scientific revolution of the seventeenth century. The other is an event that might best be called the *Industrial Enlightenment*." (*italics in original*)

The Industrial Enlightenment represents fundamental changes not only in the nature of the relationship between *Homo sapiens* and the knowledge she/he knows but also in the contents, in the dynamics, and in the political and the social organization of useful knowledge. The prominent figure of the Industrial Enlightenment was Sir Francis Bacon

(1561–1626) who characterized an idealized/utopian knowledge economy in his *Novum Organum* published in 1620. In less than four decades following his death, the *Royal Society of London for the Improvement of Natural Knowledge* was established. In a century later, the *Royal Society for the Encouragement of Arts, Manufactures and Commerce* (RSA) was founded, again, in London. The encyclopedia movement of the 18th century was a part of the same ideal of understanding the true meaning of Bacon's famous aphorism: "Knowledge is power." The Industrial Enlightenment changed the attitude towards knowledge; the new paradigm was to diffuse useful knowledge in order to ensure its most efficient usage. The genuinely Western European element is the appreciation of the facts that the most obvious material consequences of useful knowledge—if not the only ones—are technological and that technological knowledge originates from the knowledge of natural phenomena. The "organic" linkages (or feedbacks) between these two forms of knowledge were thus key to the emergence of the Industrial Revolution.

3.2. Mokyr's *Gifts of Athena*

Imagine a growth theorist working on the first steps of developing a theory's model environment. The theorist would start with the definition of model's logical time, *e.g.*, continuous *versus* discrete time, and then clarifies the demographic structure, *e.g.*, overlapping generations *versus* infinitely-lived households. Next come endowments and preferences. The latter is important because preferences should include information on objects that are in the meantime consumption goods. The theorist then starts talking about 'ideas' since the reader is already familiar with 'individuals' living in the society and 'objects' they own and consume.

Some terminology is necessary here to introduce ideas and knowledge *à la* Mokyr (2002). There exists a set of external storage devices in which information can be stored and therefore becomes readily available for retrieval. Ancient tablets, encyclopedias, and JSTOR are all such devices. The theorist may or may not assume that the establishment and operation of these devices are costless and that all individuals have free-of-charge access to these external storage devices.

An individual is defined as an intelligent member of the society. Intelligence is characterized by a set of neurobiological capabilities that allow an individual to observe, to create, and to memorize information; the human brain is simply the 'internal' storage device. An idea is defined as any piece of information about anything if at least one individual possesses it or at least one external storage device is loaded with it or both. Hence, an object, in its broadest meaning, can easily be defined as a tangible thing which is neither an individual nor an idea.

By construction, then, a piece of information is either known or not known by an individual and is either stored or not stored in external devices. This necessitates a reinterpretation of the well-known notions of rivalry and excludability since a collection of ideas becomes perfectly non-rival and non-excludable if stored in external devices and if these devices are being accessed without cost and remains perfectly rival and excludable otherwise.

Any form of knowledge is defined as a collection of some ideas. Ideas and knowledge are fundamentally different things since an idea has multiple intellectual trajectories such as “complexity, abstractness, ethics, aesthetics, language, mathematics, and ideology” as argued by Olsson (2000, p. 256). In this rigorous set theory of ideas, Olsson (2000) takes the distinction seriously, and he defines a body of knowledge as a subspace of the Euclidean space of ideas such that the dimensions of the space of ideas represent the intellectual trajectories. Building on Weitzman’s (1998) notion that new ideas are successful hybridization of existing ideas, Olsson (2000, 2005) convincingly defines the accumulation of a form of knowledge as the expansion of its subspace through the elimination of non-convexities. As a result, technological opportunity is endogenously bounded, and technological knowledge eventually stagnates if paradigm shifts that create new non-convexities are absent for some reason.

What drives technological progress is ‘useful’ knowledge, and it originates from ‘some’ collections of ‘some’ ideas. As argued by Mokyr (2002), the crucial distinction is the one between the propositional and the prescriptive forms of knowledge. Propositional knowledge is formed by the answers to the so-called ‘what’ questions. Consider the entire collection of axioms, laws, and theorems in this class which is alternatively called *episteme*. Schumpeterian growth theory and Pontryagin’s maximum principle are examples of propositional knowledge. Prescriptive knowledge, on the other hand, provides answers to the so-called ‘how’ questions directly related to the production of objects. Recipes, procedures, and blueprints are all prescriptive, and the collection of all such prescriptive forms is called *techne*. The recipe of cheesecake and the set of instructions that explain how to construct a space station are examples of prescriptive knowledge.

Prescriptive knowledge is of economic value since an individual who has somehow obtained a recipe, a procedure, or a blueprint of an object, a consumption good for instance, would have the incentive to keep this knowledge in secret and commercialize it. In contrast, propositional forms of knowledge would provide no such incentives since axioms, laws, and theorems are intangible collections of ideas without any ‘direct’ consequence relevant to the material wealth of people. This is nothing but the dichotomy between the open Republic of Science (and *episteme*) and the proprietary Realm of Technology (and *techne*); see Dasgupta and David (1994).

The key to the coevolution of *episteme* and *techne* is the circular causation between the two. The invention of objects as a time-taking process is represented by the direction of causation from *episteme* to *techne* such that each object has a particular epistemic base which is a subset of propositional knowledge. At the earliest stage of invention, the answers of 'what' questions in the relevant epistemic bases are refined into some answers of 'how' questions, *i.e.*, a collection of feasible techniques. However, this is not a finalized collection of prescriptive knowledge in the form of recipes, procedures, and blueprints. Instead, the recipes, the procedures, and the blueprints that complete the process of invention are the outcomes of a sort of secondary search process that maps the feasible techniques into manifest entities.

Consider the earliest automobiles. The epistemic base would provide the forms of what-knowledge regarding wheels, engines, and gear-brake systems. If one can refine these propositional forms of knowledge into the knowledge of how wheels do work, how engines do work, and how gear-brake systems do work, then two feasible techniques, for example, may emerge: the one that integrates wheels with an engine such that the energy of motion generated by the engine is directed to the wheels and the other that integrates the former technique with a gear-brake system that allows the user to control the motion of wheels even if the engine is still working. Apparently, the latter would be selected as the manifest entity. As another example, consider cheesecake. What-knowledge of cheese, flour, sugar, and, say, cranberries is necessarily in the epistemic base, and how-knowledge simply suggests the mixing of the ingredients and the baking of the mixture. Thus, many 'cheesecakes' are feasible, but a delicious one which is the outcome of a particular recipe would be the manifest entity.

Next, consider the direction of causation from *techne* to *episteme*. This is also a time-taking process by which certain epistemic bases in *episteme* expand as a result of the progress in *techne*. As the economy advances its technology embodied in the objects, some of these objects, *e.g.*, tools and instruments used by scientists, create externalities that result in radical expansions in some fields. The invention of the telescope for astronomy and the invention of microscope for medicine are notable examples. The historical/anecdotal evidence also suggest that the occurrence of the Industrial Revolution in Europe and other sorts of industrial revolutions, *e.g.*, the so-called Information Age, are 'correlated' with the emergence of some macro-inventions such as printing press or personal computer.

It is useful to allocate some more space on the mapping from *episteme* to *techne* since we are mainly after the process of invention when it comes to understand the first Industrial Revolution. As described by Mokyr (2002, p. 3), propositional knowledge is a "kind of knowledge accumulated when people observe natural phenomena in their environment and try to establish regularities and patterns in them." By construction, an individual knows something at the most primitive stage by saving it in her internal storage device. Since individuals record not only the propositional forms of knowledge but also the knowledge of social facts and phenomena, we should consider what might be included in an individual's mind at an arbitrary date of her lifetime before discriminating the propositional forms of knowledge.

Imagine yourself in an experiment where you are requested to document everything in your mind. Naturally, the amount of information that you can document is limited by your neurobiological capabilities of memorizing and by the existing stock of information to be memorized. The key issue is that, even for a single individual, documented knowledge at the end of such an experiment would be such a diverse collection of ideas including those the individual collects, creates, or observes daily but never recalls for any purpose and those related to intellectual fields such as arts, literature, politics, and religion as well as others. However, the name of one's new neighbor and the intellectual knowledge that one accumulates through the study of Confucian ethics, for example, are not relevant for technology in any sense since such pieces of knowledge are not parts of an epistemic base of an object. This notion suggests that (i) the propositional knowledge of an individual, a subset of the set of all ideas in her mind, includes all axioms, laws, and theorems that she knows and that (ii) some subset of all these propositional forms establishes a number of epistemic bases for objects either invented in the past or to be invented in the future.

Some form of intra-generational transmission mechanism then determines the collectively known fraction of propositional knowledge. This is not trivial since, as argued by Mokyr (2002, p. 7), "what each individual knows is less important than what society as a whole knows and can do." It is self-evident that knowledge is useful if it is available "to the right people in the right place at the right time" as asserted by Foray (2004, p. 18). Restricting the attention to scientific knowledge, collectiveness once again leads us to recall the Republic-Realm dichotomy since it is the defining characteristic of what is called open science. In his classic study of the sociology of science, Merton (1973) remarks collectiveness as an ideal norm of scientific knowledge. The most fundamental social incentive to increase the collectively known fraction of propositional knowledge is to achieve the most efficient allocation of knowledge across individuals by reducing the duplication effects. The history of science and technology indeed records a large number of simultaneous discoveries and inventions such as calculus by Newton and Leibniz and telephone by Bell and Gray, as documented in detail by Merton (1961). Research in any field of science is subject to the same friction in 2000 A.D. economies. However, the frequency of simultaneous discoveries and inventions is much lower due to the highly efficient communication through conferences, workshops, and online scholar archives. Thus, in any knowledge economy, one can simply argue that (technological) benefits of propositional knowledge is determined by the efficiency of external storage devices that transform *ex ante* useful rival knowledge into its *ex post* used non-rival counterpart. As an example, compare two economies with different sets of external storage devices. In a 4000 B.C. economy, the only way of accessing collective knowledge is to visit the place where a collection of stone tablets is located. In a 2000 A.D. economy, individuals have high-speed wireless Internet connection, and the Internet offers free access to an online source called Wikipedia.

In addition to duplication effects, a third aspect of propositional knowledge is relevant to the crucial role of collective knowledge. This is the property of tightness that is characterized by the confidence and the consensus over the accuracy of propositional knowledge. In principle, not all pieces of information in propositional knowledge correctly identify the natural phenomena and the regularities in them. Thus, individuals in the society would be willing to use propositional knowledge only if it is widely accepted to be ‘true.’ In theory, it may be preferable to assume that only accurate forms of knowledge are stored in external storage devices.

Notice that individuals accumulate propositional knowledge in an aimless way since there exists no direct proprietary value of this type of knowledge. If external storage devices are accessed without cost, propositional knowledge is both non-rival and non-excludable, and it does not include any prescriptive element such as a blueprint by definition. Only individuals that devote their work effort into inventive activities can create manifest entities, and the knowledge embodied in these finalized prototypes is intentionally kept excludable.

4. Conclusion

In the last two decades, growth theory has exhibited two remarkable transformations through the contributions of unified growth theorists on the one hand and Schumpeterian growth theorists on the other. In vision, theorists now more openheartedly acknowledge that the very long run does matter. In method, more complicated mathematical models, *e.g.*, the ones with conditional dynamical systems featuring latent state variables, are now being used. Why and how the first Industrial Revolution happened when and where and why and how industrialization diffused across the globe at varying speeds are questions of central interest for growth economists. The advances so far have greatly expanded what we know, and this enlightenment has been accompanied with a process throughout which growth theory has been transformed into a truly historical field of inquiry. In this respect, $t = 0$ in theory has now a corresponding calendar time in history, say, 1200 or 1750 A.D. for England.

Mokyr’s (2002) non-mathematical theory of ideas, knowledge, and technology provides a useful framework for growth theorists who ask ambitious questions such as why the first Industrial Revolution occurred in Britain. Since this theory basically differentiates some forms of knowledge from one another depending on their contents and functions, it fits perfectly well with the descriptions of knowledge and technology featuring in endogenous growth theories in general and second-generation Schumpeterian models in particular. Since the first Industrial Revolution has strong Schumpeterian foundations as discussed in Section 2, Mokyr's (2002) theory becomes the key that can be used to open the black box of ideas, knowledge, and technology.

Only the models where economic growth is endogenous have a chance to explain the first Industrial Revolution (Clark, 2014), and the UGT is relevant in understanding the process of economic development in its entirety unlike other types of growth theories (Diebolt and Perrin 2016). Some economists have recently developed unified growth models with endogenous technology that build upon certain aspects of Mokyr's (2002) theory (Milionis and Klasing, 2009; O'Rourke, Rahman & Taylor, 2013; Strulik, 2014; Attar, 2015; de la Croix, Doepke & Mokyr, 2018). But there exist three obstacles preventing growth theorists to exploit the full potential of Mokyr's (2002) postulates. These are related with historical complexities, dimensionality issues, and measurement problems. A short discussion of these three obstacles is now in order.

First, history is ahead of theory when it comes to understand the first Industrial Revolution. There naturally exists a high degree of historical complexity about one of the biggest events of the history of mankind. It is perhaps not feasible to come up with a complete theory that pins down exactly for which reason the first Industrial Revolution occurred in Britain. The same is true regarding the reasons behind why it occurred in Western Europe and in the 18th century. There existed a number of inventions redefining the British economy and society, not one, there existed a number of inventor types coming up with these inventions, not one, and, the last but not the least, there existed a number of locations where these inventions were transformed into innovations, not one. How a mathematical model of long-run economic growth should accommodate these different types of inventions, inventors, and locations is not obvious *a priori*. The theorists' primitive constraints of realism *versus* tractability, of fact *versus* fiction, and of complexity *versus* simplicity are binding.

The second problem is the curse of dimensionality. While it is necessary to introduce new forms of knowledge and technology to accomplish an advancement in the direction enlightened by Mokyr (2002), the analysis of dynamic general equilibrium models gets highly complicated, if not infeasible, when the number of (endogenous) state variables increases. The graphical analysis of the dynamical system in Galor's (2005) UGT, for instance, could have been accomplished only with the help of conditional dynamical systems where the dynamics of the system is conditioned on one of the variables, *i.e.*, real potential (adult) income. Then, for different sets of values of this variable around a particular cutoff value, the properties of the dynamical system, including its dimensionality, change. In Peretto (2015, 2018), on the other hand, the models are simplified enough to allow for a closed-form solution of the unique dynamic general equilibrium. It is however difficult to imagine whether the model would remain tractable if one or more knowledge and technology variables are added to the system as endogenous state variables.

Clearly, a more complicated model with more knowledge and technology variables is not necessarily a more explanatory model. This leads us to the third problem: Knowledge and technology are among the categories bounded to remain largely mysterious since finding reliable quantitative measures for such variables are extremely difficult. This is not to say that there is no measure whatsoever that can be used to extend our understanding of knowledge and technology. Sullivan's (1989) patent data running from 1661 to 1851 is just one example of how technological progress in the form of prescriptive knowledge can be measured in preindustrial times. Another example is Madsen and Murtin's (2017) recent work that focuses on the very long-run patterns of British economic growth since the 13th century. In addition to educational attainment, these authors use the number of great scientists, the stock of innovations, and knowledge spillovers through imports as measures of knowledge and technology. More generally, the measurement difficulties do not prevent growth theorists to devise mappings from unobserved driving forces of their models to the observed outcome variables for the purpose of identifying knowledge and technology variables. Aggregate productivity measures filtered out from micro-founded models, for instance, may serve as proxies for prescriptive knowledge under appropriate identifying restrictions. Such restrictions, usually in the form of knowledge production functions, are necessary to differentiate propositional and prescriptive forms of useful knowledge. Despite these comforting arguments, however, the lack of reliable measurements as a binding constraint enters the picture from a realist viewpoint of science when it comes to the stage where the theory needs to be tested with some precision and rigor.

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