The Importance of Education and Skill Development for Economic Growth in the Information Era

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ABSTRACT

The neoclassical growth accounting model used by the BLS accords a relatively small role to education as a source of recent U.S. growth. This result seems at variance with the revolution in information technology and the emergence of the Knowledge Economy, or with the increase in educational attainment and the growth in the wage premium for higher education. This paper revisits this result using activity-analysis, rather than the neoclassical aggregate production function, as the technology underlying economic growth. Each firm in the economy is viewed as a collection of constituent activities, each using inputs in a fixed proportion. The labor and capital used in a given activity are thus necessary inputs, with little substitutability among them, and the composition of the activities at any point in time is therefore a strong determinant of the demand for skills. Moreover, the changing demand for skills and education are determined by changes in the mix of activities at the firm level, the diversity of activities across firms in an industry, and the diversity of industries in the larger economy. It is then shown that the empirical sources-of-growth results reported by BLS could equally have been generated by the activity-analysis model. This allows the BLS results to be interpreted in a very different way, one that assigns a greater importance to labor skills and education. When intangible knowledge-based capital is added to the model and treated as a complementary input to skilled labor, the importance of education is greatly magnified.

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I. Introduction

The rapid advance of information technology and globalization has led to major structural changes in the U.S. economy. The extent of these changes is evident in the decline of manufacturing industry and the rise of selected service-producing sectors shown in Figures 1 and 2. The share of manufacturing in *private* GDP has been cut in half over the last half century, from 30% in 1960 to less than 15% in 2015, and the share of *private* employment has fallen from around 30% to 10%. Employment in services that involve "expert" advice, information, or interventions — finance, business and professional, education, health, law, and information services — rose from just under 20% of private employment to over 40%, and the share of value added rose from around 15% to 35%.[1] These shifting patterns reflect, in part, the outsourcing of production to lower-wage countries, labor-saving technical change, and the evolution of demand for different products.[2] The trends in business organizational services also shown in Figures 1 and 2 indicate a shift in employment within firms toward non-production activities, and reflect the growth of in-firm research and development, product design, and the emergence of sophisticated organizational management systems.

The change in the structure of employment and valued added occurred during a period that also saw a parallel increase in the higher-order cognitive and non-cognitive worker skills of the labor force, as well as a significant increase in educational attainment. Over the period from 1960 to 2015, the fraction of the U.S. population 25 years or older with at least a B.A. degree quadrupled (to 32%), and the fraction of those with at least a high school degree more than doubled (to almost 90%). These numbers represent a major shift in the structure of educational attainment in the population. Moreover, the connection between this structural change and the changes evident in Figures 1 and 2 is not entirely coincidental. Evidence

1 The statistics shown here are taken from the industry accounts of the Bureau of Economic Analysis. They are expressed as a share of the private economy because the focus of this paper is on innovation, education, and growth accounting in the business sector. The ratio of private to total value added was 87% in 2015, and the corresponding ratio for full and part time employees was 86%, so the sectoral estimates are somewhat smaller when expressed as a ratio of the totals. The time series shown in Figure 2 is pieced together from different parts of the industry Table 6.5 and is thus subject to some discrepancies.

2 Haskell et al. (2012) and Autor, Dorn, and Hanson (2013).

suggests that those service sectors where the employment increase was most pronounced -- expert and organizational services -- were also those where the high-skill, high-education professions are located.[3] The observed structural shifts are thus consistent with the growth of the Knowledge Economy.

It is one thing to regard skill development and education as important for the functioning and growth of this economy, but how important they are compared to other factors that influence the growth of GDP is a separate issue. Surprisingly, estimates from the Bureau of Labor Statistics Multifactor Productivity Program suggest that educational attainment may not be as important for economic growth as the recent focus on education and skills implies. The BLS data indicate that changes in the composition of the labor force, largely due to education, accounted for only a small fraction (7%) of the growth in labor productivity in the U.S. private business sector over the period 1995 to 2007 (the last year before the Great Recession). Robert Solow famously remarked in 1987 that "you can see the computer age everywhere but in the productivity statistics"; in the current context, you can see the revolution in educational attainment everywhere but in the productivity statistics.

Acemoglu and Autor (2012) and others have questioned how education can have played only a relatively small role in the growth of economy, given the knowledge-intensive nature of the Information Revolution. Indeed, there is a large literature on the importance of education as a source of economic growth and on the importance of skill-biased technical change. However, most of this analysis does not stray far from a production-function formulation of the problem and an emphasis on marginal productivities and factor substitutability.

The approach taken in this paper follows Nelson and Phelps (1966) and Acemoglu and Autor (2011, 2012) in its focus on the role of skills and education at the activity and task levels of the production process. However, the activity-analysis model in this paper regards the firm and its constituent activities, not the production function (skill-biased or otherwise), as the fundamental unit of analysis for studying the demand for different types of labor and capital. It thus avoids the aggregate production model function in any of its various forms. As in Nelson

3 The part of service sector designated "expert" in Figures 1 and 2 refers to those NAICS industries which are more intensive in workers with professions like medicine, law, business administration, education, or STEM occupations.

and Winter (1962), the firm is seen as an organization in which human agency determines the business model and a Schumpeterian evolutionary process determines its success. The business model specifies the kinds of goods to be produced, how they are designed and produced, where production takes place, and how they are marketed. Once the general outlines of the business model are determined, the execution of these decisions is broken down into various activities within the firm, including both the overhead and direct production functions. In the process, the choice of technique determines the nature of the inputs required, including the different types of capital and the appropriate labor skills. Substitution possibilities among the inputs are typically quite limited (accountants are not substitutes for neurosurgeons), and the demand for labor skills is thus largely a matter of the nature and scale of each individual activity. In this context, much of the observed change in the demand for skills comes from changes in the mix of outputs over the course of the Information Revolution, which reflects, in part, the high rate of product innovation during this period.

This micro way of looking at the process of production implies a much greater role for education than the neoclassical model. The skills necessary for each type of activity come embodied in people, often via their educational preparation. Education provides a pool of general cognitive and occupational expertise, and in come cases, specific vocational skills, from which firms can draw the workers they need. Put in more concrete terms, it is hard to imagine the economy of 2017 operating with a work force in which less than half the workers had a high school degree, as in 1960, and less than 10% had a college degree.

These points are developed in greater detail in the sections that follow. The Solow neoclassical growth accounting used by BLS is described in Section II, along with a critique of the theory underpinning its labor force composition adjustment in Section III. This is followed, in Section IV, by the activity-analysis framework proposed in this paper. The fixed-proportion nature of the framework is described and illustrated using several examples. This “necessary input” model is contrasted with the aggregate production function approach, with special attention to its implication for skills and education. It is shown that the empirical sources-of-growth estimates reported by BLS *could equally be generated by either model*. This result allows the same growth accounting estimates to be given different interpretations, and plays an important role is the subsequent argument that the activity-analysis interpretation assigns a greater importance to labor skills and education than the conventional approach. The three sections that follow Section IV are empirical, and examine the evidence on the trends in labor and capital to see if they are consistent with the predictions of the activity-analysis framework. Section V traces the growing importance of higher educational attainment, higher order cognitive and non-cognitive skills, and professional occupations and employment over the last half century. Section VI looks at the parallel development in the growth in Information and Communications Technology equipment (ICT) and intangible knowledge capital like R&D. Sources-of-growth estimates expanded to include intangible capital are presented in Section VII, and interpreted in light of the activity-analysis framework. A final section sums up.

II. The Neoclassical Growth Accounting Model

Many factors affect the growth of GDP, including labor and its skills but also capital formation and technical change. Any general assessment of the contribution of labor skills and education must therefore be framed in the context of all of the relevant factors. The main empirical framework that does this is the neoclassical growth accounting model developed in Solow (1957), extended by Jorgenson and Griliches (1967), and implemented as an official program by the BLS.

Neoclassical growth models share a common feature: they are rooted in the assumption of an aggregate production function relating aggregate outputs to the factor inputs of aggregate labor and capital, with a shift term that allows for changes in the productivity of the inputs: $Y_t = F(K_t, L_t, t)$. In describing the role of the shift term in the function, Solow states:

> "The variable *t* for time appears in *F* to allow for technical change. It will be seen that I am using the phrase 'technical change' as a short-hand expression for any kind of shift in the production function. Thus slowdowns, speed-ups, improvements in the education of the labor force, and all sorts of things will appear as "technical change." (p. 312)

In its most succinct form, the aggregate formulation combines various types of capital into a single total *K*, and different types of labor into a single *L*. Once formed, they are treated as substitutes, implying that the same amount of output can be produced by different combinations of capital and labor.

The basic sources-of-growth model is derived from an aggregate production function which is assumed to exhibit constant returns to scale in capital and labor, and Hicks'-neutral productivity change as reflected in a shift term A_t. Under the further assumption that capital and labor are paid the value of their marginal products, the resulting $Y_t = A_t F(K_t, L_t)$ can be differentiated with respect to time to give the sources of growth equation:

$$(1) \qquad \overset{.*}{y} = s_K \overset{.*}{k} + s_L \overset{.*}{\ell} + \overset{.*}{a} \;.$$

Dots over variables indicate rates of growth and time subscripts are dropped, here, for clarity. This formulation decomposes the growth rate of output into the growth rates of the inputs, weighted by their respective output elasticities (as proxied by income shares), and the growth in the productivity with which the inputs are used (total factor productivity, or TFP). The former is interpreted as a movement along the production function and the latter as a shift. Both processes are assumed to occur smoothly. All the elements of this equation except the last term can be measured using data on prices and quantities or assumptions about parameters like capital depreciation. This allows the productivity variable to be measured as a residual.

There is no specific provision for the contributions of education or skills in the basic formulation. This issue was addressed in the path-breaking paper by Jorgenson and Griliches (1967), who proposed a version of the production function that allowed for different types of labor, differentiated by worker characteristics like education, which have different wage rates and marginal products. The production function then becomes $Y = A\ F(K,L(H_1, \ldots ,H_N))$, where the H_i's are the hours worked in each of the N categories, total hours are $H = \Sigma_i\ H_i$, and $L(\bullet)$ is a function that aggregates the N groups into an index of total labor input. The growth rate of L is the share-weighted contribution of each groups' hours to total hours, where the s_{Hi} are each cohort's share of total *labor* income:

$$(2) \qquad \overset{*}{\ell} = \overset{*}{h} + \sum_{i=1}^{N} s_{Hi} (\overset{*}{h}_i - \overset{*}{h}) = \overset{*}{h} + q_{LC} \;.$$

The growth rate of labor input is thus the sum of the growth rate of total unweighted hours plus the labor composition effect, q_{LC}. The associated growth equation is then

(3) $$\overset{*}{y} = s_K \overset{*}{k} + s_L \overset{*}{h} + s_L \overset{*}{q}_{LC} + \overset{*}{a} .$$

The variable q_{LC} records the effect on output of a shift in worker hours among groups with different output elasticities (cum factor shares), and is positive when the composition of the labor force shifts toward higher productivity groups. In practice, multiple worker characteristics are included in the index.

It is this framework that produced the BLS estimates, cited in the introduction, that show q_{LC} accounted for only 7% of labor productivity growth in the private business sector over the period 1995 to 2007. The overall composition effect is dominated by the education effect, and the 7% estimate reflects the combined effect of the increase in the wage share of the educated (its weight in q_{LC}) and the growth rate of educational attainment as reflected in the *H's*. Estimates reported at the end of this paper also show an acceleration in the q_{LC} effect in the 1970s, and a slowdown in the late 1990s to an average of 7% for the period 1995-2007.

III. A Choice of Parables

The relatively small contribution of education in recent years seems inconsistent with the growth of the knowledge economy. Indeed, Hanushek and Woessmann (2015) begin their book on *The Knowledge Capital of Nations* with the statement that "knowledge is the key to economic growth" and go on to note the positive correlation between educational attainment and income per capita in a cross-sectional comparison of countries. Acemoglu and Autor (2012) have also expressed their reservations, as noted above. Since it is hard to imagine the complex technologies and capital of the Digital Revolution being operated with a work force equipped with only the most rudimentary cognitive skills and knowledge, it therefore seems appropriate to examine the sources-of-growth framework more closely to see what features of the model might lead to that result.

Solow himself recognized the simplification involved when he began his classic 1957 paper with "it takes something more than a 'willing suspension of disbelief' to talk seriously of the aggregate production function", and, in his 1987 Nobel Laureate Lecture, "I would be happy if you were to accept that [growth accounting results] point to a qualitative truth and give perhaps some guide to orders of magnitude" (Solow (1988), p. xxii). Writing in defense of the aggregate approach, Samuelson (1962) argues that it is a parable whose purpose is insight building.

Parables are neither inherently right or wrong, just more or less useful for illustrating some underlying truth. The growth accounting model has enjoyed great success for its insights into the general contours of economic growth. However, the aggregate model may be more successful in describing overall economic growth than in characterizing structural economic change and the implied role of education. The problem is that some of the assumptions underlying the neoclassical model require a particularly large suspension of disbelief. The first is the one-sector nature of the aggregate production function, $Y_t = F(K_t(\bullet),L_t(\bullet),t)$. The single product, Y_t, is a macroeconomic surrogate for the many products actually produced, and the aggregate production is a methodological parable for summarizing the complex processes that contribute to their production. This formulation is a useful, indeed, essential, part of the conceptual framework that underpins the aggregate circular-flow of products and payments that characterize the macro economy. However, its usefulness is questionable for addressing questions concerning changes in the structure of the economy - in the composition of Y_t - and the corresponding changes in the allocation of resources that are evident in Figure 2.

A more general representation of the structure of production is needed in order to deal with these structural issues. A step in this direction can be made by formulating the production problem in terms of the production possibility frontier, $\phi[(Y_{1,t}, \ldots , Y_{,.t}) ; K_t(\bullet),L_t(\bullet),t]]$. In this formulation, the collection of outputs at any point in time, $(Y_{1,t}, \ldots , Y_{m,t})$, is produced by aggregate capital, $K_t(\bullet)$, whose components are categories of capital identified by type *and* industry of use, and aggregate labor, $L_t(\bullet)$, whose components are categories of labor identified by their characteristics (including education) *and* industry of use. The technology shifter *t* is included to allow for increases in the efficiency with which labor and capital are used, although individual efficiency parameters $A_{i.t}$ might be used instead (or the factor augmentation equivalents). Underlying the PPF are separate *industry* production functions for each sectoral output, $Y_{i.t} = F^i(K_{i.t}(\bullet),L_{i.t}(\bullet),t)$.[4]

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[4] The assumptions required to move from the individual sectoral production functions, $Y_{i,t} = Fi(K_{i,t}(\bullet),L_{i,t}(\bullet),t)$, to an exact form of the aggregate production function, $Y_t = F(K_t(\bullet),L_t(\bullet),t)$, are restrictive. Moving from the functional form of the individual technologies to an exact functional form for the PPF is also hard.

The multiproduct way of looking at the structure of production has an important implication for studying the importance of skills and education: a movement along the production possibility frontier not only changes the composition of output, it shifts the composition of the inputs required to produce the output. With these shifts come changes in the required composition of labor skills. This means that a change in the mix of skills may occur without technical change, as for example, when the movement along ϕ is caused by changes in the structure of consumer preferences (or changes brought about by a shift in the pattern of global trade, or by non-unitary income elasticities). Indeed, aggregate output along the PPF may be unchanged.[5]

Then there is the question of technical change. This is represented in the conventional aggregate formulation as a shift in the production function holding inputs constant (or, a similar shift in the PPF). This convention implicitly views all technical change in terms of increases in the productivity of the input base, or "process innovation". This kind of innovation has made important contributions to economic growth during the course of the Information Revolution, but it is not the only kind of technical change, nor necessarily the most important. Innovation in new or improved products has also played a central role in the revolution.[6]

Product innovation changes the mix of outputs $(Y_{1.t},...,Y_{m.t})$ over time. Improved goods appear and ultimately displace their older counterparts, others drop out because of a lack of demand, while new goods enter the market. In the process, a new vector appears, $(Y_{1,t+1t},...,Y_{m+k,t+1})$, with a product list expanded by k to allow for new items. The list of individual product functions is expanded accordingly, but with $Y_{i.t+1} = 0$ for displaced goods. The individual production functions for the new or improved goods may have a different set of

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[5] The sources-of growth equation (1) is, formally, a Divisia Index (Hulten (1973)). A movement along the PPF frontier ϕ from one point to another involves line integration that does not change the value of the output index (the invariance property).

[6] Data from the National Science Foundation's Business R&D and Innovation Survey (BRDIS) suggest that process-oriented business R&D is a small share of the total, accounting for only 15% of the $224 billion in domestic R&D paid for by companies (Wolfe (2012)). The rest is for product development, though some of the new products are inputs to the production process (capital-embodied technical change, for example, or improved materials). The fraction of R&D devoted primarily to new consumer goods is not reported.

skill requirements than those they displace. Evidence suggests that this was, indeed, the case during the Information Revolution, during which the growth in digital-economy goods has led to increases in the demand for more cognitively complex skills sets. However, it is important to note that, while the technology for producing the new goods became more complex and required more complex skills, the main impetus behind the increased demand for these skills was product innovation and not skill-biased process innovation.

Incorporating product innovation into the framework of the aggregate production function requires additional suspension of disbelief. The "trick" is to regard an improved good as though it were more of the older model it supplants. This procedure has a very long and complicated history, but in essence it views goods in terms of their characteristics. When a superior good arrives in the market place with more of a given characteristic, the improvement is deemed to be equivalent to more of the old good and measured using techniques like price hedonics. The production function then becomes $Y^e_t = F(K_t(\bullet),L_t(\bullet),t)$, where Y^e_t is output expressed in "quality-adjusted" units. One implication of this formulation is that product innovation becomes mischaracterized as process innovation (i.e., as a shift in the production function via the term *t*). Moreover, this approach assumes that a quality adjustment is actually made in Y^e_t, but this appears not to be the case for many (perhaps most) goods, nor are the benefits of wholly new goods recorded in Y^e_t (Hulten (2015)). This leads to the following problem: when output growth is understated due to a failure to adequately measure product innovation, the TFP residual is also understated and, what is more important for this paper, so possibly is q_{LC}.

Two further suspensions of disbelief are also needed. The first involves the assumption the capital and labor are paid the values of their marginal products, thus allowing income shares to be used as a proxy for the underlying output elasticities in sources-of-growth formulation. This is a very strong assumption, mainly defensible as a macroeconomic approximation. Prices may well deviate from marginal products due to monopolistic pricing, labor market rigidities, discrimination, and cyclical fluctuations in economic activity. Moreover, the marginal social return to education may exceed the marginal private return implied by markets wages because of externalities of the type noted by Lucas (1988), a point elaborated in a subsequent section.

Second, the existence of separate aggregate labor and capital entities, *L(•)* and *K(•)*, and of a unique q_{LC}, requires the weak separability of the aggregate production function. This, in turn, requires the marginal rate of substitution between one type of labor and another to be independent of the amount and composition of aggregate capital (Hulten (1973)). This is a mathematical proposition, but in economic terms, it means that if a worker in a lower education category acquires a higher degree in pursuit of a wage premium, output will increase without any change in capital or technology. This is problematic because those workers with higher educational attainment often do, indeed, usually, end up in jobs or occupations with more complex technological requirements and capital. Simply educating more people will not, all else held equal, necessarily result in a significant increase in output, a point that will be elaborated in the activity-analysis model developed in the section that follows.

However, before proceeding to this model, it is important to stress again that the criticisms set out above should not be interpreted as a rejection of the aggregate neoclassical approach or the labor composition adjustment. All models are based on limiting assumptions. The q_{LC} effect is part of an immensely valuable model that is the mainstay empirical growth analysis, and integrates the role of education in growth into the context of the larger aggregate model and its assumptions. However, the critique of this section suggests that it may not capture the full effects of education buried in the underlying complexity of "reality". Indeed, Samuelson (1962) "insisted" that

> "capital theory can be rigorously developed without using any Clark-like concept of aggregate 'capital', instead relying upon a complete analysis of a great variety of heterogeneous physical capital goods and processes through time. Such an analysis leans heavily on the tools of modern linear and more general programming and might therefore be called neo-neo-classical. It takes the view that if we are to understand the trends in how incomes are distributed among different kinds of labor and different kinds of property owners, both in the aggregate and in the detailed composition, then studies of changing technologies, human and natural resources availabilities, taste patterns, and all the other matters of microeconomics are likely to be very important" (p. 193).

This is essentially the view taken in this paper. But, he goes on to say:

> "At the same time in various places I have subjected to detailed exposition certain simplified models involving only a few factors of production. Because of a Gresham's Law that operates in economics, one's easier expositions get more readers than one's harder. And it is partly for this reason that such simple models or parables do, I think, have considerable heuristic value in giving insights into the fundamentals of interest theory in all its complexities" (p. 193),

The tension between the two perspectives over the appropriate level of analysis is central to the objections against the neoclassical production function and the concept of aggregate capital raised during the Cambridge Controversies of the 1950s and 1960s (Harcourt (1969)).[7]

Given these questions and those that have been raised about the size of q_{LC}, it seems reasonable to take a deeper look into the micro foundations of the aggregate production framework, essentially disaggregating it to get at its "primitive" activity-analysis level. When approached at this foundational level, many of the issues raised in this section can be addressed, particularly those involving multiple outputs and the way labor-skills interact with capital to make educational attainment necessary for many activities.

IV. The Activity-Analysis Approach to Production

A. The Model

The neoclassical model offers a succinct and mathematically viable way of summarizing the supply-side of the economy in a way that links to the demand-side flows of product and factor quantities and payments. Activity analysis, on the other hand, is neither succinct nor mathematically convenient, but it does provide a more detailed look into the underlying processes of growth and the shifting demands for the various skills and types of capital required by different production techniques.[8] It treats the firm and its various activities, not the

[7] The objection to the neoclassical emphasis on the aggregate production function is by no means limited to the Cambridge Controversies. Opposition to the neoclassical view of economic growth as a functional transformation of capital, labor, and technology into output has a long history in the literature on organizational theory, the importance of institutions in economic history, and in Schumpeterian analysis. Nelson and Winter (1962) provide an in-depth analysis of the evolutionary nature of the process of economic growth that focuses on the firm and its activities, and the skills and competence of its workers. The activity analysis model sketched in this paper is rooted in this view of the firm.

[8] The model by Ronald Jones (1965) is an exception. It presents a general equilibrium solution to a two output, two input allocation problem in terms of an activity matrix. It then extends the solution to the growth context. On

aggregate production function, as the fundamental unit of analysis for studying the shifting demand for different types of labor and capital.

A firm's overall "technology" is defined by the various activities it operates at any point in time. Many activities are intermediate steps in the production of final output, some are sequential while others are complementary, and still others involve overhead activities like management and R&D. The mix of activities reflects the state of the available technology, the organizational business model, relative prices, the scale of operation, and expectations about the future. They interact in complex ways, so there is, in general, no exact way of aggregating these activities to form a smooth functional relationship between total input and total final output. Moreover, there is usually only limited substitutability among the various types of capital and labor within activities, which tend to be activity specific.

The following example illustrates the issues involved. A given amount of earth can be moved using a few skilled operators equipped with expensive bulldozers, or by many manual workers each equipped with cheap shovels. In the neoclassical framework, bulldozers and shovels are treated as "malleable" and thus represent different quantities of aggregate capital. In the aggregate representation of these different techniques, the technology for earth-moving would have a form like $Y=AF(K_H,K_L,H_S,H_U)$, or the factor augmentation equivalent (the capital subscripts denote "higher technology bulldozers" and "lower technology shovels", and "skilled" and "unskilled" for the labor subscripts). In order to speak of aggregate capital, *K*, and labor, *L*, this production function must have the previously noted separable form, which in this case is $Y=A\ F(K(K_H\ ,K_L),L(H_S\ ,H_U))$. The different types of labor are substitutable among each other within the labor aggregate $L(\bullet)$, as are the different types of capital within $K(\bullet)$; the aggregates themselves are substitutable along an isoquant connecting *K* and *L*. The isoquant *QQ* shown in Figure 3A allows for this substitution, which occurs as the movement along the isoquant from *A* to *B* as relative factor prices change from *aa* to *bb*. The broken L-shaped lines represent two techniques for producing the same amount of output, *Y*, and illustrate the putty-putty model of

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the other hand, it involves only the four activity parameters of a two sector economy and does not allow for the complex interaction among activities at the level of the individual firm.

neoclassical analysis in which the isoquant is the envelope of the various activities.[9] In this case, activity analysis is consistent with the aggregate production function as long as "capital" is treated as a homogeneous malleable entity that represents forgone consumption valued at investment cost. While this is a useful macroeconomic way of looking at capital -- Samuelson's parable -- it glosses over the technical differences between shovels and bulldozers and the skill differences between the workers. It is therefore not a helpful way of studying the way that the choice of technique affects the demand for skilled labor.

Figure 3B illustrates the clay-clay version of activity analysis in which different types of capital work with the requisite labor and skills and cannot be substituted across or within an activity. This implies that the separate inputs should not be combined using the $K(K_H, K_L)$ and $L(H_S, H_U)$ parings of the aggregate production function approach, but instead by the functional pairings $a(K_L, H_U)$ and $b(K_H, H_S)$. The clay-clay approach is shown in Figure 3B by the broken L-shaped lines representing the two techniques for producing the same amount of output, Y.[10] The isoquant of Figure 3A is absent from this formulation because skilled workers do not play a role in the technique $a(K_L,H_U)$, nor unskilled workers in the technique $b(K_H, H_S)$.

An important implication for this paper is that a shift in techniques from $a(K_L, H_U)$ to $b(K_H, H_S)$ cannot occur without a shift from unskilled to skilled workers and from less to more technologically sophisticated capital. In this particular case, a deficiency of skilled workers will slow or prevent the adoption of the $b(K_H, H_S)$ technology. It is also possible, in a more sophisticated rendering of the model, that a deficiency of workers with a particular skill set could induce innovation designed to compensate for the deficiency (the Habakkuk thesis), but the larger point is that in order for a firm to actually operate the activity $b(K_H, H_S)$, access to both K_H and H_S in the right proportions is necessary.

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[9] There is a putty-clay variant in the model which applies when investments are irreversible in the short run and capital can only be changed as it depreciates.

[10] Another difference between Figures 3A and 3B should also be noted: while both techniques produce the same kind of output, the inputs on the axes refer to different types of capital and labor. Thus, the factor price lines *aa* and *bb* refer to different input prices. Moreover, the strict complementarity of the techniques implies that the ratios of the marginal products of the different types of capital and labor are not unique.

Figure 3C adds yet another complication. The activities in the first two figures represent different techniques for producing the same type of output. This is not a good assumption to apply to all activities in an era with a high rate of product innovation because switching from one quality, or model, of output to another often involves a switch in the way the goods are produced and in the inputs required. For example, in summarizing their study of new IT-enhanced machinery, Bartel, Ichniowski, and Shaw (2007) make the following points:

> "First, plants that adopt new IT-enhanced equipment also shift their business strategies by producing more customized valve products. Second, new IT investments improve the efficiency of all stages of the production process by reducing setup times, run times, and inspection times. The reductions in setup times are theoretically important because they make it less costly to switch production from one product to another and support the change in business strategy to more customized production. Third, adoption of new IT-enhanced capital equipment coincides with increases in the skill requirements of machine operators, notably technical and problem-solving skills, and with the adoption of new human resource practices to support these skills."

The ability to customize output to suit the needs of the buyer represents an important change in product quality, and is linked, in this case, to increased skill requirements. The advent of the automatic teller machine, a labor saving device from the standpoint of production, is another example of how the quality of a product was also improved, in this case by making money accessible at all times of day or night. These examples are illustrated in Figure 3C by activity-specific output indexes.

B. Aggregation and Dynamics

The activities as portrayed in Figures 3A, 3B, and 3C illustrate the logic of the activity-analysis model. From an operational standpoint, they (and others like them) are generally combined with other activities to form a larger set that constitute the production plan of a firm. In formal terms, the technology of a firm *j* can be characterized at any point in time by the activity set $\mathcal{A}_{j,t}$, whose elements are the totality of activities it operates $\{a_{i,j,t}(K_{i,j,t}, H_{i,j,t}, M_{i,j,t})\}$. An output or outcome is associated with each activity, although much of the output is delivered to other activities within the firm (e.g., overhead and different stages of production along an assembly line). The vector $M_{i,j,t}$ is added to allow for the presence of intermediate goods produced and used within the firm, but also the intermediate inputs acquired externally. The set

$\{a_{i,j,t}(K_{i,j,t},H_{i,j,t},M_{i,j,t})\}$ is thus a disaggregated representation of the firm's technology, but it is not, strictly speaking, a neoclassical production function relating total output to aggregated inputs, though Samuelson might call it "neo-neo-classical".[11]

The firm is the organizational entity responsible for choosing the appropriate mix and level of activities for $\mathcal{A}_{j,t}$ from a larger set of possible techniques. Selecting the right mix and level of activities is an essential organizational function of the firm, and once the selection has been made, the capital requirements of the firm $\{K_{i,j,t}\}$ and staffing needs $\{H_{i,j,t}\}$ are determined. Prescott and Visscher (1980) point to the acquisition and proper use of human capital as centrally important for the success of an organization, and Bloom and Van Reenen (2007) have pointed to the importance of good managers and management practices. The role of human agency can sometimes get lost in the formal mathematical presentation of the various models.

Firms can be grouped into industries for purposes of analysis, though again, there are aggregation issues. Indeed, many are similar to those encountered when aggregating the internally generated "output" of activities within firms, but with the additional complication posed by different ways of classifying industries (the company versus establishment problem). However, these difficulties are not germane to the main interests of this paper, so we simply group firm-level activities into industry-level activities (however industry is defined), and then into an aggregate economy-wide activity set $\mathcal{A}_t$ whose elements include the totality of all activities, $\{a_{i,t}(K_{i,t},H_{i,t},M_{i,t})\}$. The significance of this formulation for the problem at hand is that, at any point in time, the total capital requirements $\{K_{i,t}\}$ and staffing needs $\{H_{i,t}\}$ of the *economy* are determined by the choice of activities at the firm level, the diversity of activities across firms in an industry, and the diversity of industries in the larger economy.

The mix of activities and skills can and does change over time, as witnessed by the structural changes in the economy evident in Figures 1 and 2. This structural change is the visible result of the shifting composition of the aggregate activity set $\mathcal{A}_t$ occurring in response to the revolution in information and communication technology and the globalization of the world

[11] As previously noted, the conditions for exact functional aggregation are extremely stringent. The analytics of the aggregation of multiple outputs in the presence of intermediate goods can be found in Hulten (1978). And, other aspects of the aggregation problem make exact aggregation even more difficult (e.g., the separability also noted previously).

economy. New or improved products have made older goods obsolete, new processes and activities within firms have replaced older techniques, and new forms of product distribution have displaced older outlets. New firms and industries have appeared in this process of Schumpeterian creative destruction, while older industries declined and firms exited their industry or reinvented themselves. The changes occurring in $\mathcal{A}_t$ have also changed the demands for labor and capital. This has meant a larger demand for those higher-order skills, occupations, and education that have been made necessary by the Information Revolution. One of the major implications of activity analysis framework, as it is set out above, is that *the observed structural changes could not have occurred without the parallel development of the appropriate skills*. In other words, the "necessary input" way of looking at structural change implies that education is an organic part of the dynamic evolution of the changing economy.

Education also contributes to this evolution in another way. Much of the underlying innovation originates within firms through activities like R&D, product design, and strategic planning. Much of the innovation that drives the dynamics of firms and the economy comes in the form of product innovation. These activities are education-intensive (Nelson and Phelps (1966)), and some of the innovation may come in response to chronic deficits in some skill areas (e.g., process automation). And, even when innovation does not originate in the firm, it is implemented and sustained by the efforts of its management. The activities, and the people that operate them, endogenize the innovation process (as in Romer (1986, 1990)), and, in turn, create a demand for the skills and occupations of the Digital Economy.

However, it is also important to stress (once more) that education by itself is not sufficient for creating more output growth. Moreover, it should also be noted that, while technical change and globalization have shifted the structure of activities toward those that require more complex skills, there are still activities that do not require higher levels of educational attainment. The activity-analysis framework focuses on the necessity of the *appropriate* skills for the activity at hand, and this applies to the full range of activities in operation at any point in time, not just to those involving more complex labor skills.

C. Activities and the Measurement of GDP

An output is associated with each activity in a firm's activity set, $\mathcal{A}_{j,t}$, even though some are shadow outputs delivered to other activities within the firm. The value of the output sold externally (intermediate and other) can be measured using market transaction prices and the resulting revenue divided between deliveries to final demand and deliveries to intermediate demand. This yields the accounting equation $P_{i,t}Q_{i,t} = P_{i,t}\, Q^D_{i,t} + \Sigma_j\, P_{i,t}\, Q^M_{i,j,t}$, where $Q^M_{i,j,t}$ is the delivery of the intermediate good from activity *i* to the other activities, and $Q^D_{i,t}$ is the external output delivered to final demand (for a one product firm). GDP is then defined as the summation across deliveries to final demand, giving $GDP_t = \Sigma_i\, P_{i,t}\, Q^D_{i,t}$.

On the input side, the cost of the inputs acquired externally -- labor, capital, and intermediate inputs – can be summed to arrive at total cost, and this can be divided into the value added of labor and capital, on the one hand, and the cost of acquiring intermediate inputs on the other: $C_{i,t} = P^K_{i,t}K_{i,t} + P^L_{i,t}\, L_{i,t} + \Sigma_j\, P_{j,t}\, Q^M_{i,j,t}$. Gross Domestic Income is then the sum of the value added components, yielding : $GDI_t = \Sigma_i\, P^K_{i,t}\, K_{i,t} + \Sigma_i\, P^L_{i,t}\, L_{i,t}$. These accounting identities are more complicated when there are multiple firm outputs. However, the simplified framework suffices to illustrate the accounting principle that the value of aggregate output equals the value of aggregate factor income in each year, or, GDP_t equals GDI_t.

Of what significance is this accounting result for the issues of importance to this paper? It can be used to show that the growth accounting results of BLS *do not depend on the existence of Solow's aggregate neoclassical production function*. The sources-of-growth decomposition in equation (1) can be derived directly from the accounting identities of the preceding paragraph equating GDP and GDI, but only when each side of this equation is expressed in "real" inflation-corrected terms (that is, when nominal prices are replaced with a base-year price index). When this is done, $GDP_{0,t} = \Sigma_i\, P_{i,0}\, Q^D_{i,t}$ and $GDI_{0,t} = \Sigma_i\, P^K_{i,0}\, K_{i,t} + \Sigma_i\, P^L_{i,0}\, L_{i,t}$. where , $GDP_{0,t}$ and $GDI_{0,t}$ are real GDP and real GDI in year *t* expressed in base-year price. Since the base-year final demand output price indexes, $P^D_{i,0}$, and base-year factor prices, $P^K_{i,0}$ and $P^L_{i,0}$, may have different time trends, real $GDP_{0,t}$ does not in general equal real $GDI_{0,t}$, except in the base year. In other years, there is a wedge between the two that equals a version of TFP (Hulten (2001)). This, indeed, was the way growth accounting was formulated prior to Solow's 1957 paper. What Solow did in his 1957 paper was to provide an interpretation of the growth accounting estimates by assuming the existence of an aggregate production function, $Y = AF(K,L)$ linking aggregate real output Y (as distinct from gross output Q) to indexes of aggregate capital K and labor L derived from the "real" $\Sigma_i P^K_{i,0} K_{i,t}$ and $\Sigma_i P^L_{i,0} L_{i,t}$ via TFP.[12] However, while the Solow formulation provides an ingenious and succinct parable that helps interpret the messy world of the full activity set, $\mathcal{A}_t$, this ingenuity comes at the cost of losing sight of the messy way activities are organized and the way different inputs and their characteristics actually relate to one another.

The larger point is that the neoclassical production function approach is not necessary for the BLS growth accounting results to be obtained, and it is not the only way the results can be interpreted, particularly those relating to the role of skills and education.

V. Structural Changes in Education, Skills, and Occupations

The preceding sections are largely technical in nature. The three sections that follow are empirical, and examine the evidence on the trends in labor and capital to see if they are consistent with the predictions of the activity-analysis framework. The third of these sections shows the results of a version of the sources-of-growth account expanded to include intangible capital, and interprets the role of skills and education in light of the "necessary input" activity-analysis model.

A. Educational Attainment

A look back over the last half century reveals major changes in the educational status of the U.S. population and work force. In 1960, only 40% of the non-institutionalized population 25 or older had a high school degree or more, and only 8% had college degree, according to CPS estimates; by 1985, these figures rose to 74% and 19%; and by 2013, almost 90% of this

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[12] In its most general formulation, TFP is defined as the ratio of output per unit of total factor input, or equally, the ratio of real GDP to real GDI.: $A_t = GDP_{0,t}/GDI_{0,t} = \Sigma_i P_{i,0} Q^D_{i,t} /[\Sigma_i P^K_{i,0} K_{i,t} + \Sigma_i P^L_{i,0} L_{i,t}]$. The Solow paper interprets this ratio in terms of the aggregate production function $Y_t = A_t F(K_t, L_t)$, in which case $A_t = Y_t / F(K_t, L_t)$. He also showed that the number approach implied by this formulation is, in continuous time, the growth rates of the Divisia indexes of inputs and output. Under the assumption of constant returns to scale, Solow's formulation of TFP is a special case of the more general formulation (see, again, the survey of Hulten (2001)). As an aside, the price dual to the aggregate production function, $P^Y_t = A_t^{-1} \phi(P^K_t, P^L_t)$, establishes the links between the prices of the inputs and output. By implication, the output price index, P^Y_t, cannot be used to deflate nominal GDI in estimating real GDI.

population had at least a high school degree, and more than 30% had at least a bachelor's degree. Similar numbers are reported in Valletta (2016) on an employment basis. From 1980 to 2015, the portion of the employed with a high school degree or more went from 80% to 90%; those with a four-year college degree went from 16% to 25%; and those with a graduate degree went from 7% to 14%. In any case, there has been a significant and on-going increase in educational attainment over the last three to five decades. Valletta also reports that the increase may have slowed in recent years.[13]

Many have noted that the growth in educational attainment coincides with a growth in the return to a college education. The estimates of Goldin and Katz (2010) show that the college wage premium relative to a high school degree increased from 40% in 1960 to almost 60% in 2005, and attribute this growth to an imbalance in the demand for educated workers and the supply.[14] Valletta's estimates of wage-premia are, again, consistent with the Goldin-Katz results, and they also point to a very large premium for graduate degrees (particularly professional and doctorate degrees). A rising wage-premia is also consistent with an increase in the derived demand for more highly educated workers in conjunction with a lagged response in the supply of college-educated people. Limited substitution possibilities between skilled and under-skilled workers in many of the emerging activities seen in Figures 1 and 2 were a likely contributing factor.

B. Task-Related Skills and Education

Structural changes in the distribution of task-related skills have received a great deal of attention in recent years, following the seminal contribution of Autor, Levy, and Murnane

[13] While the quantity of education, as measured by the growth in degrees, has increased, there is an open question about the quality. The NAEP report card suggests that the literacy and numeracy skills of U.S. 12th graders has been stagnant in recent years, and that a majority of students are stuck at skill levels that are rated below proficient, with one-quarter of students below "basic" in reading and one-third below "basic" in mathematics. American students also lag those in many other countries. The 2013 Programme of International Assessment of Adult Competencies (PIAAC) found that the U.S. ranked 16th of 23 countries in adult literacy, 21st of 23 countries in numeracy, and 14th of 23 in problem solving.

[14] The Goldin-Katz college wage premium reflects an average across those with college degrees. This should not be confused with the marginal return to further education. Heckman et al. (2016) find that ability is a major component of observed educational outcome differentials and argue that going to college is not necessarily a wise choice for everyone.

(2003). The authors distinguish between non-routine and routine skills, and manual versus analytical skills, and show that the non-routine analytical skills have grown in importance in the last five decades at the expense of the others. An updated version of these results, from Autor and Price (2013), found that the gap between non-routine cognitive and interpersonal skills and the other categories (routine and manual) increased from an index of 100 in 1960 to around 150 in 2010. In studying the college and graduate school wage premia associated with these different skill categories, Valletta finds a growing premium for all skills, with the largest premia for non-runtime cognitive skills. The premia have increased overtime, but have slowed in recent years.

There is an intuitive similarity between the patterns observed for higher education and higher-order skills, but the actual situation is more nuanced. Skill levels and education are not identical, a point often made in the literature.[15] Skills are appropriately defined as adeptness with respect to a specific task (complex or not), while education is a process though which information is transferred and capabilities developed. Moreover, it is widely recognized that education is only one of the channels through which skills are developed, and that other factors like family background and peer environment, and idiosyncratic factors like health and cognitive ability, also matter.

Data from the recent BLS Occupational Requirements Survey (ORS) support this view. The ORS develops a metric “Specific Vocational Preparation” (or SVP) that measures the time spent in skill development, which is described as the time spent in pre-employment training (formal education and certification and training programs), prior work experience in related jobs, and the time needed in the job itself to get to average performance (Gittleman, Monaco, and Nestoriak (2016)). When these three types of preparation are cross-classified with the actual time requirements, the authors report that post-employment training (37%) and prior work experience (39%) are the most important components of SVP, with formal education in

[15] Cappelli (2014) observes that, “The standard classification of job requirements into ‘knowledge, skills, and abilities’ reminds us that education, which has served as a proxy for skills in most discussions, only maps onto part of the “knowledge” category, leaving the other attributes of job requirements out of the picture. There are many important reasons for being concerned about education, but seeing it as the equivalent of skill is certainly a mistake (p. 51).”

third place. However, for those jobs requiring the highest levels of skills, formal education is in second place (29%) and behind prior work experience (62%).

This study presents another important finding: those jobs requiring a B.A. degree or more account for less than 25% of all jobs (or less than 30% using the O*NET educational classification). It is interesting to note, in this regard, that only some 30 percent of the adult population has one of these degrees. Gittleman et al. also report that only 15 percent of jobs were classified in the most complex category. This serves as an important reminder against an excessive focus on higher education and complex skills. One message of the activity-analysis model is that a broad range of skills are needed for economic activity.

Indeed, this evidence seems to downplay the importance of a college education. However, the ORS study also finds that higher educational attainment is positively correlated with the complexity of skills and choice of professional occupation. This comes from the part of the study that looks at three mental and cognitive dimensions of job requirements: "task complexity", "work control", and "regular contacts". The first is broken into categories ranging from very complex tasks to very simple; the second into categories ranging from very loose to very close control; the third ranges from structured and very structured regular contacts to very unstructured. One of the most interesting features of this analysis is the high correlation among the higher skill segments of "task complexity", "work control", "regular contacts" dimensions, as well as the higher skill components of educational attainment, SVP, and choice of occupation. For example, the *Management, Business, Financial"* occupational category leads the others in task complexity, looseness of work control, and very unstructured interactions. It also has the highest education attainment and longest SVP. The opposite is largely true of *service, sales and related*, and *production* jobs. The fit is not perfect, but a high degree of collinearity does suggest that certain regularities exist that characterize different jobs. Thus, while education is but one of several channels through which skills and expertise are developed, the collinearity implies a correlation between higher education and higher-order skill sets. The ORS also reports data on the wage-skill gradient similar to those found by Goldin and Katz, and by Valletta: those in jobs with the highest task complex skills, the loosest degree of work control, and the least structured interactions all earn significantly higher wages that those at the other end of these scales.[16]

C. Occupations

The occupational status of workers has been implicit in much of the discussion above, and where it is explicit, it is not the central focus. It is generally understood, however, that the occupational dimension is important in its own right because skill sets and general expertise are embodied in people and acquired by hiring or contracting. While this embodiment occurs in several ways (the ORS, for example, assigns greater importance to on-the-job training and work experience), formal education generally precedes the others and provides the general skills of literacy and numeracy which allow higher-order cognitive skills to be developed. It also supplies the high-order cognitive occupational skills needed in professions like engineering, business, law, and medicine. The magnitude of the shifts in employment shares seen in Figure 2 shows that this supply is not a trivial matter, given the growth in those sectors (expert services, business and professional services) that are most heavily populated with professional occupations.[17]

The magnitude of the occupational changes occurring in the labor market are driven home in the 2006 paper by Wyatt and Hecker, who track the occupational shifts occurring over the course of the 20th Century. They estimate that the "professional, managerial, clerical, sales, and service worker" occupational categories increased from one-quarter to three-quarters of total employment between 1910 and 2000; and that over the shorter period between 1960

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16 Much attention has been given to the importance of cognitive skills. However, recent research has also focused on the demand for non-cognitive skills, which include characteristics like self-discipline, perseverance, attentiveness, dependability, orderliness, persistence in the pursuit of long-term goals, and the ability to get along with others. Non-routine interpersonal skills were found by Autor and Price to have grown in importance relative to non-routine cognitive skills. Deming (2015) also shows that the labor market increasingly rewards social skills, and that jobs with high social skill requirements have shown greater relative growth throughout the wage distribution since 1980. He also observes that the strongest employment and wage growth has occurred in jobs that require both high levels of hard cognitive skills and soft social skills. The importance of non-cognitive skills is also emphasized in Lundberg (2016), Heckman and Kautz (2012), and Kautz et al. (2014).

17 See, also, the BLS (2014) O*ccupational Employment Statistics* survey, Acemoglu and Autor (2011). Moreover, the OECD PIACC survey estimates that occupations with the highest average literacy skill scores increased by around 20% between 1998 and 2009, occupations with highly educated professional workers increased by 9% between 1998 and 2009, while occupations with less-educated workers fell by 12%.

and 2000, the category "professional, technical, and kindred workers" grew from around 10% of total employment to almost one-quarter. These categories include the highly educated and compensated professions in the various studies cited in this section.[18]

D. Science, Technology, Engineering, and Mathematics

Developments in science and technology are at the heart of the Information Revolution and any discussion of occupations and skills should therefore include a STEM component. This is all the more important because STEM activities evoke highly educated workers in research labs and computer facilities working on complex problems. However, the 2013 study by Rothwell argues that there are actually two STEM economies. One is a "professional" STEM economy associated with higher education and high levels of compensation, which "plays a vital function in keeping American businesses on the cutting edge of technological development and deployment. Its workers are generally compensated extremely well". The other STEM economy "draws from high schools, workshops, vocational schools, and community colleges", and its members are "less likely to be directly involved in invention, but they are critical to the implementation of new ideas, and advise researchers on the feasibility of design options, cost estimates, and other practical aspects of technological development". They "produce, install, and repair the products and production machines patented by professional researchers, allowing firms to reach their markets, reduce product defects, create process innovations, and enhance productivity".

Hanson and Slaughter (2016) find that employment in the STEM professions has grown from around 3.5% of the total hours worked in the U.S. in 1993 to around 6% in 2013. In the broader view of STEM employment, Rothwell finds that 20% percent of all 2012 jobs required a "high level of knowledge in any one STEM field" based on his index of the STEM skill content of various occupations. This does not, however, imply that higher education is necessary. While the STEM professions are associated with high levels of education, Rothwell finds that half of

[18] It is important to recognize in any discussion of shifting occupational categories that the nature of occupations has changed over time in response to changes in the underlying economy and technology, and that any time series, particularly one spanning many decades, must be taken as suggestive rather than precise.

the STEM jobs are “available to workers without a four-year college degree”. He also estimates that the percent of the work force in those jobs requiring STEM skills increased from around 8% in 1900, to around 15% in 1950, to some 20% in 1980, where it has stayed since then.

The domestic supply of new professionals to the first STEM “economy” has expanded in recent years. NCES data on STEM degrees completed show an expansion from 1990 to 2011 in B.A.s (39% for engineering, a doubling for science/math), in M.A.s (90% for engineering, 87% science/math), and in Ph.D.s (76% for engineering, 60% science/math)). This domestic growth in STEM skills has not, however, been sufficient to satisfy the demand for STEM workers. Hanson and Slaughter report that foreign-born workers currently account for one-half of the hours worked in STEM occupations among workers with an advanced degree, up from one-quarter in the 1990s and one-fifth in the 1980s. In other words, immigration is an important source of skills that supplements domestic efforts at skill development.

VI. Structural Change in the Composition of Capital

The activity-analysis model of Section IV ties labor of various skills to the capital appropriate to those skills. The preceding section has documented the shift in the distribution of skills toward more complexity, as well as the occupations that embody them, and linked these shifts to the growth in educational attainment. This section documents a parallel shift on the capital side, consistent with the complementarity between capital and labor in the activity-analysis view of production.

The last 40 years have seen a dramatic shift in the composition of investment in the U.S. private business sector, away from tangible structures and equipment and toward investments in intangible capital. There has also been a shift within tangible capital toward information technology (ICT) equipment. Intangible capital is highly firm-specific and produced in-house, and includes such categories as computerized information, innovative property like R&D, and economic competencies (the categories proposed by Corrado, Hulten, and Sichel (2005, 2009)). The first is mainly software, and comprises 13% of the overall intangible investment rate in 2010. Innovative property is a diverse group that includes not only the conventional National Science Foundation (NSF) type of R&D, with its orientation to science and technology, but also other important forms of R&D such as investments in artistic originals (books, movies, and music), development of new financial products, and architectural and engineering designs. The largest category of intangible capital is economic competencies, divided into brand equity (advertising, marketing, customer support), firm-specific human capital (worker training), and organizational structure, a rather amorphous grouping that includes investments in management and human resource systems, strategic planning, and management consulting. Many of these intangibles are the source of a firm's intellectual property.

The rate of investment in these intangibles over the period 1977 to 2010 is shown in Figure 4. The rate rose significantly over the period, starting at just over 8% in 1977 and reaching just under 14% by the end of the period. The growth in importance of this type of capital is in sharp contrast to the declining rate of tangible capital investment shown in the figure, falling from the 11% to 13% range in the late 1970s to around 8% by the end of the period (9.6% in 2007, the last year before the recession). The overall trends reflect the decision by many companies to move up the global value-chain to higher valued added activities like product design and marketing, all overhead activities, as well as the decline in tangible capital-intensive manufacturing industry. It is interesting to note that the overall rate of investment, tangible and intangible combined, remained relatively constant over the period, heightening the importance of structural change in the underlying activities of the economy.

When the rate of investment of ICT capital is broken out of total tangible capital in Figure 4 and shown separately, the ICT investment share is seen to have doubled between the mid 1970s and mid 1980s, then remained relatively constant, and then surged again in the late 1990s before falling back during the post-2007 growth slowdown. However, while the investment rate of the non-ICT category (not shown) has declined in relative importance in recent years, this category of capital is far from technologically stagnant. The Digital Revolution has found its way into such non-ICT capital goods as autos and trucks, medical equipment, and machine tools (recall the 2007 paper by Bartel et al.), as well into some structures. The extent to which technology is embodied in capital is hard to determine, but my own rather dated estimate found a large embodiment effect for the period 1947-1983: the unadjusted annual growth rate of equipment, as estimated by the BLS, was 4.4%, while the quality-adjusted rate calculated in the paper was 7.3% (Hulten 1992)). The BEA does make a quality adjustment to some types of equipment, with those for computing equipment and software being notably large.

The time path of the intangible investment rate is shown again in Figure 5, with the 1960 value indexed to 100 in order to facilitate comparison with education and skill indicators. The four variables included in this figure -- the rate of intangible investment, "expert" industry employment, the college wage premium, and the Autor-Price gap between non-routine cognitive and non-cognitive skills - all show upward trends. The visible association of these trends over the course of the Information Revolution is far from dispositive, but it does not require much of Solow's suspension of disbelief to recognize in the aggregate data that which is readily apparent at the level of the research lab, corporate headquarters, or the plant floor.

VII. Growth Accounting and Activity Analysis

A. The Sources of Growth Model with Intangible Capital

What does the importance of intangible capital, skills and education in the activity analysis parable imply for the sources of growth? While neoclassical and activity-analysis models operate through different economic mechanisms, the sources-of-growth estimates associated with the former are consistent with those of the latter, as discussed in Section IV. The conventional BLS sources of growth estimates can thus be interpreted in light of either model. When this is done, the activity analysis reinterpretation assigns a much greater role to education.

The sources-of-growth estimates of this paper are shown in Table 1. Unlike the conventional BLS growth accounts, the estimates of this table include the list of intangibles studied by Corrado, Hulten and Sichel (2009). The expanded growth rate of output per hour in the U.S. Private Business sector over the period 1948 to 2007 (the last year before the financial crisis) is decomposed into the contributions of tangible and intangible capital per labor hour, labor composition, and TFP growth.[19] The top panel shows the percent contribution of the first

[19] These estimates are based on Corrado and Hulten (2010). When the list of inputs is expanded to include the stock of intangible capital, the concept of output must be expanded to include the corresponding output of intangible investment.

four to the growth in output per hour, measured as the growth rate of each multiplied by its income share, with TFP measured as a residual. It is apparent that the sources of growth changed appreciably over the course of the whole period. The contribution of intangible capital increased almost threefold (10% to 27%) from the first sub-period, 1948-1973, to the last, 1995-2007. ICT capital experienced a similar proportionate increase (4% to 13%) and the combined contribution was 40% in the last period. TFP's contribution fell from 60% to 42%. Labor composition enjoyed a "boom" in the middle period that saw its contribution increase three-fold to 17%, but this fell back to 7% during the last period.[20]

Figure 6 presents these trends in an annual time series format. The annual growth rate of output per hour, shown at the top of the figure, follows a generally declining, but volatile, path. The same is true of the TFP growth path below it, with the volatility of the former reflected in the latter (no surprise, since TFP is measured as a residual). The growing importance in knowledge capital deepening via intangibles is evident, increasing to the point where its contribution to growth rivals that of the declining TFP trend. The relatively small contribution of labor quality is also shown, indicating an upward surge in the 1980s, before falling back during the 1990s.

The neoclassical interpretation of Table 1 and Figure 6 suggests an important role for capital deepening via the substitution of capital for labor, and a relatively small role for labor composition change. The activity-analysis interpretation suggests a different view of the former, one that interprets the same patterns in terms of the structural change in the composition of activities. The shift toward technologically more complex activities seen in Figures 1 and 2 led to changes in both the demand for knowledge capital and for workers with the complex skills required to work with it, which, in turn led to changes in the demand for educational attainment, higher-order skills, and professional occupations.[21] A major

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[20] Given the prominence of R&D spending in discussions of innovation, it is interesting to note the relatively small (6%) role played by scientific "NSF" R&D from 1995 to 2007.

[21] Beaudry et al. (2016) appeal to the link between knowledge capital and college-educated labor as an explanation for a slowdown in the demand for higher-order skills and higher education after 2000, which they term the "Great Reversal in the Demand for Skill and Cognitive Tasks". They attribute the "reversal" to the slowing growth in ICT equipment and software (which are treated as a general purpose organization technology within the

implication is that the large contributions of intangible and ICT capital per worker hour evident in this table (and in Figure 6) were enabled by the growth in educational attainment, skills, and professional occupations.[22] In other words, the activity-analysis view of education's role in the growth process suggests that its contribution was almost certainly much larger than the rather small amount assigned to it by the aggregate approach of neoclassical growth accounting.

The contribution of education may be even greater still, since some of its effects may be suppressed in the residual measure of TFP. There are at least three channels through which this can happen. One of the most important for this paper is the spillover externalities associated with an educated workforce identified in Lucas (1988). In his model of economic development, educated workers interact in ways not captured by private wage premia, leading to a social return to education that exceeds than the private return. The increase in GDP associated with the excess return is not captured by the measured contribution of labor growth or the labor composition term, and is thus suppressed into the TFP residual (which is thereby overstated). Much the same can be said of R&D spillovers (Romer (1986, 1990)). By its nature, knowledge is non-rival and subject to diffusion, and the social rate of return may therefore exceed the private rate of return to the original innovator. Hall et al. (2010) review the

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firm). They use a neoclassical optimization approach in their modeling of the link, and a more limited concept of knowledge capital. The focus of this paper is on the contribution of education and skills to aggregate economic growth and productivity, using a much broader conception of knowledge capital (all intangible capital and ICT equipment) and stocks as well as flows. The data underlying Figure 6 of this paper indicate that the contributions of ICT equipment and software did decline after 2000, but also there was not much of a decline in the contribution of non-software intangible capital (although there was a large amount of cyclical variability). Still, the activity model is supportive of the idea that the demand for higher-skill labor is strongly linked to the demand for more complex technological capital.

[22] When interpreting the capital-labor ratios in Table 1 in terms of activity analysis, it is important to recognize that the table involves the ratio of different types of capital to *total* labor input; in the case of intangible capital, R, this is R/L. This is not the ratio relevant for activity analysis, which is, instead, the ratio of intangible capital to the labor actually used with intangible capital, R/L_r. The former is related to the latter by the equation $R/L = (R/L_r)(L_r/L)$. In pure activity analysis, R/L_r is given by the technology and any growth in the ratio is zero. Growth in R/L, as seen in Table 1, must therefore reflect a change in the employment ratio, L_r/L. The employment patterns in Figure 3B show significant growth in the relative shares of both expert service and overhead organizational services, suggesting that this indeed may have happened. These types of jobs are precisely those most likely to be used with intangible capital, so it is not implausible that much of the observed change in R/L was largely due to an increase in L_r/L. However, this is only a surmise, since there is no tight match between different types of intangible of capital (which are quite heterogeneous) and the requisite types of labor skills (also heterogeneous). Moreover, R/L_r itself may well have increased during the ICT Revolution as superior types of intangible and ICT capital entered production and enabled new activities or, alternatively, as the mix of activities shifted to those with a greater degree of capital intensity.

literature on the relative private and social returns to R&D investment and conclude that the latter is "almost always estimated to be substantially greater than the private returns (p. 1073)." This, too, is suppressed into the TFP residual. Finally, Acemoglu and Autor (2011, 2012) develop a task-oriented skill-biased technical change in which the parameters of the bias may be suppressed into the TFP. The conventional Solow model assumes that technical change has the Hicks'-neutral in form and is thus without a factor bias. They show that when there is a bias that favors skilled workers and occupations, education's observed contribution to growth may be understated and measured TFP overstated. By implication, part of the non-volatile part TFP growth seen in Table 1 and Figure 7 belongs, in principle, to the other sources of growth, with the further implication that the contribution of education may be understated.

B. The Sources of Growth: Firm Dynamics

The statistics of Table 1 portray growth as a rather "bloodless" and formulaic process (inputs and technology mathematically transformed into output). The actual process of growth is anything but "bloodless", involving, as it does, the birth and death of firms and the Schumpeterian struggle for survival and success of incumbent firms. Since this paper has emphasized the importance of structural changes in the micro activities that underpin the aggregate flows of inputs and output, and emphasized the importance of human agency in organizing and staffing these activities, it seems reasonable to comment further on the firm dynamics that underpin the evolution of these activities.

The private economy is composed of industries, which are themselves typically composed of both large and small firms, as well as older and newer ones. Research has shown that all firms are not equal when it comes to growth, and that those that are relatively young and rapidly growing are responsible for a disproportionate amount of net job creation (Haltiwanger et al. (2010); Strangler, (2010); and Sadeghi et al., (2012)). Strangler finds that, in a typical year, fast-growing young firms ("gazelles") made up less than 1% of all companies, but generated about 10% of all new jobs. Sadeghi et al. report that the 0.5% of all companies classified as "high-growth firms" between 2008 and 2011 were responsible for a third of all gross job creation among firms whose employment increased over the period. Moreover, smaller firms are also an important source of R&D spending. According to NSF data, small companies with fewer than 500 employees in 2009 had an average R&D investment *rate* that was three times that of the largest firms and employed a third of R&D workers, despite their much smaller sales and overall employment.

Hathaway and Litan (2014) highlight the importance of firm births and deaths. They note that one new business is born approximately every minute, and that another business fails every eighty seconds. They go on to show that jobs are both created and destroyed in the process, with net job creation of 600 thousand jobs in 2012. This "churn", as they call it, suggests a Schumpeterian view of firm dynamics in which growth is anything but a smooth and formulaic process. It is a process in which good decisions and good luck tend to be rewarded and inadequate or obsolete business models punished. By implication, human agency in the formulation and execution of business models, and in making the investments needed to enhance a firm's capabilities and products, is critical in order for new entrants to become gazelles and for incumbents to prosper.

The churning of firms through entry and exit has implications for economic growth. It is an important mechanism through which new products and processes enter the economy, and through which new markets are developed. Intangible capital and higher-order skills, cognitive and non-cognitive, play a major role in this process. However, while the quality of the "ingredients" matters, it is the skill and ingenuity of the chef in combining the ingredients and preparing the meal that matters most (to paraphrase a comment by Zvi Griliches). The most important asset of a successful new enterprise is the ability (though not necessarily higher education) of those who start and guide its development, who manage its operation, and who foster technological and organizational innovation. And, these key ingredients are sometime "imported". The study by Kerr and Kerr (2015) shows that around a quarter of all entrepreneurs in 2008 were immigrants, up from some 17% in 1995.[23] They also report that 38% of new firms had at least one immigrant entrepreneur and that the share of employees in new firms who were immigrants was 26%.

[23] The notion of "entrepreneur" used here is defined as someone who is among the top three initial earners in the new business. Kerr and Kerr also report that their findings are roughly comparable to those in the large literature they review, though a few report appreciably lower percentages.

VIII. Summary and Conclusions

The neoclassical and activity-analysis models offer different windows on the role of education in the process of economic growth, two ways of looking into the same complex processes involved. Both involve abstractions and assumptions in interpreting the same data. The neoclassical growth approach treats inputs as separate additive sources, with a high degree of substitutability among the inputs. It cuts through the clutter of details to focus on the flows of goods and payments in the macro economy and the gross determinants of these flows. Activity analysis focuses on the clutter, and what it means for the interaction of labor, capital, technology, and the evolution of firms and products over time.

The activity-analysis/task parable offers important insights into the role of skill-development and education in the functioning of the economy. Workers with different skills and levels of education are not free-standing ingredients in a recipe for making aggregate output. They are the ingredients of the specific activities for which they are needed, in conjunction with the capital and other inputs required in order to operate the activity at a given scale. Those activities that require higher-order skills and advanced education must have workers that embody these requirements. A deficit in either the necessary skills or capital limits the operation or growth of those activities. Thus, education plays a particularly important role during periods of structural changes in the economy.

Indeed, evidence suggests that the Information Revolution has increased the importance of activities that require non-routine cognitive and non-cognitive skills and associated occupations, and the ability of the education system to accommodate the increased demand was (and continues to be) necessary for the success of the Information Revolution. The large contributions of intangible and ICT capital seen in Table 1 were enabled by the increases in complex skills and education seen in this paper. Exactly how much is due to formal education *per se* is ambiguous, but the contribution is almost certainly significantly greater than that implied by the BLS labor-quality effect. Once again, it is hard to imagine today's economy operating with a work force in which less than half the workers had a high school degree and less than 10% had a college degree.

What the future actually holds for continued economic growth and employment is a matter of great conjecture. Powerful technological and global forces continue to shape the world of work, and one can only guess where they will lead in the "Race against the machine" of Brynjolfsson and McAfee (2014). Looking backward at the data, the importance of the high skill-occupation-education nexus for past economic growth seems well established. This paper has added weight to this conclusion by further developing the micro-activity foundations of the growth accounting problem. Looking ahead, it may be that robots will ultimately make most human work skills obsolete. It may be that education will increasingly be seen as preparation for a productive life of leisure. But for now, it seems reasonable to conclude that a strong educational system – one that provides a full range of skill-development – remains an essential part of America's economic prosperity. As Levy and Murnane (2013, p. 5) put it: "For the foreseeable future, the challenge of 'cybernation' is not mass unemployment but the need to educate many more young people for the jobs computers cannot do".

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Table 1

Sources of Growth in U.S. Private Business Sector
(average of annual growth rates)

	1948-2007	1948-1973	1973-1995	1995-2007
1. Output per hour	2.41	2.99	1.56	2.76
percentage point contribution to output per hour of:				
2. Tangible capital	0.65	0.76	0.52	0.67
a. ICT equipment	0.23	0.11	0.28	0.37
b. Non-ICT tangible capital	0.32	0.47	0.2	0.22
3. Intangible capital	0.42	0.3	0.39	0.74
a. Computerized information	0.06	0.01	0.07	0.15
b. Innovative property	0.19	0.15	0.16	0.32
(1) R&D (NSF/BEA)	0.10	0.08	0.07	0.17
(2) Other (incl. non-NSF R&D)	0.09	0.07	0.09	0.15
c. Economic competencies	0.17	0.14	0.15	0.27
4. Labor composition	0.20	0.15	0.26	0.2
5. TFP	1.14	1.78	0.39	1.16
percent of total contribution to output per hour of:				
2. Tangible capital	27%	25%	33%	24%
a. ICT equipment	10%	4%	18%	13%
b. Non-ICT tangible capital	13%	16%	13%	8%
3. Intangible capital	17%	10%	25%	27%
a. Computerized information	2%	0%	4%	5%
b. Innovative property	8%	5%	10%	12%
(1) R&D (NSF/BEA)	4%	3%	4%	6%
(2) Other	4%	2%	6%	5%
c. Economic competencies	7%	5%	10%	10%
4. Labor composition	8%	5%	17%	7%
5. TFP	47%	60%	25%	42%

Source: Corrado and Hulten (2010).

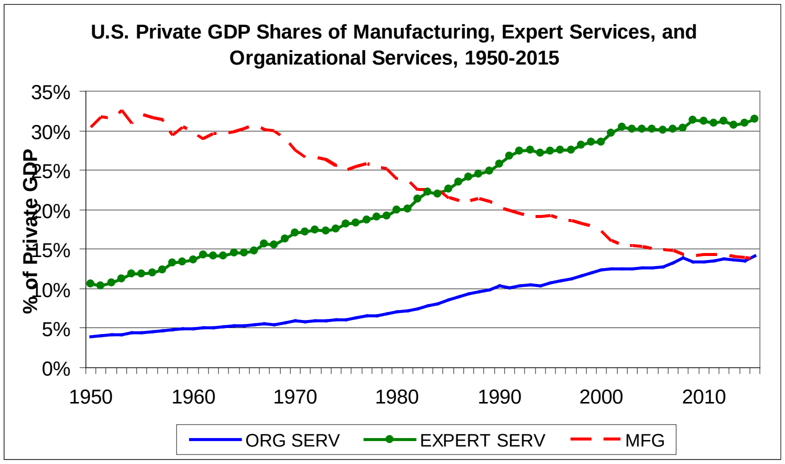

Figure 1

Source: Bureau of Economic Analysis, GDP-by-Industry, Industry Data, *Value Added by Industry as a Percentage of Gross Domestic Product*. The "expert" service sectors include the NAICS industries 51, 52, 54, 55, 61, and 62, and organizational service sectors 54, 55, and 56. MFG denotes manufacturing.

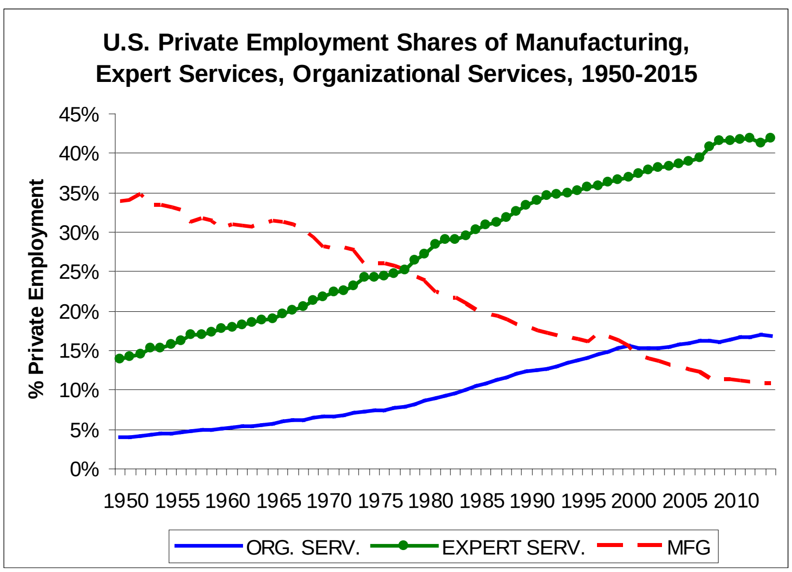

Figure 2

Source: Bureau of Economic Analysis, Industry Economic Accounts, from various parts of Table 6.5, *Full-Time Equivalent Employees by Industry*. See Figure 1.

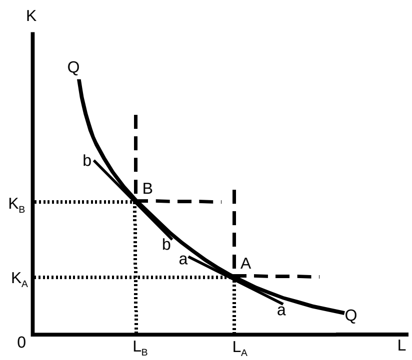

Figure 3A

Activity-Analysis Model
Two Activities and Malleable Inputs

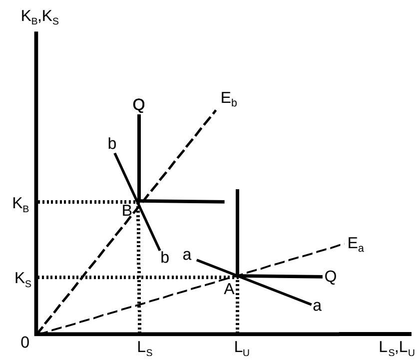

Figure 3B

Activity-Analysis Model
Two Activities and non-Malleable Inputs

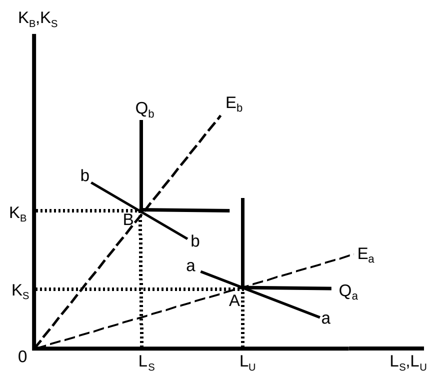

Figure 3C

Activity-Analysis Model
Two Activities and Malleable Inputs plus Different Outputs

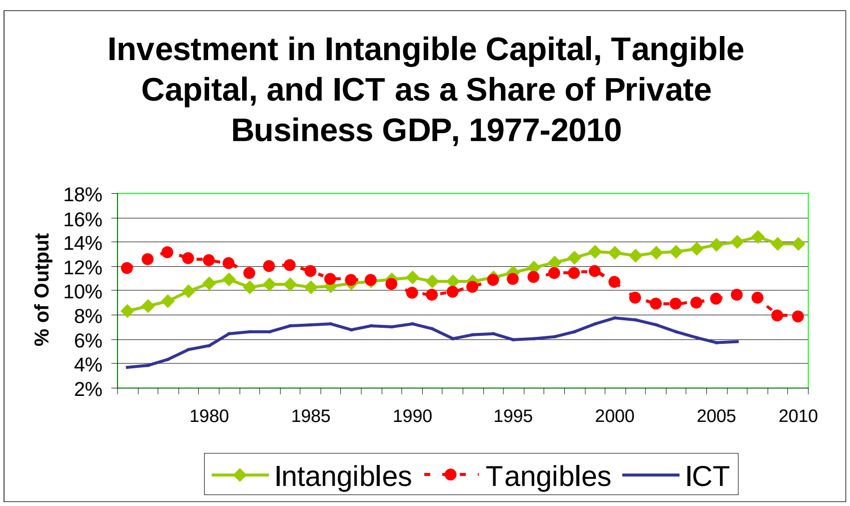

Figure 4

ICT is Information and Communications Technology Equipment
Source: Data Underlying Corrado and Hulten (2010, 2011).

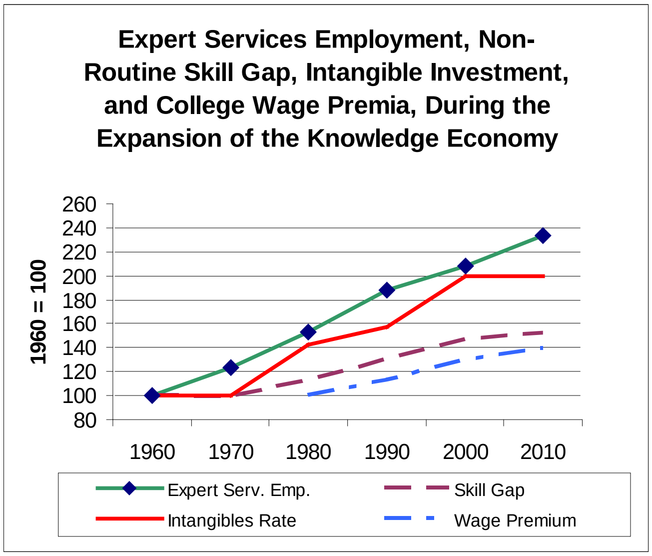

Figure 5

Sources:
1. Expert Service Industries Employment: Bureau of Economic Analysis, Industry Economic Accounts, Table 6.5, *Full-Time Equivalent Employees by Industry* (see Figure 2).
2. Skill Gap (ratio of non-routine cognitive and interpersonal indexes to the other indexes): Autor, D.H. and B.M. Price, "The Changing Task Composition of the US Labor Market: An Update of Autor, Levy, and Murnane (2003)", MIT, June (2013).
3. Intangible investment rate; see Figure 4.
4. Wage premium based on Valletta (2016) (average of college-only and graduate premia, 1980 =100)

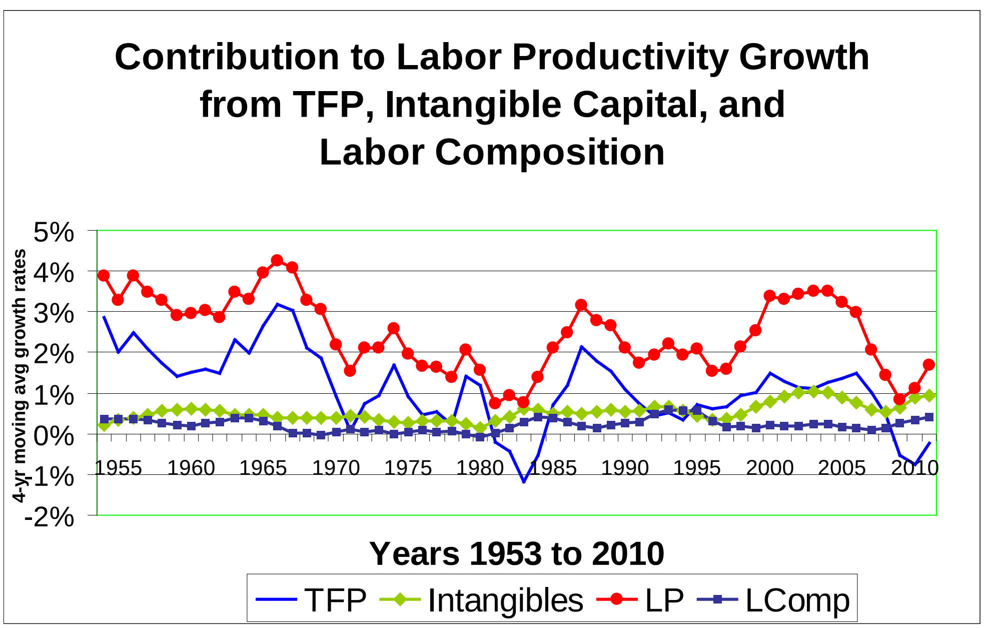

Figure 6

Source: Data Underlying Corrado and Hulten (2010, 2011).
(LP is output per hour, and LComp is the labor composition term)