On the Nature of Technical Change[1,2]

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Abstract

While understood as the essence of long-run economic growth, existing conceptions of technical change nonetheless tend to be "unbelievable" and antiquated in relation to our present state of scientific knowledge. This paper views technical change as the remixing of the most fundamental building blocks of nature that can both be observed and manipulated in order to augment the creativity and productivity of the human condition and the physical world. With on-going advances in nanotechnology and neuroscience, such building blocks now consist of the elements that comprised the original endowment of the Earth, having been remixed into countless successive physical and life forms. These elements or "natural units" that comprise nature's tool kit conform with three essential properties of a workable, baseline unit of technical change. Natural units are *immutable and non-decomposable*, thus providing an enduring baseline measure of change; they are *recombinable*, meaning that they can be continuously repurposed; and they are *transferrable* across a wide range of new vintages, including as between physical capital and labor. Once we acknowledge the fixity of our physical endowment and the fact that all new ideas and objects entail a remix of natural units or atoms, far-ranging implications ensue. Among these are that our interpretation of technical change transforms from "purely labor augmenting" to invention neutrality, thus altering our understanding of long-run growth. This interpretation also forges bridges between economics and other disciplines, including the physical sciences and moral philosophy.

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[1] For the purpose of the AEA meetings, this paper was originally entitled "Technical Change, Growth, and Development in a Fixed Physical World."

[2] The author appreciates the opportunity to have presented earlier versions of this paper at seminars or conferences at Brandeis University, the Central University of Finance and Economics, the Chinese Academy of Sciences, and the University of Macao.

1. Introduction

Much has been written regarding the nature of technical change. This is as it should be. With Robert Solow's iconic 1956 paper "A Contribution to the Theory of Economic Growth," having established technical change as the sole driver of sustained, long run growth, every economics major should understand the essential nature of technical change. Since every man and woman on the street is obliged to attribute a rise in living standards to technical change, they too should have a working conception of what technical change means. Curiously, within the economics profession, there is limited consensus concerning what technical change is and how to measure it.

This essay is motivated by two conditions. The first is the standard characterization of technical change in Solow's benchmark model of neoclassical economic growth; that technical change is "purely labor-augmenting," void of investment that reshapes the physical world. As Uzawa (1961) and others have shown, in order to characterize long-run economic growth in the steady state, this version of technical change would appear to preclude the physical construction of a space ship bound for interstellar exploration as bonafide technical change. Given the choice between foregoing the requisite steady state and foregoing a bizarrely limited notion of technical change, the economics profession has chosen a steady state with no escape from the Stone Age.

To their credit, some theorists, including Solow himself, have found this version of technical change bizarre. As he posits (2000, pp. 31,32), "…it is possible to give theoretical reasons why technological progress might be forced to assume the particular form ("called labor-augmenting") required for the existence of a steady state. They are excessively fancy reasons, not altogether believable." Acemoglu (2009, p. 62) simply characterizes the assumption as "At some level distressing."

The second motivation for this essay is far more fundamental than that of whether technical change is labor augmenting, capital augmenting, or augmenting of some other factor. It concerns the basic benchmark against which technical change can be measured. Quite possibly without such intent, two Nobel Laureates have cracked a door open to a transforming notion of the basic elements against which we – economists, scientists, and other interested persons – might measure and understand the evolution of technical change. In his induced innovation article, Samuelson asserts (1965, p. 350): "(It is) a factual assumption that capital, in natural units, is accumulating relative to labor, in natural units." This is a head-scratching statement. If pressed, most economists would likely designate a person or worker as the representative "natural unit" on the labor side of the ledger. With that being the case, Solow's statement leaves the reader pondering the meaning of a "natural unit" in the physical world.

Romer (1990, S72) may offer some clarification. He asserts that "…technological change (is) improvement in the instructions for mixing together raw materials…" Indeed, it seems reasonable to imagine that that within the physical world "raw materials" may qualify as a form of the "natural units" to which Samuelson refers in his statement. In our search for the nature of technical change, the idea that technical change entails improvement in the instructions for mixing together natural units is a useful starting point.

This paper posits a fundamental proposition. That is, the elements that formed the initial physical endowment of our Earth some 4.5 billion years ago that have constituted the building blocks for the evolution of both the biological and physical worlds continue to serve as the building blocks for technical change. Throughout this time, the building blocks have consisted of those elements of the Earth that could be observed and manipulated by the various species. Now in the 21st Century, human kind has acquired the technical capacity to observe and manipulate the Earth's original endowment at the atomic level to frame the technological advance of both the physical world and the human condition.

For Homo sapiens, during the Stone Age, arguably rocks, various configurations of wood from trees, soil, plants, and animals provided the natural units or raw materials that humans of that era were able to remix for a variety of functions. Furthermore, at that time, each human was arguably a "natural unit" having been unadorned by formal education, life-extending drugs, and other medical interventions. Over the centuries and millennia, in order to augment the possibilities for both the physical world and the human condition, humankind has dramatically extended its ability to observe and manipulate ever more granular "natural units" within the physical world. Within the discipline of economics, our understanding of technical change has failed to keep abreast of the rapid unfolding of scientific progress.

Today with the introduction, rapid growth, and application of science, notably nanotechnology and neuroscience, these natural units – capable of being observed and manipulated - have devolved to the level of molecules and cells, increasingly involving the observation and manipulation of the elements represented by the Earth's original physical endowment consisting of approximately 3.5 x 10^{50} atoms. Over the past 4.5 billion years, these atoms have been remixed to form an unfathomable number of combinations of physical and biological forms. Beginning with the Industrial Revolution, human kind has characterized on-going change during a narrow slice of this time as "technical change." While over the recent two to three hundred years, the forms of remixing have changed, the basic ingredients, the Earth's physical endowment, has not. As humankind's scientific abilities to observe and manipulate smaller units of physical mass – both within the physical world and with the human form – the remixing powers of the evolving economies has grown exponentially.

Among other implications of this formulation of technical change is the understanding that technical change is fundamentally invention-neutral, the typology used by John Hicks (1932). This rebalancing of our understanding of the scope of technical change, enabling its essential nature to be augmenting of both the physical world and the human condition, potentially transforms the construction of conventional models of long-run steady state growth. Arguably this is an important matter, but of second order importance to that of formulating a scientifically sound interpretation of technical change.

In the following section, we review the literature to understand its various attempts to clarify the nature of technical change, including whether its direction assumes a labor-augmenting, capital-augmenting, or neutral bias. A central theme of this section is that within the Solow model and other formulations of technical change, the concept of technical change has been forced to conform with a set of parameters that enable the tractability of the economic model. It is reasonable to believe that economists, perhaps with the help of scientists, should seek to first formulate a conception of technical change that is consistent with both scientific and economic principles. Models of economic growth should adapt their structure to the fundamental conception of technical change; our understanding of technical change should not be framed to render our models mathematically tractable.

In Section 3, we begin our exploration of why and how we might measure the world and its technological advance in terms of natural units. Section 4 focuses on the measure of the human form in terms of natural units and its relation to labor-augmenting technical change. Section 5 focuses on the measure of our physical world in terms of natural units and its relation to physical capital-augmented technical change. Section 6 examines the meaning of our exploration for "invention neutral" technical change as introduced by Hicks. Section 7 examines the implications of our interpretation of technical change for Kaldor's stylized facts of growth and for growth theory. Section 8 proposes a variety of implications and applications of the alternative conception of technical change developed herein. Section 9 concludes with a discussion of a range of issues raised by this essay.

2. The Prevailing Understanding of Technical Change

Following on the structure of Solow's model of neoclassical growth (1956), Uzawa (1961) showed that in order to sustain steady state in the Solow model, technical change in the steady state has to be "purely labor augmenting." The most intuitive explanation for this idiosyncratic result follows from a fundamental requirement of stable long-run growth. That is, models of economic growth require that in the long run, the inputs to production, notably capital and labor, grow at the same rate. Thus, in the steady state, the growth of labor, g_L, the growth of capital, g_K, and the growth of output g_Y are all in balance.

In most economies, we typically observe that population growth, n, is less than GDP growth, i.e., $n < g_Y$. As a result, in order to satisfy the balanced growth condition, something has to supplement or augment the natural rate of increase in the population. Convention has evolved to reference that supplementing factor as "labor augmenting technical change," which is generally denoted as g_A. Hence, in the steady state, $n + g_A = g_Y$. In Solow's neoclassical model, labor augmenting technical change performs another function. In combination with population growth, g_A is the critical factor that drives long-run growth. In the long run, without labor-augmenting technical change, income per capita stagnates.

Where does this leave physical capital, g_K? In accord with one of Kaldor's key stylized facts of long-run growth, the model assumes a fixed K-Y ratio, i.e., K/Y is constant. Therefore, $g_K = g_Y$. This requirement allows the growth of the capital stock to be entirely passive. Physical capital passively inherits whatever impetus $g_Y = n + g_A$ imparts to the economic system.[3] Because in the Solow model, capital and labor are complementary inputs and the supply of capital is perfectly elastic, the quantity of capital responds endogenously to increases in the

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[3] See Jones and Scrimgeour (2005).

supply of effective labor lock step. As a result, unlike labor, for which the natural supply is fixed by exogenous population growth, so that its effective supply requires augmenting technical change, physical capital requires no efficiency improvements to supplement its physical quantity.

Acemoglu (2003, p. 6) offers an intuitive explanation of the requirement of labor-augmenting technical change:

> Intuitively, there are two ways to increase the production of capital-intensive goods, via capital-augmenting technical change and capital accumulation, and only one way to increase the production of labor-intensive goods, through labor-augmenting technical change. Capital accumulation, therefore, implies that technical change has to be, on average, more labor-augmenting than capital-augmenting. In fact, the model implies a stronger result: with an elasticity of substitution between capital and labor less than 1, in the long run there will be no net capital-augmenting technical change, (capital's technology) will remain constant, and all technical change will be labor augmenting.

Consistent with Uzawa's Growth Theorem, Acemoglu explains that for the general case, in which the economy's elasticity of substitution is non-unitary, e.g., less than one, technical change must not only be labor biased, it must be purely labor augmenting. This is because once physical capital fully inherits the increase in effective labor due to its elastic supply, if its growth is further augmented by physical capital augmenting technical change, the result will be disproportionately large reductions in the price of capital, causing capital's factor income share to fall thus voiding the steady state.

Li and Bental (2018) appear to be the first to trace the problem of omitted physical-augmenting technical change explicitly to the "excessively fancy reasons, not altogether believable" embedded in Solow's own model. The requirement of labor-augmenting technical change for steady state growth, as Li and Bental show, is entirely the result of the idiosyncratic feature of the model, i.e., values assigned to key parameters – the inelastic supply of labor versus the perfectly elastic supply of capital, rather than the intrinsic nature of technical change.

Arguably, the Solow model simply switches physical capital for the role of labor in the Malthusian model. That is, whereas in Malthus, the augmentation of the productivity of land induces a perfectly elastic supply response of raw labor thereby maintaining labor's subsistence wage, in Solow, the augmentation of the productivity of labor induces a perfectly elastic supply response of raw physical input, thereby maintaining the base price of capital.

The above analysis leads us to a "disturbing" insight. That is the fact that the Solow model and endogenous models of economic growth that conform to the requirements of steady state growth are not built on a fundamental, immutable, scientifically sound concept of technical change. This is shown by the fact of a knife-edge condition in which technical change may be biased toward any factor, i.e., when the economic parameter, σ, is unity versus the case in which that parameter veers from unity. With the smallest epsilon slip to a non-unitary substitution elasticity, the entire concept of technical change veers from one distinct form, i.e., Hicks neutral, to another form, labor-augmenting Harrod neutral. The disturbing feature of this transformation is that an epsilon change in market behavior voids any body of scientific principle on which our understanding of technical change may have been constructed.

3. The Role of "Natural Units"

One advantage of formulating technical change as "purely labor-augmenting" is that it implies a "natural unit" against which it is possible to measure technological advance – that is raw or unimproved labor. This is made clear by the measure of "effective labor," which is simply defined as $n + g_A$. Hence, a unit of labor augmenting technical change is equivalent to that of an additional person or worker in the population count. Thus, when we measure economic change in terms of output per capita, for a given rate of savings for physical capital, the entirety of the growth of living standards can be attributed to g_A, which is equivalent to a virtual increase in the workforce. Hence, when real output per worker doubled in the U.S. from 1950 to 1968, it was as if the economy had doubled the increase in the workforce over this time relative to the 28% increase in the workforce that actually did materialize. That is, over this 30-year period, each worker became nearly twice as efficient as he or she would have been in the absence of labor-augmenting technical change.

With labor-augmenting technical change in the Solow model, there are two avenues through which technical change augments the efficiency of the workforce. One is direct; with a given amount of physical capital, individual workers become more efficient. That is, as represented by Romer (1995), workers formulate "improvements in the instructions for mixing together raw materials" say through their on-the-job experience. However, with the balanced growth requirement, such instructions cannot be translated into more technologically-advanced forms of physical capital, which would cause growth of the effective supply of capital to exceed growth of labor's effective supply, thus voiding the steady state. The second avenue for augmenting workforce efficiency in the Solow model entails workers acquiring additional physical capital through the investment that is stimulated due to the augmented labor force. Specifically, with capital and labor as complements, by augmenting the effective supply of labor, the marginal product of raw physical capital rises, thereby inducing new rounds of investment in Stone Age materials. With the supply of existing, unimproved physical capital perfectly elastic, the augmented "natural" supply of labor is able to accumulate more capital, thereby raising the ratio of raw physical capital to labor, thus making the workforce more productive. However because physical investment results in the accumulation of primitive capital, not technologically-augmented capital, changes in physical savings only result in one-time changes in living standards, A fundamental proposition of the Solow model is that rates of savings have no effect on long-run growth.

Conceivably, the greatest challenge to the technology-savvy workforce is to utilize the unbounded supply of primitive physical capital without implementing the improved "instructions for remixing" the raw materials. That is, while the technologically augmented labor force can formulate instructions for wheels and smartphones, it cannot invest in the actual transformation of primitive capital, i.e., the rocks and other Stone Age raw materials, to increase the efficiency of the physical world. It is quite likely that having resolved the knife-edge dilemma of sustaining long-run full employment of both labor and capital in the Harrod-Domar model, Solow created another knife-edge problem that is no less vexing for our understanding of economic growth, i.e., the absence of technical change in the physical world.

4. The Three Properties of Natural Units

We begin our investigation of the nature of technical change by setting forth certain fundamental principles regarding the properties of a "natural unit" that serves as both the baseline measure of technical change and the fundamental building block for technical change. A natural unit of technical change, that which Romer refers as "raw materials" and that against which we can measure technological advance, embodies three properties. These are:

1. *Immutable and non-decomposible*. As a unit of account, the inherent structure of the unit should not be vulnerable to change over time. The purpose of the unit of account is to be able to assess the extent to which, over a given period, the natural unit has acquired greater value. The measure needs to be sufficiently granular, so that it itself is not subject to being supplanted, destroyed, and no longer existing.
2. *Recombinable*. As a building block for technical change, a natural unit should be capable of being mixed and recombined with other natural units into more effective, valuable vintages of physical or human capital. For purposes of remixing, a natural unit must be observable and able to be manipulated.
3. *Transferrable*. Finally, to enable efficiency and growth, the natural unit should be capable of being reallocated or transferred across broad categories of factors or production, including capital and labor. As such, where markets exist for natural units, their prices and supply elasticities become equalized across factors.

A useful metaphor is that of Lego, i.e., a game with a finite, but large number differently shaped, plastic bricks that can be combined to create a variety of functioning objects, including vehicles, buildings, and working robots. Anything constructed can then be taken apart and the pieces used to make other objects. In a Lego world, a Lego piece satisfies all of the properties set forth above. Each brick is immutable. The bricks are recombinable. Within the separate worlds of vehicles, buildings, robots, each individual set of bricks is transferrable, from one vehicle, city, or robot to another; however, a robot brick is typically not transferrable across vehicles and robots. The metaphor would be more complete if the same bricks were transferrable among and used in the construction of an inclusive set of possibilities encompassing vehicles, buildings, and robots.

Within the context of a Lego game, the most basic unit that can be observed and manipulated is the Lego brick. Over time, technology, including nanotechnology and neuroscience, has made the “natural unit” within the physical world and human form more granular, so that it has now devolved to 118 elements in nature. As such, this essay proposes the following definition of technical change:

> *Technical change is the remixing or recombination of natural units – the atoms constituting the original endowment of the Earth and the fundamental building blocks for creating greater social value.*

Within a fixed physical world as prescribed by the Law of Conservation of Mass, all economic growth results from technical change. This definition is consistent with:

- Solow's emphasis that in the long-run technical change is the driver of all economic growth;
- Samuelson's representation of "natural units" as the basic measure of economic change; and
- Romer's description of technical change as novel instructions for remixing of remixing raw materials.

The following section illustrates the role of elements in the physical world.

4. Natural Units in the Physical World

The physical world has evolved over the past 4.5 billion years. Every vintage of change has embodied a remixing of the original endowment of nature's 118 elements. The Museum of the Terracotta Soldiers in Xi'an China includes a plaque that shows the elemental composition of the second chariot of China's first emperor, *Qinshi Huang* shown in Figure 1. As shown in Table 1, the Museum performed an "analysis of the composition of the materials of the major parts of (the) bronze chariot and horses." The Table shows the composition of the principal elements composing the chariot and horses, with copper and tin, together forming bronze, and iron. These three elements typically accounted for more than 90% of the components included in this iconic mode of transportation.

Conceivably, the chariot could have been formed by other elements, including carbon, oxygen, and hydrogen in wood and cloth. The central fact of the continued existence of the chariot is the choice of elements that were used for its construction – those shown in the table – which have enabled its form, magnificence, and deep historical symbolism to survive for more than two millennia. Only this choice of building blocks could have resulted in such a durable and artful legacy of the rein of the First Emperor of China.

Below, we also show the six elements that generally represent significant shares of the composition of modern-day semiconductors. The functions of these elements are also shown:

Element	**Use**
B: Boron	3 valence electrons: used for p-doping of silicon
N: Nitrogen	The cover layer on top of the wafer
O: Oxygen	Oxidation of silicon, insulating layers
F: Fluorine	Used for etching in combination with other elements
Si: Silicon	Bulk material in semiconductor industry
P: Phosphorus	Valence electrons: used for n-doping of silicon

The distinguishing feature of each semi-conductor embodying these elements is the unique way in which the elements are remixed. During 2015-2017, the U.S. Patent and Trademark Office granted 79,034 patents in the semi-conductor classification generally representing recombinations of the elements shown above. With each valuable patent, the participating elements became more valuable than they had previously been.

Markets exist for all of the elements referenced above. Among the 118 elements that exist, we can identify 88 for which active markets have been formed.[4] Of the 118 elements, 13 are unstable with no markets; the remaining 17 show no market activity. Each of these elements with markets shows a transactable price. For any object, we can identify the physical units and the cost of the raw materials, the natural units, embedded in the object. Given a market for the object, we can measure the market price of the products and the cumulative value added as the difference between the market price and the cost of the bundle of elements or building blocks required to assemble the product.

5. Natural Units for Labor

Measuring labor in natural units, while seemingly more straightforward – a worker or person should suffice – is, in fact, more problematic than the counterpart exercise for the physical world. The convention in economics is to convert much of growth analysis to per capita

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[4] Source: https://en.wikipedia.org/wiki/Prices_of_elements_and_their_compounds (June 2013).

or per worker terms, such as output per capita/worker or capital per capita or per worker. Perhaps 1.5 million years ago, at the outset of the Homosapien era, people and workers were "natural units." However, in the intervening period:

- The world's population has increased by billions,
- Longevity has trebled, and
- The capacity for formulating ever better "instructions" has advanced.

Each of these changes embodies a physical dimension.[5] That is:

- Population growth results from the mixing of eggs, sperms, and medical intervention;
- Longevity results from the design of medicine/drugs and the removal, repair, and implant of organs and the manipulation of cellular structures;
- Through experience, education, and learning, brains create, absorb, and accumulate knowledge, neuron-by-neuron and synapse-by-synapse.

Population growth leads to a *widening* of human capital; experience, education, and learning *deepen* the stock of human capital. Longevity serves both functions, expanding the numeric population and providing greater incentive and opportunity for human capital deepening. A fundamental way to interpret the contribution of population growth to innovation is to understand that the nature and nurture of each individual is unique; each person has unique capabilities and possibilities. Having each person in the population pool enhances the probability of any given invention materializing. Holding the research capabilities and time allocation of each individual fixed – indeed as Romer (1995) acknowledges there are limits to each – Jones and Volrath (2013) show that in a generalized model of knowledge creation, population growth is the principal constraint on innovation. Hence, from the perspective of innovation and technical change, the process of fertilization and procreation is as important as learning. All additions to the stock of human capital result from the remixing of natural units.

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[5] For a primer of the role of atoms in the human body, see: https://www.khanacademy.org/science/biology/chemistry--of-life/elements-and-atoms/a/matter-elements-atoms-article

The Scientist magazine's choice of the ten top innovations for 2018 demonstrates how life sciences research has devolved to the level of the cell, molecule, and atom. As shown in Table 2, the list includes the following innovations, all of which operate at the cellular level or below:

- Cyto-Mine (Sphere Fluidics)z: allows researchers to screen up to 40 million cells for a desired property.
- Tapestri (Mission Bio): a microfluidic platform for high-throughput, single-cell DNA sequencing sample prep that can handle up to 10,000 cells simultaneously.
- Fluidity One (Fluidic Analytics): calculates the average size of proteins in a sample and also measures their concentration.
- MAD7 (Inscripta): the sequence for this novel DNA-cutting enzyme is available online for all research and development uses.
- BD AbSeq Assay (BD): allows researchers to simultaneously analyze RNA and protein levels in thousands of individual cells.

The scope and pace of life-science research has altered the natural unit that constitutes the human body. A million years ago, the human body was fundamentally intact and not breached other than by food; that time, the most basic natural unit capable of being observed and manipulated for the purpose of augmenting labor productivity was the whole human body. Today the most basic natural unit has devolved to the cell, the DNA, and to molecule. As evidenced by The Scientist's top 10 innovations, the extent and detail of remixing within the human body operates at levels of instructions that have reduced the natural unit to sub-cellular dimensions. As in the physical world, technical change in the human condition involves the observation and manipulation of molecular-level building blocks. In both the physical world and the human condition, the 118 elements that form the Earth's original endowment constitute the "natural units" of technical change that conform with the three fundamental properties set forth in Section 3 above.

5. Invention-Neutral Technical Change

John Hicks (1932) coined the term "invention neutrality" to represent the condition in which an invention results in equi-proportional increases in the marginal products of both capital and labor, holding fixed the initial factor intensities. As such, intention-neutral technical change is equally augmenting of the efficiency and quality of the physical world and human capabilities. This characterization of technical change contrasts with the conventional characterization of technical change as "purely labor augmenting."

Several observations conform with the notion of invention neutrality. A common measure of technical change in the economics literature is that of the patent. Most patents embody invention neutrality. That is, the patent embodies an idea, the new instructions referenced by Romer that represent the innovation output of an individual's inventive ability. The instructions, in turn, offer the promise of a novel and useful object formed from the physical world. By their nature, patents represent a bridge between innovation in the human and physical worlds. The returns to patent assignees represent compensation for the value added resulting from the remixing of natural units in the physical world.

The other, far more general, evidence of invention neutrality rests on the casual, but reasonably compelling, observation that it is difficult to distinguish between the evolution of the human factor, including its scale, and that of the physical world. When one observes a city with its bustling workforce or an individual on public transit interacting with a smartphone, it is not easy to discern different rates with which elements of the physical world have been technologically augmented and those of aggregate human condition have been augmented. Put another way, it is difficult to distinguish whether over the past one thousand years the greater increase in value resides with the stock of human labor or the physical capital stock. If not invention neutrality, then what accounts for this stylized fact of balanced technology augmentation?

Invention neutrality is manifest in another forms. Countless inventions simultaneously augment both the physical world and the human condition. The three forms of human-augmenting technical change cited in the previous section – procreation, longevity extension, and knowledge deepening – each has a counterpart involving the remixing of natural units in the physical world.

Fertility treatment, birth control, and ultrasound and other medical interventions serve optimal reproduction outcomes. A wide range of innovations originating in the physical world ranging from spectacles and automobile safety measures to the top ten life science innovations shown in Table 2, extend longevity and general life functioning. Computers, classrooms, and laboratories are essential physical world counterparts for the learning and research enterprise. All of these innovations yield market value, while also enhancing the returns to labor. All are consistent with stable factor-income shares for physical capital and labor.

The previous paragraph underscores the complementarity and neutrality of innovation outputs resulting from improved instructions for mixing natural units both within the physical world and within the human form. Innovation itself – the process of discovering new instructions – requires interaction between the physical world and human world. That human ingenuity translates into innovation in the physical world is evident. Less evident, but widely documented, is the fact that change in the physical world is the essential motivator of human ingenuity. Adam Smith (1776, p.), for example, observes how the division of labor in the physical world facilitates our imaginations to conceive of machines that substitute for labor:

> The invention of all those machines by which labour is so much facilitated and abridged seems to have been originally owing to the division of labor. Men are much more likely to discover easier and readier methods of attaining any object, when the whole attention of their minds is directed towards the single object, than when it is dissipated among a great variety of things.

Arrow (1962, p. 155, 157) ties the learning phenomenon specifically to that associated with the investment process:

> I do not think that the picture of technical change as a vast and prolonged process of learning about the environment in which we operate is in any way a far-fetched analogy (p. 155)….(I take) cumulative gross investment (cumulative production of capital goods) as an index of experience. Each new machine produced and put into use is capable of changing the environment in which production takes place, so that learning is taking place with continually new stimuli (p. 157).

Hence, as argued by Smith and Arrow, the inputs to innovation – human ingenuity and learning acquired from interactions with the physical environment – are deeply complementary inputs to the invention process, further reinforcing our understanding of invention-neutrality. In a more general sense, not only is Smith-Arrow interactive invention a key ingredient of technical change, physical-human interaction has been the essence of biological evolution. The life of both Homo sapiens and earlier species is one in which humans have acquired an enlarged brain, tactile abilities, social connectedness all for the purpose of augmenting the human capacity to observe and manipulate the physical world. Technical change – both its inspiration and effects – across the physical world and the human condition are inseparable; its efficiency enhancements for the physical world and the human condition are broadly uniform and neutral, thus accounting for substantial and relatively stable factor-income shares for both capital and labor.

6. Technical Change and Growth: Kaldor Revisited

How do we reconcile our original endowment approach to measuring economic growth and technical change with the conventional total factor productivity approach? First, we contrast our approaches using a general neoclassical production function.

$$Y = Tf(K,L), \tag{1}$$

where Y, K, and L represent measures of output, capital, and labor respectively and T represent total factor productivity. We can rewrite (1) as $T = Y/f(K,L)$. The principle difference is that in the standard approach, the physical, natural units of K and L expand, so that $dT/T < dY/Y$; given constant returns to scale, $g_T = g_Y - \alpha g_K - (1-\alpha)g_L$. In our scheme, K and L are fixed by the Earth's initial endowment, so that $dT/T = g_T = dY/Y = g_Y$.

We first note that the proposition $g_Y = g_A$ is entirely consistent with Solow 1956's result, i.e., in the steady state all economic growth results from technical change. Standard growth accounting, originating with Solow 1957, fudges the matter by accounting for the "proximate sources" of growth, notably the accumulation of physical and human capital, leaving the measure of TFP to sources that are unaccounted for, otherwise characterized as "our ignorance."[6]

Among the more notable examples of this statistical accounting is Alwyn Young's "The tyranny of numbers: confronting the statistical realities of the East Asian growth Experience"

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[6] See for example, Bosworth and Collins (2008).

(1995). Accounting for the growth surge in the "Asian Tigers" – Hong Kong, Taiwan, Singapore, and S. Korea – Young attributes the greater part of the transformation to physical and human capital "investment." Hence, in the case of Singapore, between 1996 and 1990, presumably all of the change in that country resulted from "capital deepening" in which the same technological vintage of capital and knowledge that prevailed in 1966 were vastly copied and reproduced during the subsequent 30 years. For those entering Singapore's workforce in 1966, who witnessed the dramatic transformation of Singapore during their working lives, technical change in Singapore was entirely stagnant. Whereas in 1966, workers entering Singapore's textile industry were restricted to a single sewing machine. Twenty-four years later, in 1990, when they retired, each was able to multiply the speed of her production with 3.4 1960-vintage sewing machines in hand.

Before leaving this matter, we acknowledge that not all production results from technical change. Indeed, in an automobile assembly plant the bulk of production entails the use of established, routine instructions for producing automobiles that emerge from the assembly line. Arguably, much, perhaps all, of the "natural units" – physical matter – used have been repurposed from never-previously-used matter. What distinguishes technology-induced growth from routine production is, as Romer describes, is "improvement in the instructions for mixing…" Having only to help match the full-employment GDP output of the previous year, 98% of the 42,357th car that emerges from the Chevrolet assembly line need not entail significant "improvements in instructions" of the assembly of an automobile.

In his influential 1957 paper, Nicholas Kaldor summarized the statistical properties of long-term economic growth, identifying the following six "remarkable historical constancies revealed by recent empirical investigations." Our alternative interpretation of technical change recommends the following revisions to four of Kaldor's six stylized facts.

1. Output per capita grows over time.
    1a. *Output per person grows over time: returns to human capital are relatively stable.*
2. Capital per capita grows over time.
    2a. *Technology intensity, i.e., capital per original natural unit in both the physical world and the human form grows over time.*
3. The capital-output ratio is approximately constant over time.

3a. *The physical and human capital-output ratios are approximately constant over time.*

4. Capital and labor's shares are approximately constant over time.
5. The return to capital has no trend.

5a. The real return to both physical and human natural units has no trend.

6. Output per capita varies widely across countries at a point in time.

The key difficulty with Kaldor's facts is that they confound natural units and technical change into a single category called "capital." The stylized facts reference "Labor" without distinguishing between the natural units that constitute a human being and human capital that accumulates through the investment process. In the case of physical capital, it is widely believed that the elements that constitute or motivate physical objects, e.g., carbon, nitrogen, iron, oil, are continuously available at prices that exhibit no trend.[7] However, once these natural units have been remixed so as to create functioning goods, such as smart phones, airplanes, and dishwashers, the value of the included natural units rises significantly. Notwithstanding, the marginal product of the last unit of technology, i.e., the marginal remixed natural unit, exhibits no trend.

This condition holds for labor. A subset of the Earth's natural units reside in the workforce. It is not unreasonable to assume that, as in the Malthusian world, the returns to raw, unimproved agricultural labor remain more or less fixed at a subsistence wage. As with physical objects, the accumulation of capital through investment in education, experience, training, significantly raises the returns to the collection of natural units in the human body. Again, as with the physical world, the marginal returns to investment in new technology falls to relatively constant, trendless levels. In the model advanced by Acemoglu (2003), allowing for both physical and human-augmented technical change, and the human-capital augmented models of Lucas (1991) and Rebelo (1998), it is assumed that in the steady state, the returns to investment in physical and human capital equalize.

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[7] A study published in the Proceedings of the National Academy of Sciences by Graedela (2015) et al focuses on the "supply criticality" of 62 elements. They find supply limitations for many metals important in emerging electronics (e.g., gallium and selenium), as well as those used for steel alloying (e.g., chromium and niobium) and high-temperature alloys (e.g., tungsten and molybdenum). Certain elements, including the platinum group metals, gold, and mercury pose serious environmental implications. Although silicon is the second most abundant element in the Earth's crust, following oxygen, the supply of pure electronics-grade silicon is limited and increasingly expensive.

This revisionist analysis of capital and labor measured in natural units being available at fixed prices, thus implying that the supplies of both capital and labor are available in perfectly elastic supply, throws doubt on the fundamental assumption of the Solow model and Acemoglu's intuition (2003, p. 6):

> Intuitively, there are two ways to increase the production of capital-intensive goods, via capital-augmenting technical change and capital accumulation, and only one way to increase the production of labor-intensive goods, through labor-augmenting technical change….

In fact, if the supplies of natural units bundled in raw capital and raw labor are both effectively perfectly elastic, then according to the conventional logic, supply-augmenting technical change should not be required for either capital or labor. The fallacy is that Solow and Acemoglu reduce the demand for capital to quantity measures, not recognizing that labor-augmenting technologies require complementary investments in technologies that augment physical capital. As such, long-run growth requires embodied investment, that which remixes the Earth's endowment of natural units, in *both* capital and labor.

Cognizant of this critical distinction between the natural units comprising capital and labor and the augmented technologies, i.e., the remixing, we revise Kaldor's stylized facts of growth. All but items #4 and #6 – the constancy of capital and labor's income share and the variability in output per capita across countries – are subject to revision.

6. Applications

What are the practical applications of such an interpretation of technical change? In responding to this question, we must not forget that the answer deserves to be assessed against whatever might be the practical – or impractical – applications of the alternative interpretations of technical change. The first, critical, point that needs to be made is that acceptance of the nature of technical change advanced in this essay does not preclude the use of established methods of assessing economic growth and change. The most fundamental aspiration of this paper is to deepen our understanding of the nature of technical change, including the implications of its essence for the relationship between economics, science, and other disciplines.

In many ways, the perspective of this essay and related practices in economics can be woven into the same fabric.

One result of integration is the use of this elemental structure to construct a bottom-up value-added chains for product – as well as for living organisms. As such, the value chain begins with the fundamental building blocks – those increasingly able to be observed and manipulated in the name of technological advance. Such a lattice of value added structure makes more transparent the points of access for technology to enter with "new instructions" for remixing the elements of the physical entity. Within this context, the Human Genome Project that has identified and mapped all of the genes of the human genome from both a physical and a functional standpoint was a major step in constructing the value-added chain for the human body and laying the foundation for further research initiatives, such as CRISPR and DNA editing. By incorporating molecules and cells and their substructure as the unit of observation and manipulation, nanotechnology and neuroscience, as well as the formative fields of nano-economics and neuro-economics, are filling in the lower portion of the value chains, opening the door wide for understanding the role of the most basic building blocks in technological advance.

At a macroeconomic level, our interpretation of technical change in which all long-run economic growth has its origins in remixing, embodied investment, and technical change, the measure of GDP growth, suitably accounting for the human factor and the consumption of natural resources, serves as a reasonable measure of technical change. A strict implication of this interpretation of technical change is that the growth of individual industries may also be interpreted as purely the consequence of technical change. In the same way that underutilized rural labor reallocates in the technologically-dynamic urban industrial sector in the Lewis and Fei-Ranis Two-Sector Growth model, the elements embedded in physical capital reallocate from lesser productive settings to more productive settings. Driven by relatively robust rates of technological advance, price and quality effects may also shift demand.

A principal contribution of this alterative conception of technical change may alone justify its introduction. That is, by interpreting technical change as invention neutral, this formulation of technical change, enables the Solow model and our general understanding of the driver of long-run growth to escape the knife-edge problem of a non-unitary supply elasticity that spills the requisite definition of technical change into the "disturbing" territory of becoming "purely labor augmenting."[8] With this interpretation of technical change in which the transferability of natural units between the physical world and human condition results in uniform supply elasticities, implies that technical change must be uniformly augmenting of the physical and human factors. A corollary of this result is that, contrary to Solow 1956, both physical capital and human capital saving and investment emerge as critical drivers of invention-neutral technical change and long-run growth.

7. Conclusions and Discussion

This paper attempts to build a bridge between economics and science for the purpose of introducing a more authentic, free-standing understanding of the phenomenon of technical change. A number of implications follow from this conception of technical change. These include the following:

- Technical change is invention-neutral; that is it is symmetric and balanced as between labor and capital.
- All economic growth is embedded in physical matter – there is no "disembodied" technical change.
- As physical matter is remixed to create greater value, the value and price of remixed natural units rises, as it does for labor.
- Schumpeterian growth prevails 1-for-1, i.e., innovation requires the repurposing of a fixed supply of physical matter.
- At full employment, the rate of growth of technical change is simply the rate of growth of GDP.

Billions of years ago, Earth and its inhabitants were endowed with a fixed physical endowment. Every object and individual we encounter has a deep scientific and historical past; the natural units that comprise these physical objects and life forms have an unbounded future. This perspective will hopefully offer a perspective and analytical foundation for deepening our understanding regarding the ways in which discipline of economics can mix with other disciplines to expand our understanding of the possibilities for using the tools of economics to understand and shape the phenomenon of human choice.

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[8] See Jefferson, 2018.

Clearly, the interpretation of technical change advanced in this essay also raises deep ethical issues. These are already receiving wide attention, however, the third property of a natural unit advanced by this paper – that of transferability – in particular raises problematic ethical issues. The disturbing issue of transferability is the physical and scientific possibility of transferring and implanting inventions from the physical world into life forms, such as DNA editing, and, in turn, transplanting life forms into objects within the physical world, such as artificial intelligence. The implication is a blurring of the distinction, long a hallmark of economics analysis, between physical capital and labor. This expanding set of scientifically and technically feasible arrangements may pose the deepest of questions and challenges to the concept of human nature. In this sense, this conception of technical change not only builds bridges between economics and science; it also summons connections between economics and the humanities, including the field of moral philosophy.

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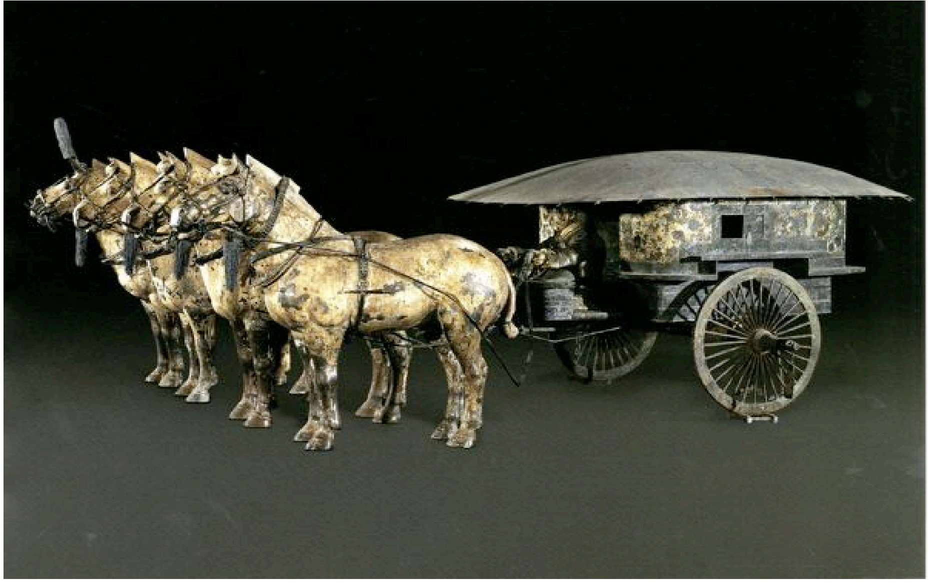
Figure 1. The Second Chariot: Its Elemental Composition



二号车主体材质成分分析结果

The result of the analysis on the composition of the materials of the major parts of bronze chariot and horses NO.II

名称	主要化学成分(%)			
	铅Pb	锡Sn	铜Cu	总含量
车轮牙	0.12	9.17	84.45	93.74
车辐	0.37	9.21	86.01	95.59
毂	0.54	8.32	83.77	92.63
盖弓	3.76	6.47	83.16	93.39
槫(tuán)	0.21	2.53	84.81	87.55
轼与輢的结合处浇铸流出物	2.81	8.60	81.20	92.61
轼缝中填充物	1.02	9.22	82.85	93.09

Table 1. The Results of the Analysis of the Composition of Materials of the Major Parts of Bronze Chariot and Horses No. II				
Part	Principal chemical elements (%)			
	Lead (Pb)	Tin (Sn)	Copper (Cu)	Total content
Wheel Rim	0.12	9.19	84.55	93.74
Wheel Spokes	0.37	9.21	86.01	95.59
Wheel Hub	0.54	8.32	83.77	92.63
Framing for the Hood	3.76	6.47	83.16	93.39
Truss	0.21	2.53	84.81	87.55
Casting between Fenders and Armrests	2.81	8.60	81.20	92.61
Filler for the Gaps in the Armrests	1.02	9.22	82.85	93.03

Table 2. Winners of The Scientist's Top 10 Innovations of 2018

1) Cyto-Mine (Sphere Fluidics) – This new single-cell technology allows researchers to screen up to 40 million cells for a desired property, such as specific antibody secretion, and to then dispense and image cells that fit the bill into microtiter plates.

2) Tapestri (Mission Bio) – Tapestri is a microfluidic platform for high-throughput, single-cell DNA sequencing sample prep that can handle up to 10,000 cells simultaneously.

3) Fluidity One (Fluidic Analytics) – This protein-analysis tool calculates the average size of proteins in a sample and also measures their concentration.

4) Chromium Immune Repertoire Profiling Solution (10X Genomics) – This technology allows researchers to distinguish each and every T and B cell in a sample, along with the genetic sequence of the Y-shape receptors on each cell.

5) Omnitrap (Fasmatech) – Omnitrap is a radio frequency ion trap that processes proteins of even high molecular weights—a limitation of older trapping technologies—to gain information on the molecules' sequences, structures, and molecular interactions.

6) Acouwash (AcouSort) – AcouWash can wash cells from one medium to another, enrich or concentrate cell samples, and separate cells based on size, all using ultrasound.

7) Dharmacon Edit-R Fluorescent Cas9 Nuclease mRNA (Horizon Discovery) – This mRNA codes for a nuclease that circumvents the problem of off-target cutting by lingering Cas9 nucleases during CRISPR-based genome editing.

8) MAD7 (Inscripta) – The sequence for this novel DNA-cutting enzyme is available online for all research and development uses.

9) Tycho (NanoTemper Technologies) – Tycho makes performing quality control of protein samples quick—a single run takes just three minutes—and informative, yielding data on protein–nucleic acid binding.

10) BD AbSeq Assay (BD) – This product allows researchers to simultaneously analyze RNA and protein levels in thousands of individual cells.

Source: http://virtual-strategy.com/2018/12/01/announcing-the-winners-of-the-scientists-top-10-innovations-of-2018/