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The enigmatization of economic growth

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Abstract
In virtually every material science, the process of growth is not only well understood, it has been systematically reduced to its thermodynamic and/or kinetic equivalent. That is, growth is a function of resource and energy availability, whether it be within a stationary or non-stationary environment. This begs the question, why is economics the outlier, the exception? Why are models of economic growth decoupled from the basic science of material processes? This paper attempts to answer this question by focusing on the formalization of growth. It will be argued that for a number of reasons, the economics profession has enigmatized material processes, introducing concepts that were orthogonal to the laws found in the material sciences, leading to the current situation where a whole new generation of enigmatic approaches (quality ladders, institutions, etc.) has emerged to understand previous engimas.

Keywords economic growth, mainstream models, enigmas, consilience

JEL Codes O40, O47, O57, Q43.

1. Introduction

In virtually every material process-based field/discipline, the process of growth is not only well understood, it has been and is systematically reduced to its thermodynamic and/or kinetic equivalent (biology, ecology, demography). In short, growth is either a function of growth in energy availability/use – whether it be within a stationary or non-stationary environment – or an increase in second-law efficiency. The quintessential example is photosynthesis where the growth of biomass is a function of solar radiation, the latter being the force that acts on carbon dioxide and water to produce carbohydrates/sugars. This begs the question, why is economics the outlier, the exception? This paper attempts to answer this question by focusing on the very way in which the profession has formalized material processes. It will be argued that for a number of reasons, the economics profession, by enigmatized a simple energy-based material process, has generated findings (i.e. the Solow residual) which have prompted/led to the increased enigmatization of the growth process.

The paper is organized as follows. To begin with, we present a consilient approach to modeling material processes in general, namely the energy-organization approach according to which output is increasing in terms of two universal factor inputs, namely broadly-defined energy and broadly-defined organization. This will then provide the basis for a comprehensive review of the literature organized around two themes, namely steady-state growth and non-steady state growth (technology shocks). This will be followed by a discussion of consilient approaches to growth – that is, approaches that incorporate elements or aspects of physics. We end with a set of external – read: scientific – guidelines for future work on growth.

Table 1 Material processes, energy and organization

Material Process	Energy Input	Organizational Inputs
Chemical Processes	Heat	Kettles, Ladles
Manufacturing Processes	Kinetic Energy	Simple and Complex Tools
Photosynthesis	Solar Radiation	Molecular Structure of the Raw Materials
Mitochondria	Glucose	Molecular Structure of Raw Materials

2. Consilient formalizations of growth

While this may come as a surprise to some, economics is not the only scientific discipline in which growth and the growth process are integral parts. In fact, essentially all material sciences focus on growth and hence have developed analytical frameworks to describe and understand it. Take, for example, biology, specifically plant biology which has modeled growth in terms of photosynthesis, where solar radiation powers a series of chemical reactions which result in the production of glucose. As in all other material sciences, energy is the essential factor input. Unlike material processes as studied by engineers, there are no tools (simple or complex) involved. Similarly, unlike cell growth where the set of instructions is contained in the organism's RNA or DNA, there is no specific set of instructions nor of supervision. Table 1 presents a list of material processes and the work-energy- and non work-energy-based factor inputs.

Beaudreau (1998) provided a consilient approach to understanding material processes and growth in general – that is, across disciplines. The energy-organization (hereafter EO) approach models material processes in terms of two universal factor inputs, namely broadly-defined energy and broadly defined organization, the former being physically productive, while the latter being organizational. In keeping with basic mechanics and thermodynamics, energy and energy alone can accomplish work, the implication being that all other factors are organizational in nature.

$$W\ (t)\ =\ \eta[T\ (t), S(t), I(t)]E(t) \quad (1)$$

The latter, in turn, is a function of $S(t)$ the supervisory input, $T(t)$, tools, and $I(t)$ information. In keeping with basic physics, the latter three factor inputs are not physically productive, but rather are organizational in nature, affecting second-law efficiency.[1] Better tools (i.e. Watt's external condenser, the Boulton-Watt dual-action steam engine, electric unit drive) increase energy efficiency by minimizing losses. As η is bounded from above, it stands to reason that organizational innovations will have limited effect on output and output growth (Beaudreau and Lightfoot, 2015). Equation 1 provides a simple description of the EO approach to material processes, with *E*(*t*) being the energy input and η being the thermodynamic concept of second-law efficiency. This can be seen as a measure of energy productivity, which in this case, is a function of the relevant organizational variables, including tools ($T\ (t)$, supervision

[1] One could argue that they are organizationally productive in the sense that they affect the "quality" of the material process which has a bearing on second-law efficiency – that is, the productivity of energy.

$S(t)$, and information $(I(t))$.[2] Beaudreau (1998) maintained that this simple model was universal in scope, being applicable to all material processes.

The EO approach to growth is straightforward, namely that growth of the output is an increasing function of growth of the energy input as well as growth/innovations in η, second-law efficiency. The key as far as we are concerned is the universality of Equation 1. Any and all growth processes in the material sciences is/are predicated on growth in the energy input, and, the case that concerns us here, growth in the organizational context. For example, in the case of economic material processes, growth requires an increase in energy as well as an equivalent increase in tools and supervision – conventional capital and labor.[3]

This raises the question of productivity or, put differently, the contribution of factor inputs to output and growth. In keeping with basic mechanics and thermodynamics, the only physically productive factor input is energy/force. All others are organizational inputs, which together define the material process, but are not productive in the traditional sense.[4] Put differently, they increase with output, but are not the ultimate cause.[5] Frederick Soddy captured the essence of material processes – animate and inanimate – in the following parable.

> "At the risk of being redundant, let me illustrate what we mean by the question 'How do men live?' by asking what makes a railroad train go. In one sense or another, credit for the achievement may be claimed by the so-called 'engine-driver,' the guard, the signalman, the manager, the capitalist, the share-holder,-or again, by the scientific pioneers who discover the nature of fire, by the inventors who harnessed it, by labour which built the railroad and the train. The fact remains that all of them, by their collective effort could not drive the train. The real engine-driver is the coal. So, in the present state of science, the answer to the question how men live or how anything lives, or how inanimate nature lives, in the sense in which we speak of the life of a waterfall or of another manifestation of continued liveliness, is, with few and unimportant exception, 'By sunshine.' Switch off the sun and a world would result lifeless, not only in the sense of animate life, but also in respect of by far the greater part of the life of inanimate nature" (Soddy, 1924, p. 4).

3. Literature review: steady-state growth models

In this section, we review the steady-state growth literature, focusing on the underlying microfoundations – that is, the implied formalizations of material processes, with the EO approach as our guide.

For the most part, this literature consists of models/approaches that are based on neoclassical production theory where the emphasis is on labor and capital, and in more

[2] While all are ultimately energy based, the corresponding energy has no bearing on output. For example, labor or supervision is energy-based (workers or control devices). Information, specifically information transmission, storage and retrieval, is also energy based.
[3] In artisanal material processes, the energy input is provided by human beings, specifically by human muscles. See Beaudreau (1998) for a detailed taxonomy of material processes and energy inputs.
[4] For more on the role of tools in material processes, see Alting (1994) and Beiser (1983).
[5] In most material processes, organizational inputs are minimal (e.g. photosynthesis).

recent cases, other factor inputs such as materials, services and energy (Berndt and Wood, 1975).

The Harrod-Domar (HD) and Solow-Swan (SS) models are steady-state neoclassical growth models, as both focus on labor and capital, and both derive the equilibrium steady-state growth rate. As such, both see labor and capital as being physically productive. Where they differ is in terms of factor substitution with HD being based on fixed proportions and thus no possibility of labor-capital substitution, and SS allowing for unlimited substitution. Ultimately, the steady- state growth rate is defined as the sum of the rate of growth of the labor input and the rate of technological change. Technological change is incorporated in both, but not modeled explicitly (i.e. exogenous). In short, technological change is of the manna-from-heaven type, with no specific structure. It is fair to say that the HD and SS approaches to growth are the *de facto* gold standards of the growth literature as virtually all subsequent work is a variant of these models.[6]

The enigmatization of growth that is inherent in these models, we maintain, owes in large measure to the enigmatization of the underlying material processes, which in turn can be traced back to the earliest attempts on the part of moral philosophers and political economists to understand wealth and its creation. For example, in Chapter 1 of Adam Smith's *An Inquiry into the Nature and Causes of the Wealth of Nations*, industrial material processes are modeled as being labor based, with labor productivity (a scaler) being a function of (*i*) worker learning (*ii*) reduced down time, and (*iii*) the introduction of machinery. Ironically, while labor had been reduced to a marginal factor input, overseeing steam-powered machines, Smith put it at the center of his analysis, a decision that would be heavy in consequences. For roughly a century, labor was front and center, while the steam engine was couched in a parameter.

Table 2 Neoclassical and other enigmas

Enigma	Violation
Capital is physically productive	Principles of basic mechanics
Labor is physically productive requires both, yet worker-less factories exist	Machine operatives production
Physically productive labor and capital can be substituted	Neither is physically productive
Energy/force is ignored	
Production functions exist	
Solow residual	

As it turned out, this became the central theme of Karl Marx's labor theory of value, namely that labor was the only productive factor input and as such was entitled to the entirety of the product. Ironically, throughout Marx's life, labor was little more than an organizational factor input, overseeing the workings of machines. Its brawn no longer powered the material processes of the industrial revolution, yet it remained at the center of the discourse.

The resulting crisis in classical economics (after all, Marx should be considered to be a *de facto* classical economist), led eventually to the neoclassical rejoinder, one that evacuated the

[6] The Harrod-Domar model has made a comeback of late, being the basis of Thomas Piketty's work on capital in the 21st century.

problem of (unearned) profits by simply decreeing capital to be physically productive. No justification was, nor could be given based on the role of tools in classical mechanics and applied physics. While a stop-gap measure intended to calm the waters, it would go on to muddle them even further. By the end of the century, material processes in economics were defined in terms of two, organizational, non-physically productive factor inputs, namely labor (supervisors) and capital (non-productive tools).[7]

While both are necessary factor inputs, the problems stemmed from and continue to stem from the underlying implications, namely that both are assumed to be physically productive with an average and marginal product. Ironically, neoclassical stalwart Alfred Marshall, in his 1890 magnum opus, *Principles of Political Economy*, referred to workers as “machine operatives,” yet continued to view them as being physically productive. The list of associated enigmas is provided in Table 1, where we see that unlike elsewhere the material sciences, organizational inputs (i.e. tools) are assumed to be physically productive. Similarly, labor or what is essentially a supervisory factor input is also assumed to be physically productive. Together, these two assumptions are the metaphorical equivalent of a fuel-less or energy-less automobile complete with driver – or glucose-free mitochondria. Another interesting enigma is the concept of labor- capital substitution and the resulting implications, namely that output can be maintained by giving up one and getting one of the other. How this came to being is a mystery given that neither is physically productive – hence the enigma.

However, the greatest enigma is and will always remain the Solow residual.[8] Ironically, the neoclassical approach to understanding material processes spawned, in the post-WWII period, the greatest enigma of all times. In short, using an inappropriate accounting framework (Divisia and Tornquist, indexes), roughly half of the observed growth was attributed to capital and labor, leaving the other half as a residual.[9] Put differently, half of the observed levels of growth was attributed to non-productive, organizational units, and the rest was a mystery. One could argue that this is a second-order enigma, having been born of the first, more basic enigma, namely neoclassical production theory.[10]

When growth rates plummeted in the 1970s and 1980s, the standard pat response was that the rate of technological change had, for all intents and purposes, fallen to zero. As little was known of the underlying dynamics and causes of the residual in the post-WWII period, myriad hypotheses were advanced, ranging from the welfare state, to fiscal policy, to import substitution, to the OPEC-induced energy crisis, to unionization, etc.

Unfortunately, all of these were little more than hastily-crafted, often times, ideologically-inspired ex-post rationalizations, with little-to-no basis in science. The proof is that some four decades later, not one of these hypotheses has been confirmed empirically.[11] In time however, the profession responded with a veritable flurry of activity aimed at modeling the residual, understanding the productivity slowdown and ultimately affecting the policy debate

[7] For more on the nature of tools (capital) as seen by engineers, see Beiser (1983) and Alting (1994).
[8] Interestingly and to a certain extent very telling, economics is the only material science in which roughly half of growth consists of a residual. That is, in all other material sciences, the residual is negligible and often attributed to measurement issues.
[9] See Denison (1962, 1985) for an early attempt at understanding the growth residual.
[10] This is not particularly surprising as if the base is mis-specified, anything that follows will also be.
[11] Interestingly, this did not prevent successive governments from taking action on virtually all policy fronts, with the disappointing results that are there for everyone to see.

(i.e. increasing growth). The result has since become known as New Growth Theory, which we now examine.

3.1 Endogenous or new growth theory

The birth of the residual in the post-WWII period gave rise to yet another series/generation of enigmatic approaches to understanding material processes and growth, also known as New Growth Theory (NGT). Not surprisingly, these approaches were orthogonal to the science of material processes and their growth, owing in large measure to the enigmas referred to in Table 2. In essence, the profession set out to understand the enigma that was the Solow residual with what turned out to be a new generation of enigmas, including notions such as creative destruction, AK models, and institutional economics.[12]

In this section, we choose not to review the many contributions to this literature since Romer's path-breaking work in the 1980s. Rather, our focus will be on its implications and more importantly, on its success or lack thereof of NGT in shedding light on the processes underlying economic growth. With this in mind, we start with its implications. In short, there are three basic implications, namely that in so far as growth is concerned, history matters, institutions matter and geography matters. By the latter, it should be understood that time and place are integral components of technological change, and as such, growth. In this regard, it has much in common with the field of evolutionary economics pioneered by Nelson and Winter (1973). Within this framework, NGT maintains that markets in general underinvest in knowledge (Romer, 1986), that monopolistic competition is more conducive to innovation and that multiple equilibria are not only possible, but likely. In short, it sees innovation as a succession of monopolistically competitive technologies, instigated by existing and new firms (sometimes referred to as quality ladders).

Given the paucity of knowledge about the Solow residual, NGT was a welcomed addition to the literature. After all, it sought to shed light on the greatest enigma of the 20th century, in addition to providing a framework for understanding the process of growth in general. The problems, however, were many. As far as we are concerned, it unwillingly or unknowingly contributed to further enigmatizing the question of economic growth. It did so by increasing the dimensionality of the problem in a number of directions. For example, instead of focusing on the Solow residual which is a material process-based residual, it couched the discussion in the larger question of innovation in general – that is, innovation involving processes, products and institutions. In fact, much of the discussion and examples found in the theoretical and empirical literature are taken from the realm of product innovation, not process innovation. While there is nothing intrinsically wrong with this, it detracts from the question/problem at hand, namely understanding output growth. Put differently, quality ladders add little to our understanding of material process-based growth.

While the original NGT framework defined a whole new world for innovation and technological change, there was no subsequent attempt to narrow the focus to material process innovation.

This has made for a situation in which process and product innovation are used interchangeably, when in actual fact, the latter has little to no bearing on growth (i.e. of the underlying material process). A good example of this is the R&D literature where process and

[12] See Krugman (2013) for an in-depth critique of NGT.

product innovation are lumped into one, overriding variable, namely R&D. Clearly, product innovation cannot and will not increase the growth of output.

4. Literature review: non-steady state models (shocks)

This sub-field of the growth literature is as enigmatic as its steady-state counterparts. In essence, it attempts to identify the factors that contributed to the first (18^{th} century) and second industrial revolutions (late 19^{th}/early 20^{th} century), what most agree were singular occurrences. Unlike the steady-state literature, work in this field is shock specific, with virtually no attempt to provide a general theory of industrial revolutions – that is, a general theory of industrial revolutions.[13]

McCloskey (2004) pointed to what have been two approaches to industrial revolutions (mostly the first), namely material and non-material. The former refers to the various known and documented technological advances that led to first industrial revolution, while the latter refers to the institutions – including culture – that spawned these changes. In this regard, non-material approaches have much in common with NGT where institutions are front and center.

In general, material approaches have focused, for the most part, on the process-based innovations that led to the well-documented increase in output in the early 19th century (Boulton-Watt double-acting steam engine, Paul's power carding and spinning machines, Arkwright's spinning frame). Surprisingly, this literature is decidedly neoclassical in nature, with the various techno- logical innovations being seen as affecting the technology (A) scaler. The underlying mechanics are, for the most part, not specified. As such, subsequent developments such as the development in the 1840s of high-pressure steam engines, and the development in the 1880s of the steam turbine, both of which paved the way for greater machine speeds and productivity, are ignored.

While these models or theories of industrial revolutions are enigmatic with regard to the basic neoclassical production function (i.e. they affect A), they are, in essence, consistent with the underlying principles of the material sciences. This owes in large measure to the emphasis placed on the role of energy in the various aspects / dimensions of first industrial revolution. For example, the Watt atmospheric steam engine (with external condenser) in coal mines, the Boulton-Watt dual-action, reciprocating engine in spinning, carding and weaving material processes. In short, the first industrial revolution witnessed a massive increase in energy use/consumption, resulting in an equally massive increase in wealth. In other words, they are consistent with the laws of physics / mechanics / thermodynamics. What could be regarding as an important advance in the understanding of economic growth was, however, lost in the ensuing analysis of its effect on productivity and output. Specifically, it was seen as increasing both labor and capital productivity, two inert factor inputs. In short, the steam engine was modeled as a scaler affecting, in a one-shot manner, capital and labor productivity.

Dissatisfaction with material approaches to industrial revolutions led, in the 1980s and 1990s, to a new approach, namely non-material where the emphasis was on the institutional and cultural underpinnings of the technological and institutional change that characterized the industrial revolution eras. Drawing largely from institutional economics, it sought to identify the exact set of circumstances or causes. Among the leading non-material approaches is Joel

[13] A recent exception is Beaudreau (2018) which develops a pull-push theory of industrial revolutions.

Moykr's *Republic of Letters* according to which the enlightenment in England – what he refers to as the Baconian programme – combined with a growing interest in practical knowledge, led to the industrial revolution (Moykr, 2016). A good example of this, he argued, is the Birmingham Lunar Society where men of science rubbed shoulders with entrepreneurs / practical men. Another is Deirdre McCloskey's notion of "Bourgeois Dignity," according to which societal values towards business in general and endeavouring to make a return on one's investment, laid the ground for the industrial revolution (McCloskey, 2010). In both cases, non-economic factors were responsible for the cataclysmic change that was the first industrial revolution.

From a scientific point of view, these approaches only serve to further muddy the waters for the simple reason that they are virtually not testable. In short, the data set is limited to a single observation, thus eliminating any possibility of testing for regularity. Both Moykr and McCloskey are aware of this, and have responded with a barrage of anecdotes filling volumes. For example, McCloskey develops her thesis in a trilogy of works, including *Bourgeois Dignity, Bourgeois Values and Bourgeois Equity*. The sheer volume, however, does not take away from the fact that her theory is not testable.[14]

4.1 Policy implications

As the endogenous growth literature (steady state and episodic shocks) has grown in size and scope, the list of possible causes has exploded, as has the breadth of the enigma. Instead of providing specific answers to specific episodes of growth, it has increased the dimensionality and potentiality of the various causes of growth.

Nowhere is this more apparent than in the policy implications or lack thereof. Take, for example, Mokyr's notion of the "Republic of Letters" or McCloskey's notion of "Bourgeois Dignity." The obvious question is what are associated policy implications, if any? The last century has witnessed an unprecedented increase in useful knowledge, yet no industrial revolutions have occurred. The same holds for bourgeois dignity. Presently, the world is spending upwards of $1.135 trillion per year on research and development, yet growth rates remain low – compared to the post-WWII period.[15]

It is our view that this is not surprising in the least bit, in light of the enigmatization described here. In short, policy measures are set against enigmas that are intended to explain enigmas that themselves, had resulted from the original enigmatic representation of material processes. Is it any wonder that the results have been and continue to be less than ideal? One could argue that, despite the efforts of the past forty years, the profession is further today from understanding growth than it ever was, owing to the continued divergence from the physics of material processes, or what we refer to here as enigmatization. While growth is understood to the point of no longer being an issue/question of concern in the other material sciences, it remains more of a mystery in economics than ever.

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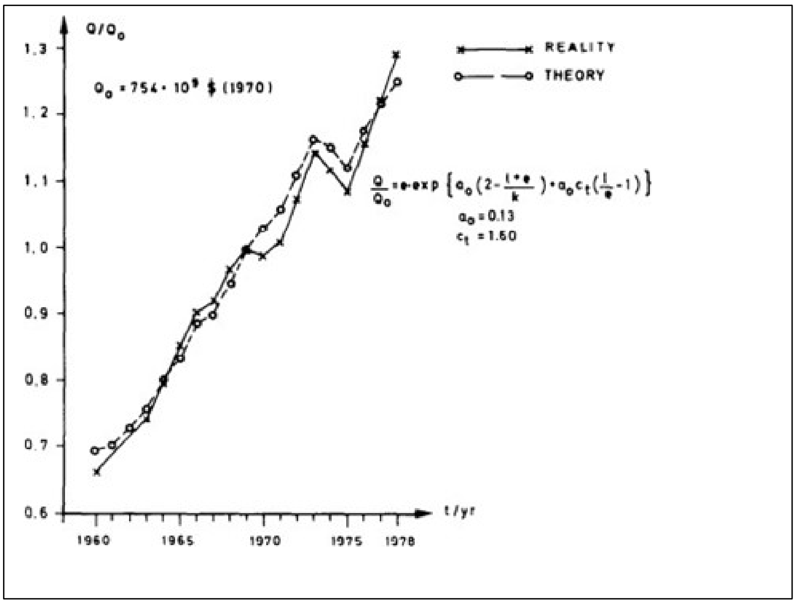
[14] In fact, numerous problems have been noted in the case of both of these theories. Seventeenth and eighteenth century Great Britain was not the first society to witness an explosion of bourgeois values. As for the Republic of Letters, critics point out that similar conditions existed throughout Europe at the time, leaving unanswered the question of why Great Britain?
[15] See Beaudreau and Lightfoot (2015).

5. Consilient approaches

In this section, the discussion will be limited to two approaches, namely LINEX (Kummel 1982, Kummel et al 1998, Lindenberger and Kummel 2002) and Energy-Organization EO (Beaudreau 1998). Other approaches such as the ecological approach and the biophysical approach, while relevant, are not considered for lack of a complete theory of material processes by which it should be understood, an approach that considers the role of all factor inputs (i.e. capital and labor), not just energy.

Figure 1 Actual and predicted growth of U.S. GDP 1960-1978



Source: Kummel (1982)

Let us begin with the question of post-WWII growth. A consilient approach would attribute the high rate of growth to a high rate of growth of energy use / consumption. As it turns out, the LINEX and EO approaches corroborate this result. Referring to Figure 1, we see that manufacturing output in the U.S. tracks almost perfectly energy use/consumption, with a dip in the 1970s. According to Kummel (1982), this corresponds to the productivity slowdown, where energy use decreased. The EO approach also attributes post-WWII economic growth to energy use/consumption. Table 3 shows how growth in manufacturing output in the U.S., Germany and Japan (USVA, GERVA, and JAPVA, respectively) tracks energy use/consumption (USEP, GEREP, and JAPEP, respectively) – specifically how output and energy growth both fell precipitously from 1973 onwards. Both approaches maintain that the record growth in labor and multifactor productivity owed to an increase in energy-use intensity – that is, the increase in energy use/consumption per unit of labor/capital. Implicitly, the enigma that is the Solow residual is resolved, with productivity growth being attributed to greater energy use per unit of labor/capital.

This brings us to the question of the productivity slowdown. In keeping with the laws of classical mechanics, both attribute it to the fall in the rate of growth of energy use/consumption, itself the result of the OPEC-induced price increases. In other words, higher energy prices and the specter of even higher future prices, reduced the rate of growth of energy use/consumption. Once again, the enigma of the productivity slowdown is resolved, being attributed to the decrease in the rate of growth of energy use/consumption.

Table 3 Output and input growth rates: U.S., German and Japanese manufacturing

	U.S.		
	1950–1984	1950–1973	1974–1984
USV A	2.684	3.469	0.121
*USAI**	2.674	3.472	0.310
USEP	4.052	5.371	0.246
USN	0.662	0.900	-0.091
USK	3.694	3.614	3.4008
	Germany		
	1963–1988	1962–1973	1974–1988
GERV A	2.462	6.522	1.486
*GERAI**	2.433	5.190	1.080
GEREP	2.894	5.883	1.366
GERN	-0.785	0.592	-0.938
GERK	2.945	5.620	1.406
	Japan		
	1965–1988	1965–1973	1974–1988
JAPV A	3.826	8.844	3.099
*JAPAI**	3.566	9.856	1.538
JAPEP	3.559	11.320	0.965
JAPN	-0.082	2.297	-0.367
JAPK	7.520	13.536	5.182

* $\hat{\beta}_1 \frac{\dot{ep}(t)}{ep(t)} + \hat{\beta}_2 \frac{\dot{l}(t)}{l(t)} + \hat{\beta}_3 \frac{\dot{k}(t)}{k(t)}$, where $\hat{\beta}$ the estimated output elasticities, are taken from Beaudreau (1995)

In more recent work, Beaudreau (2017) re-examined the underlying hypothesis, namely higher energy prices leading to a lower rate of growth of energy use/consumption. Specifically, he showed that while fossil-fuel prices increased in the mid-1970s, the price of electricity (primary source of energy in manufacturing) remained relatively constant and moreover, the real price of energy (and electricity) had, by the 1980s, returned to its pre-OPEC crisis level, yet the rate of energy use/consumption did not rebound. Drawing from his work on the economies of speed, he invoked the laws of kinetics to attribute the decrease in energy use/consumption to the problems inherent in speeding up material processes.[16] More to the point, he argued that maximum machine speed had, by the late 1960s/early 1970s, been reached in most industries, making for a slowdown in the rate of increase of machine speeds and consequently in productivity.[17]

To recapitulate, over two centuries ago, political economists approached the question of understanding the steam-engine powered industrial revolution, by enigmatizing the process for the first time, attributing physical productivity properties to capital and labor, two organizational, non-energy-based factor inputs. This then resulted in a second round of

[16] In essence, he argued that increased energy intensity manifested and manifests itself in greater machine speed (Beaudreau, 2017). LINEX and EO leave unspecified the mechanics by which increased energy intensity increases output.
[17] In essence, he argued that the productivity slowdown was a manifestation of a larger phenomenon, namely the end of the “Age of Speed.” In other words, machine speeds, like all other speeds, had reached their upper limits.

enigmas in the form of the Solow residual, where the brunt of post-WWII growth was attributed to what Moses Abramovitz referred to as our "our measure of ignorance." By then, waist deep in enigmas, the profession set out to understand the enigma caused by enigmas with yet another round of enigmas that included Romer's AK model, Schumpeterian quality ladders, etc. – in short, New Growth Theory. This has made for the current situation where the profession now finds itself inundated with enigmas when the answer, according to material scientists, is as simple as the basic principles of mechanics and thermodynamics. This has resulted in a situation in which the study of material processes in economics is a virtual island onto itself, with enigmatic notions and concepts, and with two centuries of growth still to be explained.

Table 4 Incursions into the material sciences: missed opportunities

Adam Smith (1776)	Fire Power
Robert Owen (1820)	Scientific Power
Karl Marx (1867)	Classical Mechanics
William Stanley Jevons (1865)	Coal is the mainspring of modern material civilization
Alfred Marshall (1890)	Labor "as Machine Operatives"
Thorstein Veblen (1921)	Power resources
Frederick Soddy (1922)	Cartesian Economics

6. The exceptions: mainstream incursions into the material sciences

In this paper, we have argued that the many formalizations of material processes and their growth throughout the 19th and 20th centuries have led to a series of enigmas, the sum total of which has left the profession with an understanding of material processes that is orthogonal to the laws and principles that govern all other material sciences. We would, however, be remiss to maintain that there were no exceptions. After all, the 19th century witnessed important developments in the science behind the steam engine, namely thermodynamics. As it turns out, a number of ranking political economists did make incursions into the material sciences.[18] However, most of these were either (*i*) in direct contradiction with their more fundamental contributions, or (*ii*) of secondary interest or concern.

Table 5 provides a non-exhaustive list of these references to elements of material sciences, mostly regarding the role of energy in production. Take, for example, Adam Smith whose magnum opus, the Wealth of Nations, was inspired by Matthew Boulton's experience with steam power at his Hockley Brook factory. In 1776, the science of steam or fire was inexistent, prompting him to refer to it in primitive terms, namely as fire power. Why he chose to see it as increasing labor productivity is a question open for debate. Was it to assuage/reassure labor, or was it a vestige of a bygone era when labor was not only the source of energy/power (i.e. brawn). Perhaps the most perspicacious of these writers in so far as references to the material sciences is concerned was German economist Karl Marx, whose 1867 *Das Kapital* contains a surprising account of the basic elements of process engineering, complete with references to the role of power and force as the ultimate drivers of

[18] One could argue that 19th century political economists were more attuned to these developments given a common/similar focus, namely understanding the steam engine. Physicists strove to understand the laws governing heat, while political economists strove to understand the laws governing production with machinery.

material processes (Chapter 15 entitled On Machines and Machinery). What is astounding is its orthogonality to Chapters 1-7 where he develops the labor theory of value (surplus value) based in large measure on classical production theory.

Another surprise is neoclassical pioneer William Stanley Jevons who in *The Coal Question,* published in 1865, trumpeted the essential role of coal in material civilization, going as far as arguing that it constituted the "mainspring". Contrast this with what would become the neoclassical theory found in his 1874 classic *The Theory of Political Economy* where coal/energy is entirely absent (Jevons, 1874). What is also surprising is the fact that by then, the laws of thermodynamics were well established.

7. Summary and conclusions

One could argue that the history of economics or the science of wealth is the story of a profession which in spite of itself, has attempted to understand material processes in what is was and an intellectual vacuum, choosing to ignore developments in related material sciences – and in science in general. The result has been a series of enigmas which as we have shown have engendered subsequent rounds of enigmas, with the result that today, the question of growth is more misunderstood than ever. Over the course of its history, notions of capital and labor (physical) productivity were advanced, while the energy input, the cornerstone of the science of material processes, was ignored completely. Instead, enigmatic, oftentimes orthogonal rationalizations were advanced, resulting in even more enigmas that not surprisingly engendered a whole new generation of enigmas to explain them.

In this paper, a roadmap to the enigmatization of economic growth was provided, one that goes a long way explaining why, as Paul Krugman remarked in a 2013 *New York Times* editorial, the promise of New Growth Theory has fizzled out. Our starting point was that material processes are well understood outside of economics, where there has been and continues to be no need for arcane notions like the Solow residual, or other "measures of our ignorance." In keeping with basic mechanics, all work is ultimately the result of the use of force/energy. More importantly, there can be no exceptions, nor violations to the laws of physics. The notion that generic technological change can miraculously increase output is an affront to basic scientific knowledge, one that borders on the sublime.

It is our view that economics in general and growth theory in particular have suffered as a result. For one, economics is the only material process-based discipline where growth is largely not understood, and what is assumed to be understood (i.e. the role of labor and capital) is, in reality, an illusion, an enigma. Second, despite four decades of what was a concerted attempt to understand growth, the verdict is one of complete and utter failure – or what Krugman refers to as "fizzle".

Lastly, it is our view that the blame for what we refer to as the enigmatization of economic growth lies squarely on the shoulders of the profession. While the problem of growth in the other material process sciences has been resolved, it remains very much an open issue in economics. And the reason is clear, namely the concatenation and multiplication of enigmas. When one tells a lie, one is often times forced to tell another or others to cover it up. The enigmatization of basic material processes in the 19th century led to more enigmas and even more to attempt to understand them.

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