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THE TALE OF TWO TRAVERSES

Innovation and Accumulation in the First Two Centuries of U.S. Economic Growth

by

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1. Introduction: Taking a Suitably Long View

Modern economic development as it has been experienced in the United States over the nation's first two centuries was far from the economic growth theorists' conceptualization of a "steady-state" process. It is true that during the Republic's first hundred years the gross national product (measured in constant dollars) increased at a long-term pace that remained close to 4 percent per annum. In the same vein, it may be observed that although the trend rate of real GNP per capita slipped to the neighborhood of 3.2 per cent for the next hundred years, it remained within one-half of percentage point of that average pace throughout that century. Similarly, economists and others with an eye for statistical constancies continue to remark upon the stability of the long-term trend rate of growth recorded for real GNP per head of population, which between 1890 and 1990 remained in the narrow range from 1.7 to 2.0 percentage points per annum. Yet, beneath the surface placidity of these measures of macroeconomic growth, much has been changing. Indeed, it may be said that those ongoing transformations that have been an essential concomitant, and indeed, among the vital conditions permitting the maintenance of economic advance over the long-term.

When viewed in the perspective afforded by the two-century considered here, the dramatic shifts occurring among the proximate sources of rising real income per capita in the U.S. economy come more clearly into focus. Growth accounting provides a quantitative framework that is particularly well suited for identifying shifts occurring of that time-scale, far more than it is in the tasks of short- and near-term macroeconomic analysis in which it has come to be widely employed. Similarly, the corpus of growth theory upon which we are able to call – in its classical and new incarnations – to help penetrate beneath the surface of a "growth accounting" description of the economy's developmental path, finds its most proper use within the historical long run. It is hardly the analytical instrument with which to attack the problems of disequilibrium dynamics that dominate the concerns of macroeconomic policy makers and applied economists -- popular as it now is to enlist the rhetoric of economic growth when debating all sorts of policy issues.

As the task of understanding the forces that have driven those changes is the major challenge addressed in these pages, it is useful to begin with a rapid outline sketch of the scene presented by the macroeconomic growth record. The trend rate of growth of labor productivity had accelerated from its level in the early nineteenth century up until the final quarter of the twentieth century, and from the latter part of the nineteenth century onward a similar path was followed by the growth rate of the productivity of all factors (labor and capital) combined. Moreover, the nature of the productive factors, and the proportions in which these have been utilized, have undergone significant sustained alterations.

Thus, the changing magnitudes and the altered constellation of relationships observed over these two hundred years among the long-term trend growth rates of aggregate real output and inputs presents the historian of the U.S. macro-economy with a number of imposing interpretative issues. We are faced with nothing less daunting than the task of making sense of what might be termed "the evolving morphology of American economic progress." What can be provided on this occasion by way of a response to this challenge necessarily will be less than a full explanation, and much less than a definitive account of the salient features of that dynamic process. Instead, what is offered is a summary historical interpretation developed along the lines already explored in previous works by the author in the course of a long and enjoyable research collaboration with Moses Abramovitz (1912-1999.)[1]

1.1 Interpretative Orientation

The principal elements of that account can be classified under two main headings, which might be referred to in an approximate way as subsuming "global dynamic drivers," on the one hand, and "evolving national and regional contexts," on the other. Under the first heading are included forces having largely to do with the development and dissemination of scientific, technological and organizational knowledge of an essentially trans-national (Northern Atlantic region) character, but which, quite naturally, came to be expressed in particular forms in the North American setting. In the second category are influences that reflected more uniquely American attributes of the economic environment. Among the latter were cultural legacies, social and political styles, institutional habits and routinized commercial and technical practices surviving from the past, learned conditions that were formed by the peculiar experiences of an immigration society newly colonizing a vast and sparsely settled region that was richly endowed in its natural resource *potential;* and still others, which reflected particular American national responses to political and social circumstances that unfolded on the world stage during the twentieth century. We see the historical drama of the U.S. economy's development, and the changing characteristics of its growth-path, as having been shaped by the interplay between those two sets of forces.

Thus, at the center of the present interpretive account are placed those powerful forces of the progress of knowledge that best can be identified as "generic dynamic drivers": these are the cumulative, internationally shared advances in science and technology, considering the latter of those changes broadly to embrace knowledge pertaining to the organization and management of economic activities as well as to the industrial arts. The evolution of technological practices during the course of the nineteenth and twentieth centuries is conceptualized as a trans-national, global process whose changing underlying tendencies in regard to pace and direction manifested themselves particularly clearly in the American economic environment.

This was in some part due to the precocious contributions that inventive activities in

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[1] See Moses Abramovitz and Paul A. David, "Economic Growth in America: Historical Parables and Realities," De Economist, vol. 121(3), 1973a; Moses Abramovitz and Paul A. David, "Reinterpreting Economic Growth: Parables and Realities of the American Experience," American Economic Review, vol. 58(2), May, 1973b; Moses Abramovitz and Paul A. David, "Technological Change and the Rise of Intangible Investments: The US Economy's Growth Path in the Twentieth Century," in D. Foray and B.-A. Lundvall (eds.), Employment and Growth in the Knowledge-Based Economy, London: Edward Elgar, 1996; Moses Abramovitz and Paul A. David, "Convergence and Deferred Catch-Up: Productivity Leadership and the Waning of American Exceptionalism," Ch. 2 of Ralph Landau, Timothy Taylor and Gavin Wright (eds.), The Mosaic of Economic Growth, Stanford, CA: Stanford University Press, 1997; Paul A. David, "Invention and Accumulation in America's Economic Growth: A Nineteenth Century Parable," in International Organization, National Policies and Economic Development, a supplement to the Journal of Monetary Economics, vol. 6, 1977, pp. 179-228; and Moses Abramovitz, "The Search for the Sources of Growth: Areas of Ignorance, Old and New," (Presidential Address), Journal of Economic History, 53(2), June 1993, although separately authored, proceed explicitly within the context of this collaborative interpretation. The present exposition draws extensively upon the text of Moses Abramovitz and Paul A. David , "Two Centuries of American Macroeconomic Growth: From the Development of Resource Abundance to the Era of Knowledge-Driven Progress." [Available at: http://siepr.stanford.edu/papers/pdf/01-05.htmlAlthough credit for everything useful that is contained herein must be shared fully with Moses Abramovitz, he bears no responsibility for the defects of this presentation.

the young Republic made to forming the directions in which the pool of industrially useful knowledge was expanding. But, perhaps more importantly, since Americans were notable borrowers of technologies (and underlying scientific principles) from Europe, it reflected the comparatively greater plasticity of the economic environment in this region of Europe's New World settlements: the young and undeveloped state of the country left much scope for institutions, capital structures and cultural attitudes to become adapted in ways that were congruent with successful economic exploitation of the productive potentialities that were being created by "the progress of invention." By the same token, the emergence of the logic of knowledge-based economic development in the U.S. during the twentieth century, and many of the institutional adaptations that have supported and reinforced that process by mobilizing private and public resources on a large scale for investment in education, training, and scientific and technological research activities, are not to be understood as a unique, national phenomenon. Rather, these should be seen as early manifestations of a broader and more global process, to which economic and political features of the U.S. setting imparted particular, concrete forms that would subsequently become institutionalized and adapted to other settings.

Although the pace and character of technological change figures centrally in this reading of the historical experience of growth, there is no intention to cast it in the role of a wholly independent, autonomous force driving the economic growth process. On the contrary, quite clearly many of the determinants of the generation and diffusion of innovations were endogenous to the economic system in which such developments took place. At the same time, the main features of the course of technological and organizational innovation that we view as powerfully shaping the economy's growth-path in each century, were neither formed exclusively by the concurrent American economic environment, nor were their effects confined to U.S. domestic product and factor markets.

Technological advance has shaped the path of U.S. economic development directly and indirectly through many channels. Of course, we see such developments as contributing in a straightforward way to improving the overall efficiency of the economy's use of the factors of production. But the effects of changes in technology extended beyond that, and impinged upon the endogenous dynamic processes through which productive inputs are created. This applies not only to the impact of technological change upon the derived demands for stocks of conventional capital in the form of reproducible structures, equipment and livestock. The ways in which the size and commercial value of the known reserves of non-reproducible (depletable) natural resources are influenced by technologies of exploration, resource extraction, and processing, also are embraced within this view. So too are the shifts in the derived demands for specific intermediate inputs of natural resources, shifts that may emanate from technologically induced changes in the mix of goods and services produced by other sectors of the economy. In addition, of course, there were direct and indirect impacts upon the market for labor services of different kinds, stemming from the combined effects of technological change and the alteration of the nature and extent of available capital equipment.

Another way of putting the foregoing propositions is to say that our reading of the both the macroeconomic and the microeconomic evidence from U. S. economy's experience over the past two centuries leads to a view of technological change (broadly conceived) as having not been "neutral" in its effects upon growth. The specific meaning of "non-neutrality" in this context is that technical and organizational innovation had effects upon the derived demands for factors of production, and these tended to alter the relative prices of the heterogeneous array of productive assets in the economy.[2] But, significantly for our interpretation, the size of the respective asset stocks also was affected in the process. By directly and indirectly impinging on relative real rates of remuneration established in the markets for particular types of human labor and skill, and for the services of specific tangible and intangible capital, the course of technological and organizational innovation altered key conditions governing the growth rates of the various macroeconomic factors of production.

Two main motifs therefore will recur in the following discussion. The first theme is that because the *non-neutrality* of the impacts of innovations on the demand side of the markets for productive inputs, technological change must be understood as contributing to complex *interactions* among all the proximate “sources of growth” -- even though the latter are usually presented by exercises in “growth accounting” as distinct and separate dynamic elements contributing to the rise of labor productivity and per capita real output. The second theme is an extension and elaboration upon the first: it concerns the differences between the twentieth and the nineteenth century in regard to the predominant patterns of bias in those non-neutral technological impacts. The result has been a relative shift away from the accumulation of stocks of tangible reproducible capital and towards the formation of intangible productive assets by in investments in education, training and the search for new scientific and technological knowledge.

1.2 Methodology and Macroeconomic History

"History," said Voltaire, "is a fable agreed upon." This oft-quoted aphorism's truth impresses itself particularly upon economic historians seeking an explanatory interpretation of the quantitative record of macroeconomic performance presented in the following pages, or indeed any other account of long-run economic changes that is set out in such highly aggregated terms. Supply-side approaches to all but the most short-run macroeconomic phenomena have been embraced almost universally in recent decades, and most of the economics profession appears to have been thoroughly persuaded by Paul Samuelson's (1962) contention that the idea of a well-behaved production function leads to the most coherent and analytically attractive "parables" that can be told involving aggregate supply relationships in the economy.[3] Surely any history of an economy's growth composed to keep up with these intellectual fashions can be no more than "a *parable* agreed upon."

Although the concept of an aggregate production function still draws some detractors, it has no want of tacit as well as explicit endorsements. Quite plainly, it underlies the now-standard procedures of modern "growth accounting." That is no less the case when it is

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[2] For further discussion of “neutrality” concepts see section 2, below, and Moses Abramovitz and Paul A. David (2001): Endnote 1 to Part Two. Only under rather special circumstances -- such as are readily hypothesized by economic theorists, but not evident during most of the long-period intervals in the U.S. historical record -- should we envisage such changes as altering the marginal productivities of all inputs in exactly the same proportional degree, and (under competitive market conditions) thus leaving the structure of relative input prices unaltered.

[3] These observations appear to hold even more strongly today than when they were first offered by Moses Abramovitz and Paul A. David, “Economic Growth in America: Historical Parables and Realities,” De Economist, vol. 121(3), 1973a; Moses Abramovitz and Paul A. David, "Reinterpreting Economic Growth: Parables and Realities of the American Experience," American Economic Review, vol. 58(2), May, 1973b; although an interlude of doubts -- or at least quiescence -- preceded the revival of enthusiasm for neoclassical supply-side macroeconomics in the mid-1980s.

pushed into the background and so remains implicit in the supposition that there are well-defined elasticities of aggregate real output with respect to each of the classes of aggregated productive inputs; and that these elasticities are legitimately treated as parameters (within trend periods at least) that correspond directly in magnitude to the respective shares of the real gross product that are paid to the factors of production.

To accept the notion of an aggregate production function for the purposes of organizing and examining the data in this way, however, does not require turning a wholly blind eye to the dangers of reifying the concept. It certainly is possible to conceive of ways in which stable relationships among aggregate output and inputs, and the appearance at the macro-level of regularities in the time trends of relative factor proportions, could emerge directly from market interactions occurring at the microeconomic level.[4] But, it is not necessary for the present interpretative purpose to develop explicitly an alternative approach of that sort. The language of production function analysis may be employed descriptively at the aggregate level without suggesting that this notional construction had a literally correspondence with some pre-existing set of constraints that were determining the historical growth path of the U.S. economy.

Consequently, the concept's use here should be read as metaphorical. It refers to hypothesized aggregate supply-side relationships of a persisting or gradually changing kind, and which provide an historical summation of myriad dynamic processes that were being played out in reality on the microeconomic level.[5] Quantitative macroeconomic stories related in such terms may be expected to direct attention to potentially important issues, and to highlight promising specific hypotheses that deserve more detailed historical investigation. In sum, we view our "parables" about the historical behavior of the aggregate production function to have an allegorical value: if they are not taken literally, they can perform the useful heuristic role of indicating in a short-hand way the character of underlying economic tendencies that were manifesting themselves at the level of sectors, industries, firms and households.

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[4] One such approach has been explored in the "evolutionary economics" literature, from Richard R. Nelson and Sidney G. Winter, "In Search of a Useful Theory of Innovations," Research Policy, 1977, 6(1), 31-4, to J. Stan Metcalfe, "The Evolutionary Explanation of Total Factor Productivity Growth: Macro Measurement and Micro Process," CRIC Discussion Paper No. 1, University of Manchester, June 1997, eschewing the notion of optimization subject to production function constraints at the micro-level as well as at the macroeconomic level, and seeking to account for statistical regularities at the macro-level as emergent properties of the interplay of underlying dynamic processes -- through which innovations are generated and new products and processes are selectively retained in commercial applications by "boundedly rational" agents operating under uncertainty in imperfect markets.

[5] This is a view that has been explicitly expressed previously, not only by "evolutionary" economists, but by others of a putatively more "orthodox" cast who have carried out extensive empirical studies employing aggregate production function concepts. See, e.g., M.I. Nadiri, "Some Approaches to the Theory and Measurement of Total Factor Productivity: A Survey," Journal of Economic Literature, 8 (December), pp. 1137-77; Griliches (1970), Moses Abramovitz and Paul A. David, "Economic Growth in America: Historical Parables and Realities," De Economist, vol. 121(3), 1973a; Moses Abramovitz and Paul A. David, "Reinterpreting Economic Growth: Parables and Realities of the American Experience," American Economic Review, vol. 58(2), May, 1973b; Moses Abramovitz and Paul A. David, "Convergence and Deferred Catch-Up: Productivity Leadership and the Waning of American Exceptionalism," Ch. 2 of Ralph Landau, Timothy Taylor and Gavin Wright (eds.), The Mosaic of Economic Growth, Stanford, CA: Stanford University Press, 1996; Moses Abramovitz and Paul A. David, "American Macroeconomic Growth in the Era of Knowledge-Based Progress:The Long-Run Perspective," Ch.1 in The Cambridge Economic History of the United States, Vol.III:The Twentieth Century, S.L. Engerman and R. E. Gallman, Eds., New York: Cambridge U.P., 2000.

In advancing analytically grounded parables that tell a story consistent with highly aggregative data, however, we therefore seek eventually to pass beyond speculation about "figmentary entities," and to review other evidence that more immediately and directly addresses the underlying microeconomic developments. There is an inevitable tension between the values of simplicity and clarity of exposition that can be achieved in presenting rather broad-brush parables on the one hand, and on the other hand, the realization of the aim of such heuristic story-telling -- which is to indicate the salient points at which the resulting tale makes contact with the specific complexities of the historical experience of growth. Readers of the following exposition therefore should be prepared for a form of "histoire raisonnée" that shifts back and forth between those two poles of attraction.

1.3 The Organization of the Interpretive Argument

The following section opens with a narrative overview that relates the specific features of American industrial development, structural and institutional change, and technical and organizational evolution with the broad interpretive themes that will be developed more analytically. Following that, the main quantitative outlines of the aggregative record of growth for the U.S. private domestic economy over the past two hundred years are set out briefly in section 2.2. Based primarily on the findings of a standard growth accounting exercise, these reveal both continuities and profound differences between the nineteenth and twentieth centuries in the pattern of growth rates. They also serve to define the main issues of interpretation and explanation on which the growth accounts themselves remain silent. Section 3 develops an explicit aggregate production function framework and shows how it may be employed to link growth accounting with a simple, growth-theoretic explanatory framework along the lines of the well-known model of Solow (1956). This is taken a step further, by augmenting the formal model to allow for the accumulation of intangible, as a well as tangible capital assets, and allowing for non-neutrality in the rates of factor-augmenting technological and organizational innovation.

Next, in section 4, the macroeconomic evidence is re-examined within this analytical framework. A connection between the changing direction of the bias of technological change and the rise of the measured TFP residual in the early part of the twentieth century is suggested in sub-section 4.1. The quantitative grounds are set out in sub-section 4.2 for a broad characterization of the thrust of nineteenth century technological progress as having been *labor-saving but tangible reproducible capital-using* in its effects. In sub-section 4.3, the analysis turns to consider the respects in which the twentieth century witnessed significant new departures from those tendencies. The salient macroeconomic trends are shown, by arguments analogous to those applicable to the nineteenth century experience, to be consistent with the broad characterization of technological change as having become *intangible capital-using but tangible reproducible capital-saving*, as well as remaining relatively labor-saving.

By taking into consideration the relatively rapidly growing inputs of intangible capital that were omitted from the standard Solow growth model, one arrives at an augmented set of growth accounts and a further "refinement" of the residually estimated, multifactor productivity growth rate during the twentieth century. This extension of the growth accounting framework to include unconventional, intangible capital inputs will be seen to underscore what is undoubtedly the major puzzling feature of the U.S. growth record during the closing quarter of the twentieth century: the striking collapse of the multifactor productivity growth rate. But it also redirects attention in a rather dramatic way the question of the degree to which the observed "productivity slowdown" in the post-1966 period may be reflecting deficiencies in the existing statistical apparatus employed to measure real product growth.

Broadening the scope of the growth accounts to include the formation and utilization of intangible capital, we are led toward a somewhat unorthodox picture of the long-term trends in the supply of private sector savings behavior. This view is commented upon briefly section 5, where it is noted that there is little evidence to suggest that adverse shifts in domestic savings behavior during the twentieth century have increasingly been constraining the long-term growth of labor productivity and per capita real incomes in the U.S. Instead, savings behavior would appear to have been largely responsive to the effects of induced shifts on the demand side of the relevant asset markets, by gravitating towards to new and unconventional forms of “savings.” This development has seen a dramatic growth of the relative importance in the national wealth portfolio not only of stocks of consumer durables, but, stocks of intangible knowledge-assets created by expenditures on organized R&D, and, still more significantly, intangible human capital formed by public and private investments in education and training. The drafts being made by the latter upon the actual and potential disposable income of American households during the final quarter of the twentieth century have become impressively large. They represent the other, oft’ hidden side of the diminished flow of personal savings that may be seen in the official National Income Accounts.

Section 6 concludes by commenting briefly on the relationship between the American historical experience of long-term economic growth, and recent thinking about growth theory -- both in its neoclassical formulation and the so-called “new” varieties.

2. A Quantitative Overview of Two Centuries of U.S. Economic Growth

The interpretation of long-term growth in the U.S. in this essay is pitched at a highly aggregative level, but it is important to try to maintain its connections with the underlying realities, which were played out by households, farms, firms and industries in specific regions of the country. Indeed, inasmuch as the macro-level interpretation that is elaborated in later sections is meant to inform and organize our views of those myriad details of historical development, we may begin with a brief narrative overview of specific features of American industrial development, structural and institutional change, and technical and organizational evolution—recapitulating a number of the broad interpretive themes advanced by Abramovitz and David’s account of the forces shaping and re-shaping U.S. macroeconomic growth over the past two hundred years. This takes to heart the maxim: “Life is short, have your dessert first.”

2.1 Narrative Overview

The era ushered in by the Industrial Revolution of the late eighteenth century in Britain saw a definite and increasingly pronounced movement in the direction of what we today think of as conventional “capital-deepening” economic development – the accumulation of stocks of fixed tangible reproducible assets that rose in relationship to the concurrent flow of real output. Part of this tendency involved the growing relative importance of fixed capital vis-à-vis working capital inventories, reflecting the development of tighter technological complementarities between new, inanimately powered production facilities and natural resource inputs, including capital-energy input complementarities; there were relative labor-saving advances, stemming from the creation and extension of the possibilities of substituting machinery and non-human power sources for human effort and skill, but which turned out also to be less conserving in their usage of the raw materials that were being mechanically processed. Although the exploitation of these new technological possibilities became palpable first in the British economy of the late eighteenth century, they began to manifest themselves with increasing force in the U.S. even within the first half of the nineteenth century.

The American Economy's Development Path in the Nineteenth Century

In the U.S., the period stretching from the 1830s through the 1880s saw manufacturing in general follow the path of transformation of production systems that had already been blazed in the textile sector. But the transition from the artisanal shop to the factory in this period was neither equally swift nor uniform in what was entailed across the range of industries, as the work of Jeremy Atack and Kenneth Sokoloff has pointed out.[6] Even as late as 1870, a substantial portion (albeit the minor part) of value added in a number of consumer goods industries (such as boots and shoes, clothing, furniture, meat-packing and tobacco) came from establishments employing fewer than seven workers, and using no inanimate power sources; and there were still some branches of production in which artisanal shops remained the norm. The growth in the scale of production units, and their accompanying transition to greater use of water-powered and steam-driven machinery, entailed changes in the technology of manufacturing processes, and in the organization of work, materials procurement and marketing. But the success of the new factory regime was especially dependent upon the reduction of transportation costs and increasing access to reliable, "all-weather" transportation facilities.

These developments were accompanied by increasing "roundaboutness" of production, and the substitution of tangible capital for artisanal labor in a widening range of industries that came to cater to and encourage the formation of mass markets for their output. The transformations thus entailed increases in the ratio of tangible capital to output at the macroeconomic level, and expansions in the scale of productive plant – with corresponding resource savings and increasing capital and raw materials intensity of production – at the microeconomic level. The new possibilities for profitably substituting capital for labor emerged through processes of experienced-based learning, and trajectories of deliberate inventive exploration. The latter paths of innovation had been historically selected by the conditions of relative labor scarcity, and relative natural resource abundance under which early manufacturing activities were established in the U.S. These were characteristically "biased" in a direction that was increasingly "labor-saving" and "capital-using". The overall impact of this bias in nineteenth century industrial innovation, therefore, was towards raising the ratios of tangible reproducible capital to labor, and to real output. Indeed, those ratios in the economy rose more than would have been called for merely by the inducement that changing relative factor prices provided to substitute capital for labor, within the constraints

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[6] Jeremy Atack, "Economies of Scale and Efficiency Gains in the Rise of the Factory in America, 1820-1900," in Peter Kilby (ed.), Quantity and Quiddity: Essays in U.S. Economic History, Middletown, CT: Wesleyan University Press, 1987, and Kenneth L. Sokoloff, "Productivity Growth in Manufacturing during Early Industrialization: Evidence from the American Northeast, 1820-1860," in Stanley L. Engerman and Robert E. Gallman (eds.), Long-Term Factors in American Economic Growth, Chicago and London: University of Chicago Press, 1984.

of an unchanging set of technological possibilities.[7]

While these tendencies toward "biased" technological change were broadly evident elsewhere in the nineteenth century industrializing world, we see them as having come to be realized most fully and most prominently in the setting of the U. S. The reasons for this, and its implications for the comparative international performance of the American economy both before and after the 1890-1913 era (during which U.S. industries ascended to a position of world leadership), are matters that will occupy us, particularly in Part Three. There we will bring our interpretation to bear upon the question of international convergence and catchup in levels of productivity and per capita real income that occurred in the second half of the twentieth century.

A second key aspect of the mid-nineteenth century transformation which scarcely can be held to have been a uniquely American development was the extension of an increasingly dense railroad network, and the ensuing reductions in transport charges and transit times that underlay the shift from waterborne carriage and overland freight and passenger haulage by wagon and stage-coach. These were improvements to which not only greater coverage of the continent with trackage, but increasing train speeds and capacities, and the elimination of gauge-breaks and the growth of "through-freight" service were contributing, especially after the Civil War.[8] Their impacts in the restructuring and regional economic integration of the economy, and their further ramifications in the re-organization of industrial and commercial enterprises, were both far-reaching and profound.

Internal transport improvements contributed to breaking down the "protective tariff-walls" of distance, frozen lakes and rivers, and muddy roads that previously had sheltered inefficiently small local manufacturers and wholesalers. Expanded market access, by the same token, continued to increase the economic viability of ever-larger, fixed-capital intensive industrial establishments and thereby contributed to the aggregate capital-intensity of the manufacturing sector. Thus, over the period from 1870 to 1900, according to Robert Gallman's (1986) estimates, the aggregate ratio of reproducible capital to value added (in constant prices) rose by 81 percent in the manufacturing and mining sectors, whereas it had risen by 57 per cent over the previous thirty-year interval.[9]

This picture just sketched of industrial transformation as the new and significant tendency of the post-bellum decades (1870-1900), however, must be tempered by a recognition of that sector's comparative situation vis-à-vis the rest of the U.S. economy. The level of the aggregate mining and manufacturing capital-net output ratio (in current prices) remained below the corresponding ratio of the comprehensively defined agricultural business sector, even though it was moving upwards towards it during these decades. Although, by the same measure for the industrial sector, the roundaboutness of the industrial commodity-producing sectors well exceeded that characteristic of commerce and other private business,

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[7] This theme is more fully elaborated in section 2 of this Part, but the reader may wish at this point to consult Endnote 1 to Part Two for clarification of the concepts of "labor-saving" and "capital-using" bias, and the corresponding notions of "neutrality" of technological progress to which these terms implicitly make reference.

[8] See Albert Fishlow, "Productivity and Technological Growth in the Railroad Sector, 1840-1910," in Output Employment and Productivity in the United States After 1800, Vol. 30. New York: National Bureau of Economic Research, 1966.

[9] See Robert Gallman, "The United States Capital Stock in the Nineteenth Century," in Engerman and Gallman (eds.), 1986: Table 4.8.

the manufacturing and mining capital-output ratio was only approximately one-fourth of that prevailing in the transportation and public utilities sectors. Thus the growth of the demand for transportation, and the latter's connection with the public utilities infrastructure requirements of an increasingly urbanized population, were the powerful proximate driving forces in the economy-wide rise of the capital-output ratio.

Continuity and Change in the Trajectory of Technological Innovations

New and contrasting tendencies in the progress of technologically relevant knowledge became evident from the closing decades of the nineteenth century onwards. A further step in the progression of industrial development, following on from the supplanting of the artisan shop by steam-powered factories, saw the beginnings of assembly line methods of mass production. This was a movement that may be said to have sprung from the fusion of two manufacturing principles. The first of these derived from the continuous flow transfer techniques (for the *disassembly* of animal carcasses) that were being implemented and elaborated in Chicago's large meat-packing plants during the late 1870s and 1880s; the second involved the methods of production by interchangeable parts that during the same period had been brought to full practical realization in the manufacture of the Singer Co.'s sewing machines, and McCormick harvesting machinery.

Yet, more than two more decades passed before the culmination of developments along this characteristically American trajectory of technological evolution, in 1913, when the Model T automobiles began rolling off the assembly line of Henry Ford's Highland Park Factory on the northern edge of Detroit. Great advances of production engineering had been made by the Ford Motor Co. during 1908-13, involving the integration of machine shop, mechanized foundry and sub-assembly operations, the automated conveyor slide, and the accompanying implementation of Frederick Taylor's ideas in the standardization of work routines and establishment of "work standards"at Highland Park.

But those developments went beyond merely revolutionizing the business of building motor cars, which hitherto had been essentially an artisanal shop product. As David Hounshell (1984: p. 261) rightly has observed: "The Ford Motor Company educated the American technical community in the ways of mass production."[10] A deliberate policy of openness was embraced during the design and construction of the Highland Park plant, and this, along with the subsequent publicity that Ford himself gave to the idea of "mass production," contributed to the rapid diffusion of these new techniques throughout American manufacturing. They were quickly imitated by other automobile producers, even those producing far smaller runs of cars. Within a decade, conveyor systems were being applied to the assembly of many other new and complex durable goods, including vacuum sweepers and radios, among the range of electrically powered household appliances that were gaining popularity in the 1920s. In 1926, Henry Ford himself described the generic principles of mass production as "the focusing upon a manufacturing project of the principles of power, accuracy, economy, system, continuity, and speed."

Accompanying the dawn of the "Fordist" stage in the evolution of manufacturing, the opening decades of the twentieth century saw the fruition of earlier departures in the inorganic and organic chemicals industries, and in electrical manufacturing and supply industries. These heralded the rising importance of science-based industry and organized

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[10] David Hounshell, From the American System to Mass Production, 1800-1932, Baltimore: The Johns Hopkins University Press, 1984, p. 261.

industrial innovation. Ultimately, the late nineteenth century developments in those two particular fields – associated with the work of Haber, Solvay and Dupont, and that of Edison, Ferranti and Siemens – greatly expanded the sphere of new industrial applications of organic chemistry, telecommunications, avionics and the commercial exploitation of biological knowledge in agriculture, animal husbandry and medicine.

An increasing ability to control, and hence to predict the experimental process, and the movement of essentially trial-and-error learning activities from semi-controlled industrial environments into the laboratory, speeded the organized search for technologically exploitable knowledge. The reduction of the expected costs and uncertainties surrounding the inventive process, in turn, worked to increase the rate of return on R&D investment, and hence increased the readiness of firms to commit resources to new process and product research on a regular basis. Integration of R&D as a competitive strategy within the orbit of business management planning was thereby encouraged, as was the extension of the R&D approach to the area of production engineering – particularly in those industries (such as heavy chemicals) where the production of new products entailed radical redesign of manufacturing processes.

Two further consequences may be seen to have been entailed by the foregoing developments. First was an increasing demand for scientists and engineers and supporting personnel, who could carry on the necessary knowledge-generating and knowledge-applications activities. That created new incentives for individuals to seek (and invest in) the necessary university training. The prospective demand from industrial employers also stimulated efforts on the part of colleges and universities to adapt existing curricula, or establish entirely new areas of instruction that would be better attuned to those needs. This was a movement that around the turn of the century was already beginning to carry the land grant colleges beyond an initial commitment to responding to the vocational needs of farmers, and into the realms of mechanical and mining engineering. Secondly, and somewhat analogously, the development of organized research in corporate laboratories brought both growing company financing of R&D expenditures, and political interest in the expansion of public and private charitable patronage of research to create a basic knowledge infrastructure that would further raise the private rate of return on applications-oriented R&D. Most of the developments just cited, however, remained nascent, or very limited in quantitative importance at the dawn of the twentieth century. They were harbingers of the coming morphology of growth that would assume full-blown form in the U.S. after World War II.

It is important for our story, however, to re-emphasize that the U.S. economy did not pioneer single-handedly in the fundamental advances of scientific and engineering knowledge that formed the basis for the rise of its newest forms of industrial activity. International (especially trans-Atlantic) participation in the process of invention, and the rapid diffusion of new contributions to the technologies emerging in the fields of machine tools, chemicals, electricity, and automotive engineering, already was quite striking in the period 1870-1913. Yet, in being quick to move towards exploiting the commercialization opportunities that had been created by the advances of the underlying knowledge base, the industrial sector of the American economy already had achieved a particularly advantageous long-run position in this regard when the nineteenth century drew to its close – the recurringly depressed macroeconomic conditions and financial instabilities of the 1890-1907 era notwithstanding. The start that had been made towards the creation of a whole group of new industries came on top of the solid foundations laid in the post-Civil War decades: a heavy industrial, mining and minerals processing sector, which was served by an extensive network of railroads that gave all-weather access to a national market of continental dimensions.

The Exploitation of Natural Resource Abundance

Many features of the industrial structure that at this time was undergoing consolidation and reorganization reflected specifically American conditions that in the preceding century had shaped the path of the country's economic development. These were first, the great abundance, variety and cheapness of natural resources and primary materials; second, the emergence in the course of that century of the largest-scale domestic market in the industrializing world. Both conditions favored a fuller exploration and exploitation of that century's dominant trajectory of technological progress than was possible in European circumstances. The technological path was materials-intensive and tangible capital-using but scale-dependent, and American conditions were especially congruent with it. Large market scale encouraged the invention and use of expensive machinery whose costs could be spread over large sales to a wide market. Abundant and cheap materials facilitated the invention of relatively crude and simple forms of tools and power-driven machinery. These made extensive and seemingly extravagant use of natural resources. Yet, because the latter were complementary with greater use of sophisticated machinery and animate power sources, this profligacy was more apparent than real; it reduced overall production costs by allowing firms to dispense with relatively expensive workers, and especially with higher skilled craft labor. At the outset of its industrial development America possessed abundant virgin forests and brushlands, and, in the Age of Wood that preceded the Age of Iron, this profusion of forest resources generated strong incentives to improve methods of production that facilitated their exploitation, to use them extravagantly in the manufacture of finished products (such as sawn lumber and musket-stocks), and to lower the costs of goods complementary to wood (such as iron nails, to take an humble example). In describing America's rise to woodworking leadership during the period 1800-1850, Nathan Rosenberg aptly writes:

> "[I]t would be difficult to exaggerate the extent of early American dependence upon this natural resource: it was the major source of fuel, it was the primary building material, it was a critical source of chemical inputs (potash and pearlash), and it was an industrial raw material par excellence."[11]

Beyond that stage, the industrial technology that had emerged by the decades at the close of the nineteenth century and the beginning of the twentieth century was based firmly on the exploitation of the continent's endowment of minerals: on coal for steam power, on coal and iron ore for steel, and on copper and other non-ferrous metal for still other purposes. American enterprise, reprising its early nineteenth-century performance in rising to "industrial woodworking leadership" by combining technological borrowing from abroad with the induced contributions of indigenous inventors, now embarked upon the exploration of another technological trajectory: the new path was premised upon, and in turn fostered the rapid and in some respects environmentally destructive exploitation of the country's vast mineral deposits, just as in the preceding era wastefully impatient use had been made of the nation's virgin forest resources.

During the second half of the nineteenth century and continuing into the early twentieth century, the dominant path of technological progress and labor productivity advance continued to be naturally resource-intensive, but made increasingly heavy use of

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[11] Nathan Rosenberg, Perspectives on Technology, Cambridge: Cambridge University Press, 1976: Ch. 2.

mineral resource inputs, as well as being more markedly tangible-capital-using. This particular path of innovation was, moreover, scale-dependent in its elaboration of mass-production techniques and high-throughput operating strategies for business organizations. Although the characteristic features of this technological trajectory individually can be traced to back to industrial initiatives in both Britain and the U.S. earlier in the nineteenth century, the ensemble found fullest development in the environment provided by the North American continent.

As has been indicated, one source of the country's advantage in following this particular trajectory of biased innovation stemmed from the congruence between its pattern of input complementarities, and the North American continent's abundant and cheap supplies of primary materials. The new methods of production substituted tangible capital equipment for labor, while making more intensive use of raw materials and energy. Their profitability was therefore enhanced where the relative prices of the latter inputs were lower in the mid-nineteenth century phases of this evolution, the costs of coal as a source of steam power, of coal and iron ore for steel-making, and of copper and still other non-ferrous metals, bulked larger in the total costs of finished goods than subsequently has come to be the case. Those economic circumstances, from the middle of the nineteenth century onward, had acted as a stimulus for programs of public and private investment aimed at discovering, developing and intensifying the commercial exploitation of these mineral resources. Ultimately, as the results of state and federal programs of geological exploration bore fruit, those earlier historical conditions became the foundations for America's growing comparative advantage as an exporter of natural resource-intensive manufactures during the period 1880-1929.[12]

Of course, there were also powerful commercial incentives for private investment in minerals exploration and development. These derived largely from the perceived growth of demand, as American manufacturing shifted away from heavy concentration on the processing of agricultural and forestry products, and towards the production of minerals-based capital and consumer goods. There was, therefore, a fruitful interaction between the development of primary materials supply, the advance of American technology, and the growth of manufacturing, construction and transportation activities serving the large domestic market.[13]

Thus, the twentieth century's opening quarter saw the continued influence of some of the same features of the U.S. resource endowment. Thereafter, for a variety of reasons that we discuss in Part Three, natural resource abundance in general, and mineral resource abundance specifically, became of smaller importance over the broad spectrum of American economic activity. In special ways, however, it remained a potent influence. A notable instance is the continuing discoveries and advances in the exploitation of the country's known petroleum resources, which were extended westward to the southern California basin during the opening quarter of the century.[14] These developments yielded far more than the

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[12] See Gavin Wright, "The Origin of American Industrial Success 1879-1940," American Economic Review, 80(4), 1990: pp. 651-68. See, esp., Chart 5 and Table 6.

[13] See Endnote 2 to Part Two.

[14] See H.F. Williamson and A.R. Daum, The American Petroleum Industry, Evanston, Illinois: Northwestern University Press, 1959; H.F. Williamson et al., The American Petroleum Industry: The Age of Energy, 1899-1959, Evanston, Illinois: Northwestern University Press, 1963; Paul A. David and Gavin Wright, "Increasing Returns and the Genesis of American Resource Abundance," Industrial and Corporate Change, 6(2), 1997, pp. 203-45.

nation's growing exports of crude oil and high value distillates, such as gasoline and kerosene, and even more than the resource base for the future industrialization of the part of the country that bordered on the Pacific Ocean.[15] Elsewhere at home, petroleum products became part of the underpinning for the rise of car, truck and tractor production and the expansion of the automotive services sector during the 1929-66 era until it was responsible for roughly a tenth of gross domestic product originating in the U.S. economy. Still more directly, the abundance of domestic petroleum supplies yielded by exploitation of the oil fields of West Texas, Oklahoma and southern California contributed to the creation of a wide group of new petrochemical-based manufacturing industries in which America took a technological lead.[16]

Another important set of region-specific influences was linked to the development of an economically large national economy that was integrated by transport and communications systems of continental reach, and which, in comparison with other contemporaneous societies, would soon become remarkably homogeneous in its political and social structures. From an early point in its history, the U.S. was among the pioneers in the elaboration and replication of large, spatially distributed technological systems, including systems of business organization and public service provision. Like airline systems, the multi-divisional and multi-plant corporations, and the public school and university systems, the electricity supply and telephone systems first developed locally and regionally to achieve conventional economies of scale. They were then replicated across localities and regions to form dense and extended networks (with corresponding network externalities) that differentiated the American economy from all but a few others by the mid-twentieth century.

Rising Intangible Investments and the Transformation of Human Resources

Formation of these large production organizations and systems of distribution that were complex and intricate created new demands for manpower, with needs for novel skills emerging as old ones were rendered obsolete or redundant. The absorption of European immigrants into the American workforce in the post Civil War decades was facilitated by the substitution of mass production technologies that reduced artisanal skill and training requirements for production workers, while raising demands for non-production workers in clerical and managerial positions. Yet, over the course of the twentieth century the overall demand-side impact has been quite unambiguously that of supporting a rise in the minimum level of educational attainment in the population, while expanding the proportion of the workforce that had undergone prolonged periods of formal education.

The twentieth century has witnessed two distinct waves of human capital formation. The first of these was centered in the first quarter of the century and involved the extension of High School education to a large segment of the population, whereas the "college education" movement, which formed the second wave, gathered momentum after the mid-point of the century. In the closing decade of the nineteenth century, only rather less than half of the population in the age range from 5 to 24 years was enrolled in some regular educational institution. From that low base c.1890, the pace of progress began to quicken: this was

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[15] On California's industrial development esp., see Paul W. Rhode, Growth in a High Wage Economy: California's Development, 1900-1960, (Unpublished Ph.D. Dissertation), Stanford University, 1900.

[16] On U.S. petrochemical manufactures more generally, see Ashish Arora, Ralph Landau and Nathan Rosenberg, (Eds.), Chemicals and Long-Term Economic Growth: Insights from the Chemical Industry, New York: John Wiley and Sons, Inc., 1998, esp. Chs. 3, 5, 7.

reflected two decades later by the accelerating rise of the average number of school years completed by all males in the age group 25 and older: it rose by 6.4 percent in the decade 1910-20, by 7.6 percent in the following decade, and so on, until the decadal rate of advance topped 10 percent during the 1940s.[17] The average number of years of schooling among American males was thereby raised from 7.56 to 11.46 between the birth cohort of 1886-90 and that of 1926-30, and the average annual rate of increase shifted upwards by a bit more than 1 percentage point.

Claudia Goldin's (1998) research brings out the striking fact that approximately 70 percent of this increase was accounted for by increases in *secondary* schooling alone.[18] The male high school graduation rate, for example, stood at 10-15 percent for the cohort born in the 1890s, but rose to nearly 50 percent for those born after World War I. High school thus became part of the system of mass education in America during this era, whereas previously it was typically either the final stage of the training of school-teachers, or a requirement for the tiny minority of the population who sought a Bachelor's degree (or the professional equivalent thereof). Whereas almost one-half (49 percent) of the high school graduates of the mid-1880s went on to receive a Bachelor's degree from an American institution of higher education, the widespread extension of high school education in the following decades brought that fraction down to 30 percent by 1906, and to 22 percent by 1926.[19]

Although the stock of graduates from U.S. institutions of higher education was rising very rapidly early in the century, it was still negligibly small, and its formation was neither a significant claimant upon national resources nor a noticeable influence upon the quality of the workforce. To the extent that investments in education beyond the common school level could be rated as important on either count during the first quarter of the twentieth century, they were entailed in the public high school movement. The latter took root first in the Midwest during the 1880s, spread quickly to other regions in the North before 1914, and by the 1930s had largely been completed – with the widespread achievement of generally high attendance rates, a significantly lengthened average school year, and substantial graduation rates – everywhere in the country save for the still largely agricultural South.

The early phases of this movement, however, cannot properly be understood as merely an automatic, market-induced adjustment of the nation's labor supply, in response to occupational demand shifts driven by technological and organizational innovations in industry. It seems only reasonable to suppose that an important impetus for this movement derived from the increasingly widespread public awareness of the developing statistical association between high school attendance and subsequent access to "better quality jobs," even jobs in blue collar occupations. By working backward from the comprehensive

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[17] The figures for 1910-40 are based on Edward F. Denison, The Sources of Economic Growth in the United States and the Alternatives Before Us, New York: Committee for Economic Development, 1962, Table 4, col. 2. These estimates were made using the cohort method, subject to an upward adjustment of 0.2 percentage points per annum to allow for a suspected reporting error. For educational attainment estimates based upon U.S. Population Census data for the period 1940-60, see Moses Abramovitz and Paul A. David, "Technological change and the rise of intangible investments: the US economy's growth-path in the twentieth century," in Employment and Growth in the Knowledge-Based Economy: OECD Documents, Paris: OECD, 1996: esp., Table 2 .

[18] See Claudia Goldin, "America's Graduation from High School," Journal of Economic History, 58(2), June 1998: pp. 345-74.

[19] See Footnote 12 above.

schooling data presented in the 1940 census, Claudia Goldin and Lawrence Katz have been able to show that the percolation of high school graduates throughout the manufacturing sector initially was extremely uneven; that those industries which had been built upon on the newly emergent science-based technologies -- such as aircraft, electrical machinery, and petroleum refining -- employed large numbers of high school graduates in both blue- and white-collar jobs, and it appears that this pattern goes back at least as far as the 1910s.[20] Detailed job descriptions and qualifications, developed by the Bureau of Labor Statistics between 1918 and 1921, reflected the increasing role of schooling-based skills, such as "knowledge of weights and measures," "record-keeping and computations," "knowledge of how to set machines and test results," "special ability to interpret drawings," and so forth. Yet, these were quite atypical among the mass of manufacturing pursuits, and in the older, staple industries such as meat-packing and cotton manufactures, virtually no jobs are listed as having any required level of schooling at all; even a "loom fixer," the most important and skilled worker in the weaving room, was not expected to have more than a common school education. Furthermore, even in the newer industries drawing on newer technologies, the job descriptions of this era suggest that very limited levels of cognitive mastery actually were expected. Actual command of scientific knowledge as a job requirement was limited to a tiny fraction of the overall work force, and these positions typically required post-secondary training if not professional degrees.

The new and more rapidly growing industries, nonetheless, had ample reasons for adapting their hiring criteria and job descriptions to match the curriculum of high school education. Another recent reading of the evidence from the pre-1929 era, by David and Wright (1999), suggests that in setting hiring standards certain personality traits, such as patience, reliability, and general amenability to instruction, were given equal if not greater prominence than were the more strictly academic cognitive qualifications. In the technologically more sophisticated industries, and especially in branches of manufacturing where continuous production processes raised both productivity and the damage that incompetent or carelessness could cause, employers increasingly sought workers who could accustom themselves to changing work routines, and would be dependable in executing mechanically assisted tasks. High school attendance and high school completion appear to have constituted signals of these attributes, and of the motivation to respond to experience-based wages and job promotion incentives that were designed to stabilize and upgrade the quality of the workforce in the leading manufacturing firms during this era. Thus, it was in their interest both to advocate and to exploit the public's subsidization of the secondary education system as a screening mechanism, through which "signals" of those desirable qualities could more readily be acquired by workers who also would be willing to enter blue collar occupations.[21]

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[20] Claudia Goldin and Lawrence F. Katz, "The Origins of Technology-skill Complementarity," Quarterly Journal of Economics, 113, (August) 1998: pp. 693-732. For further discussion, see Paul A. David and Gavin Wright, "Early Twentieth Century Productivity Growth Dynamics: An Inquiry into the Economic History of 'Our Ignorance'." Stanford Institute for Economic Policy Research Discussion Paper No. 98-3, (April) 1999, esp. pp. 25-7 and Table 5.

[21] In explaining cross-state variation in the spread of high school education, Claudia Goldin ("America's Graduation From High School," Journal of Economic History, 58(2), June 1998: pp. 345-74) reports that the relative importance of manufacturing in a state was in fact a negative influence. Furthermore, in his study of evolving employment relations in Philadelphia, Walter Licht (Getting Work: Philadelphia, 1840-1950, Cambridge MA: Harvard University Press) reports that increases in the compulsory school-leaving age were never welcomed by either employers or by the bulk of the students; these policy changes were part of the broad policy trend to exclude teenagers from the labor force, and for the most part not a response to rising educational demands by employers.

But, there were other social, political considerations that came into play in America's precocious initiation of mass secondary education. Middle class support for public education beyond the grade school level, especially in preparation for the "genteel," non-manual pursuits, was increasingly vocal during the decades immediately surrounding 1900, and this impetus was reinforced by political concerns to promote "Americanization" among first-generation citizens. Such motives were quite compatible with perceptions on the part of employers that increasing cultural homogeneity of young members of the workforce would serve to increase the interchange-ability and adaptability of the labor force, thereby facilitating the replication of standardized work routines and labor management practices within and across regional labor markets -- at least as far as concerned the white workforce. These influential currents of opinion, which issued in the provision of tax-funding for state and local programs of mass secondary education, may be seen as part of the response evoked by the heavy influx of "new" immigrants from southern and eastern Europe in the period. Consequently, beginning most notably in the Midwest (and, more general in those regions of the North where there were relatively fewer youths from low-income foreign-born households, who needed the earnings from their labor in factories and shops), the 1890s saw an increasing fraction of young Americans attending and completing High School.

Thus was set in motion the dramatic and sustained growth of the nation's stock of intangible human capital, led by the increasing educational attainments of its workforce. Reinforced by industrial and derived occupational shifts that increased the demand for longer schooling, it laid the foundations for the subsequent transition to mass college and university attendance that marked the post-World War II era, and which has continued the upward course of the U.S. population's average educational attainment. Of course, the pace at which the schooling level of the workforce as a whole could rise during 1886-1926 was slower than the speed at which high school completion was diffusing through the population. As the more schooled males were the last to enter the workforce, the full effect of the increase in years of schooling had to wait for the retirement of successive cohorts of older workers since so few of them had as much as a year of high school attendance.

Indeed, according to Goldin, of the cohort of males born in 1886-1890 who survived to report their educational attainment to the 1930 census takers (when they were 40-44 years old), 72.5 percent had fewer than eight years of formal schooling, and only 17 percent had 12 or more years.[22] Among the entire U.S. male population aged 25-34 years old at the time of the 1930 census, 24.4 percent reported having had four years of high school education and beyond, whereas the corresponding figure among the 25 to 34-year-olds in 1910 had been only 15.7 percent. The average speed at which high school completion had spread through the male population of prime working ages was thus about 2.2 per cent per annum during the 1910-30 interval. The comparable rate rose on average to 7.5 percentage points per annum over the interval between 1930 and 1960, by which date well more than a majority of them (53 percent) had at least completed high school, and a significant minority had completed four years of college.[23] Something must also be given to the effects of closing immigration to the U.S. after 1918, in creating conditions that facilitated the speed of the shift towards higher

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[22] See Claudia Goldin, "America's Graduation from High School," <u>Journal of Economic History</u>, 58(2), June 1998: pp. 345-74: Table 1.

[23] The figures cited in the text refer, respectively, to the numbers of Bachelor's degree recipients in 1888, 1910 and 1930, expressed as a percentage of the total number of high school graduates four years previous to each date. See U.S. Department of Commerce, <u>Historical Statistics of the U.S.</u> (1975), v.I: Series H-759.

average educational attainments, and so provided the skills and worker qualities that were complementary with the new technologies and the more complex systems that were being developed.

"College education" had been a rarity among the American populace until the latter decades of the nineteenth century. The seventeenth and eighteenth century origins of institutions such as Harvard College, Columbia College and Yale notwithstanding, it was not until the 1860s that Americans first began hearing about the “business colleges” and “state teachers’ colleges” that eventually would bring higher education within the grasp of the common citizen. By 1880, however, some 811 higher education institutions (HEI’s) were already in existence, having a combined faculty of roughly 11,500 and awarding something in the order of 13,000 bachelors degrees annually, though it was not until 1888 that the total number of academic doctorates awarded annually in the whole country moved past the 100 mark.[24] While it took more than a half-century for the number of HEI’s to double from the level that had been reached in 1880, the average number of faculties per institution had undergone a 3.5-fold expansion during those 50 years, and the annual number of Bachelor’s degree recipients per institution had increased 5-fold. Still, only 2 percent of America’s 23-year olds received a Bachelor’s (or equivalent professional degree) in 1910, and in 1930 the corresponding figure remained below 6 percent.

The major period of advance in the college and university education of the labor force, therefore, has been a feature of the post-1929 era, and it only began to make a large impact on the quality of the workforce during the late 1960s and 1970s when the large birth cohorts of the post-World War II “Baby Boom” were moving through the universities. Between 1930 and 1948 the number of college graduates expressed as a proportion of all those who had graduated from high school four years before was raised from 22 percent to 27 percent, a level that was maintained through to the mid-1960s. Thereafter, the early years of the Vietnam War era witnessed a further sharp rise, so that by 1969 the 31 percent level had been reached. At that date the number of Bachelor’s degree recipients represented more than one-fourth of the nation’s 23 year-olds, twice the proportion that had been achieved in 1948. The “golden era”of post-World War II economic growth also saw the first substantial movement into post-graduate education since the 1920s, as the numbers receiving doctorates swelled from approximately 4,000 in 1948 to 28,000 in 1969.[25]

Tangible Capital-Saving Innovations and Quickening Total Factor Productivity Growth

The substitution of fixed capital for skilled artisanal labor that was characteristic of the preceding era now gave way to a new twentieth century tendency that was augmented in strength by the prospects of declining fertility and slowed labor force growth (unrelieved by any possibility of revival of mass immigration). With the resumption of rising real wages following World War I,[26] capital-labor substitution continued to be encouraged, but there also

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[24] The diffusion of high school completion proceeded at a matching pace among the female population, but the initial and hence the terminal levels of the fraction of women ages 25-34 who reported having had four years of high school and beyond were even larger than in the case of the males (58.0 in 1960). See the estimates based on corrections of the original census figures by Susan O. Gustavus and Charles B. Nam, “Estimates of the ‘True’ Educational Distribution of the Adult Population of the United States from 1910 to 1960,” Demography, 5(1), 1968: pp. 410-21.

[25] See A&D (2001) Endnote 3 to Part Two.

[26] On the altered industrial labor market conditions that emerged after 1917, and behavior of real wages, see Paul A. David and Gavin Wright, “Early Twentieth Century Productivity Growth Dynamic: An Inquiry into the

were opportunities to reduce unit costs of production by developing ways of intensifying the utilization of fixed facilities. This was a strategy that was first implemented in the late nineteenth and early twentieth century consolidation of railroads, and the technological innovations designed to increase train-speeds and power utilization. Its roots can also be found, as Alfred Chandler has pointed out, in the high throughput manufacturing regimes that appeared after 1870, when production and direct-selling were extended to serve increasingly wide markets.[27]

Along with the new managerial focus and increasing expertise devoted to increasing the throughput rate of production and marketing enterprises, there came savings on the costs of inventories of goods in process and stocks of finished products, all of which worked in the direction of lowering the marginal capital-output ratio in the nation's manufacturing sector.[28] With the coming of enhanced transportation and communications facilities, it also was feasible to achieve high stock turnover rates, and narrowed margins in the distribution trades; the late nineteenth century thus saw the appearing of the pioneers of that strategy among the large-scale retail businesses -- such as Marshall Fields, Macy's and Sears Roebuck. But, throughout the next half-century, in the distribution sector small, low-turnover and high-markup firms managed to co-exist with the high volume enterprises to much greater degree than was feasible in manufacturing. Local market power, arising from locational convenience, certainly afforded small stores a measure of protection from the competition of supermarket chain-stores, and other high-turnover retailers. But the persistence of the share of the market throughout the interwar era and early post-World War II years, also owed something to the imposition of differential taxation of chain-stores by state legislatures early in the twentieth century, and the introduction of "price maintenance laws" (starting with the passage of the Robinson-Patman Act of 1936).[29]

The technological developments that expanded the scope for continuous process industries, such as the reorganization of batch production systems to move them towards an around-the-clock shift-working basis, and the managerial changes that were required to coordinate the flows of men and materials in these high-throughput operations represented innovations of the "tangible fixed-capital augmenting" kind. These contributed to the turn-around in the trend of the real tangible capital-output ratio, which in the first decade of the twentieth century commenced a secular fall not only in the manufacturing sector, but in the private business economy at large.

A marked acceleration of total factor productivity (TFP) growth took place in the U.S. manufacturing sector following World War I. This surge saw the annual growth rate jump fully 5 percentage points between the second and third decades of the century, and it contributed substantially to the absolute and relative rise of the TFP residual that we observe

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Economic History of 'Our Ignorance'," Stanford Institute for Economic Policy Research Discussion Paper No. 98-3, (April) 1999, esp. 19-25.

[27] See Alfred D. Chandler, Jr., The Visible Hand: The Managerial Revolution in American Business. Cambridge, MA: Harvard University Press, 1977.

[28] On inventory stocks and investment, see Moses Abramovitz, Inventories and Business Cycles, with Special Reference to Manufacturers' Inventories. New York: National Bureau of Economic Research, 1950. On increased throughput rates and savings on working capital, see Alexander J. Field, "Modern Business Enterprise as a Capital-Saving Innovation," Journal of Economic History, 47(2), June 1987: pp. 473-85.

[29] For further discussion, see, e.g., Alexander J. Field, "The relative productivity of American distribution, 1869-1992," Research in Economic History, 16, 1996: pp. 1-37.

(in Part One) when the "growth accounts" for the first quarter of the twentieth century and those for the latter half of the nineteenth are compared.[30] Annual measures of TFP in U.S. manufacturing are not available for this era, but it seems nonetheless clear that the discontinuity revealed by comparison of the decadal average rate of growth for 1919-29 with that for 1909-19 was not an artefact of cyclical fluctuations accentuated by wartime and postwar demand conditions. The recent statistical analysis by David and Wright[31] of the available annual figures for labor productivity (real gross product originating per full-time equivalent manhour in manufacturing) confirm and upward shift in the trend rate of growth from 1.5 percentage points per annum during 1899-1914, to 5.1 during the period 1919-29.

While this historical break in the productivity trend was not a phenomenon unique to the manufacturing sector, it was heavily concentrated there. John Kendrick's (1961) estimates of the decadal increase in total factor productivity (TFP) during 1919-29 at approximately 22 percent for the whole of the private domestic economy, whereas the corresponding figure for manufacturing was 76 percent, and for mining 41 percent. The proportionate increase of TFP in transportation, communications and public utilities exceeded the average for the U.S. private domestic economy as a whole by lesser amounts, while the farm sector was in last position with a relatively low gain of 14 percent.

At the heart of the story, then, was manufacturing, where the acceleration was particularly pronounced and pervasive among the main industrial groups. The movements of the partial productivity indexes for these same industry groups over the course of the 1919-29 interval shows a striking positive correlation, which was a departure from the tendency in the preceding decades. For industrial labor productivity increases to be associated with decreasing capital productivity, rather than capital-deepening, reflected in a rise in real capital inputs per unit of real output, manufacturing industries both in aggregate and at the industry group level were undergoing "capital-shallowing" or rising capital productivity after 1919.

A long period of stasis in the real unit costs of industrial labor during 1890-1914 came to an end with the outbreak of World War I, and the ensuing rapid rise in the price of labor inputs vis-à-vis the prices of both capital inputs and gross output was sustained during the post-War decade. The change in relative factor prices thus was in a direction that would be expected to induce the substitution of capital for labor within the pre-existing set of production technologies. Therefore, it is particularly striking that after 1919 the rise of capital-intensity in U.S. manufacturing proceeded at a greatly *retarded* pace. Between the 1889 and 1909 census benchmark dates, the ratio of capital inputs per unit of labor input was rising at the average rate of 2.6 percentage points per year, and the pace quickened to 2.8 percent per annum over the decade 1909-19. But, as John Kendrick's (1961) figures show, despite the upsurge of real wage growth, during the 1920s the growth in capital-intensity slowed to (1.2 percentage points per annum) well below half its previous pace. This change, and the emergence of tangible "capital-shallowing" tendencies with which it was linked represented a new departure, which one of us (David 1990, 1991) has connected to the

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[30] See Paul A. David, "The Dynamo and the Computer: An Historical Perspective on the Productivity Paradox," American Economic Review, 80(2), May: pp. 355-61; "Computer and Dynamo: the Modern Productivity Paradox in a Not-Too-Distant Mirror," in Technology and Productivity: The Challenge for Economic Policy, reminded economists and economic historians of the surge which followed an extended industrial "productivity pause" that extended throughout the period 1890-1918.

[31] Paul A. David and Gavin Wright, "Early Twentieth Century Productivity Growth Dynamics: An Inquiry into the Economic History of 'Our Ignorance'," SIEPR Discussion Paper No. 98-3, Stanford Institute for Economic Policy Research, April 1999.

concurrent diffusion of a new factory regime in which the productive potentialities of the electric dynamo were, at last, fully exploited by the "unit drive" system in which independent motors were place on each machine.[32]

It is also worth noticing that there was an easing of another previous source of upward pressure on the aggregate capital-output ratio. That pressure had come from the demand to create urban infrastructures – in the form of housing, streets, sewers and local transportation facilities – to serve the commercial distribution and industrial centers of new regions of the country that were being opened up for population-intensive forms of economic exploitation. James Duesenberry[33] long ago observed that the successive waves of internal migration, which had carried the "urban frontier"westward during the nineteenth century, had the effect of increasing the demand for fixed capital in new locations, yet did not cause an offsetting, commensurately rapid run-down of the corresponding capital stock components in the older cities of the Eastern seaboard. Of course, the urban infrastructure of the latter region were coming to be more intensely utilized to accommodate the large influx of immigrants arriving from Europe in the period 1880-1914. But, until late in the century, the balance of those forces, working in combination with the related demands for expanded transport infrastructure in the West, was operating in a way that held the marginal capital-output ratio above the average capital-output ratio in the economy as a whole. With the closing of the frontier and the choking off of European immigration (by World War I, and the subsequent imposition of legislative restrictions in the U.S.), this the former demographic mechanism no longer functioned to sustain a secularly high ratio between the level of the desired fixed tangible capital stock and the level of the real gross domestic product.

Management of large technological and commercial systems also called for new techniques for "communication and control."[34] These, rendered more effective the push for ever-higher rates of utilization of fixed capital facilities, and faster stock-turn to lower the costs of inventory holds of goods in process. The same capital-saving motivation in the drive for improved "control" had played a role in initiating pioneering U.S. advances in information systems -- from the telegraph system's close relationship to the railroad industry's operations and the activities of wholesale distributors starting in the mid-nineteenth century, to the twentieth century development of a nation-wide telephone network, and of computer systems in the twentieth century. To cite another, and emblematic link of this kind, the modern digital computer grew out of Vannevar Bush's designs for "differential analyzers," an analogue computer that was sought for the purpose of performing the calculations necessary for real time management of electrical power supply systems.[35]

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[32] This explanation recently has been elaborated upon by Paul A. David and Gavin Wright, "Early Twentieth Century Productivity Growth Dynamics: An Inquiry into the Economic History of 'Our Ignorance'," SIEPR Discussion Paper No. 98-3, Stanford Institute for Economic Policy Research, April 1999.

[33] James Duesenberry, Business Cycles and Economic Growth, New York: McGraw-Hill, 1958.

[34] This general theme is treated in James R. Beniger, The Control Revolution: Technological and Economic Origins of the Information Society, Cambridge, MA: Harvard University Press, 1986. On the role of "internal" communications technologies in the growing size of business organizations in the period 1850-1920, see JoAnne Yates, Control through Communication: The Rise of System in American Management., Baltimore: The Johns Hopkins University Press, 1989.

[35] See James R. Beniger, The Control Revolution: Technological and Economic Origins of the Information Society, Cambridge, MA: Harvard University Press, 1986, esp., Ch. 9, on the historical roots of modern information and control technologies,. The differential analyzer, built by Bush in 1930, was the first automatic computer general enough to solve a wide variety of mathematical problems; it preceded Wallace Eckert's more widely mentioned "mechanical programmer" (1933), which linked various IBM punch-card accounting

Engines of Growth -- The Recurring Dynamics of General Purpose Technologies

Thus, however distinct and different was the new technological thrust that has characterized the twentieth century -- encouraging through its demand effects the rise of investment in intangible productive assets in the form of more highly educated people and stocks of R&D-generated innovations, and reducing the demand for conventional tangible capital goods in relationship to real output -- in these developments there also were some important continuities from an earlier epoch. Perhaps the most striking among these was the way in which a succession of "general-purpose technologies" came to be elaborated and implemented in the U.S. during the twentieth century. General purpose technologies open up new opportunities for innovation -- in both inventive and entrepreneurial activities -- rather than offering a complete, self-contained and immediately applicable solution to one or another specific problem.[36] In that sense, their nature enables further changes, inducing further investment of resources in the creation of clusters of complementary innovations; and their pervasive penetration into products and processes across a wide and varied range of industries permits their own further elaboration and enhancement to exert a greatly magnified impact on productive performance throughout the economy.

Thus, in the twentieth century, the extensive deployment and continuing development of the electric dynamo, mass production in fixed transfer-line factories, telecommunications via the electromagnetic spectrum, internal combustion engines fueled by petroleum distillates, and, most recently, the microelectronics-based digital computer -- represented a recurrence of dynamic patterns of innovation and diffusion that were experienced earlier, in the age of the steam engine, factory system, railroad and telegraph.[37] The sources of the scientific and engineering knowledge underlying the creation of these "enabling technologies" have been international, rather than peculiarly American. But these innovations found practical expression and extensive commercial development first and most fully in the United States' highly flexible and adaptive social and economic environment.

Consequently, the specific forms that emerged from the initial implementation of these general purpose technologies during the twentieth century owed much to the particular legacy of the country's nineteenth century development. Their subsequent diffusion within a widening international sphere, in turn, has transmitted to many societies in the economically developed world some portion of the legacy of that earlier era of "American exceptionalism." Abroad, as previously had been the case within the sphere of the U.S. domestic economy, the drive to exploit this accumulating body of knowledge and know-how has been a powerful

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machines to permit generalized and complex computation.

[36] On "general purpose engines," and the generalized concept of a "general purpose technology" (GPT), see Paul A. David, "General-purpose engines, investment and productivity growth: from the dynamo revolution to the computer revolution," Ch.7 in Technology and Investment: Crucial Issues for the 1990s (E. Deiaco, E. Hornell and G. Vickery, (Eds.), London: Pinter Publishers, 1991; Timothy F. Bresnahan and Manuel Trajtenberg, "General Purpose Technologies: Engines of Growth," Journal of Econometrics, 65, 1995: pp. 83-108; Elhanan Helpman, ed., General Purpose Technologies and Economic Growth, Cambridge, MA: MIT Press, 1998; Paul A. David and Gavin Wright, "General Purpose Technologies and Surges in Productivity: Historical Reflections on the Future of the ICT Revolution," (Paper for the International Symposium on Economic Challenges of the 21st Century in Historical Perspective, in Oxford, 2-4 July, 1999), University of Oxford Discussion Papers in Economic and Social History (June), 1999.

[37] For comparative discussion of these and other historical episodes, see Richard G. Lipsey, Cliff Bekar and Kenneth Carlaw, "What Requires Explanation?," Ch. 2 in Helpman, General Purpose Technologies (1998).

force for "convergence" -- reshaping the organization of production and distribution globally, and transforming the nature of work, consumption and leisure activities in the process of raising material standards of living.

2.2 An Overview of the Macroeconomic Record and the Questions It Raises

Six salient features characterize the United States' two centuries of modern economic growth, as that experience is profiled by the aggregate statistical picture that has been constructed for the private domestic economy.[38]

(1) Sustained growth with modern characteristics began in America during the first half of the nineteenth century. It started slowly with an average rate of per capita output growth well below one percent a year over the first half of the century. There was substantial acceleration between the first and second halves, and again at the turn of the century. Since then, for a full century (1890-1989), per capita output growth has risen steadily at a rate hovering around 1.8 percent a year when measured by private output across "long periods." As a result per capita output now stands at a measured level six times as high as a century ago [A&D(2001),Table 1: I].

(2) The sources of per capita growth have changed dramatically. A first change was in the relative importance of labor input per head versus output per unit of labor input. In the first half of the nineteenth century, they were of equal importance. In the second half, the labor productivity share rose to two-thirds. And then for three-quarters of a century (1890-1966), the growth of labor input per capita turned negative, and labor productivity growth has utterly dominated the growth of output per capita [A&D(2001),Table 1:II]. But the period of Slowdown since 1966 has seen what is probably a transient reversion to the pattern of the nineteenth century. The coming-of-age of the Baby Boom cohorts combined with an accelerated entry of women into paid work to make labor input again an important source of output growth [A&D(2001),Table 1:III].

(3) Other major developments consist of the changes in relative importance that occurred among the sources of labor productivity growth [A&D(2001),Table 1:IV]. In the nineteenth century taken as a whole, and more particularly in the second half of the century, the growth of tangible capital per manhour was the most important proximate source of labor productivity growth. It was largely responsible for the great speed-up of growth between the first and second halves of the century. In the twentieth century, however, the growth rate of tangible capital per manhour was slower, and its decline in relative importance was large [A&D(2001),Table 1:IV-Addendum] .

(4) In some part, its decline was offset by the growing twentieth-century contributions of Labor and Capital Quality, essentially by the rising educational level of the workforce and by the growing importance of short-lived, high gross return capital equipment relative to that of land and long-lived structures [A&D(2001),Table 1:IV]. The rise of education may be seen

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[38] References are made in the following to A&D (2001) Part I, Tables 1:I through 1:IV The quantitative picture of U.S. macroeconomic growth in the nineteenth century presented here differs in some particulars from that in Robert Gallman's chapter in Volume 3 of the Cambridge Economic History of the United States. A&D (2001) Pt. One: Endnote 10 provides a detailed reconciliation of the two views, showing that the differences arise largely from differences in the choice of periods, our use of gross private domestic product measure of output rather than net domestic product, and of manhours rather than worker-years for the measure of labor services.

as a symptom of a still broader rise of knowledge-carrying intangible assets, a development that we have still to take fully into this account. But the relative rise of rapidly depreciating capital equipment within fixed reproducible business assets, is another expression (and a tangible one) of the economy's emergence from an earlier epoch of extensive growth to its present dependence on technological progress.

(5) The "crude" measures of TFP growth that are available for the nineteenth century economy include such gains as derived from both technological and organizational innovations proper, improvements of the allocative efficiency of business enterprises and markets, and economies of scale. Extensive growth, involving rapid population growth and land settlement, together with its concomitant provision of a great transportation network of local, regional and national roads, canals, river ways and railroads was the material basis for great gains from economies of scale, as well as the erosion of local monopolies and their attendant inefficiencies. These may have been a very large element in the TFP growth up to the 1890s. In the twentieth century, however, this gave way to more rapid technological progress based on the advance of practical knowledge with an ever more important scientific base. That progress went on for three-quarters of the twentieth century at a rapid pace. As measured by the Refined TFP growth rate (which is nonetheless inclusive of the gains deriving from economies of scale), the pace of advance became more than 3.5 times faster than in the second half of the nineteenth century [A&D(2001),Table 1:IV].

(6) Rising total factor productivity thus became the principal source of the rapid twentieth century average growth rates of both labor productivity and real output per capita. Yet, this is only one facet of the more complicated and interrelated temporal evolution taking place in the configuration of growth sources. The great rise in the importance of the contribution made by (refined) TFP growth between the centuries emerges clearly, and more dramatically in real product growth per capita than in labor productivity [from A&D(2001),Table 1:IV]

Table 1
The Relative Importance of the Sources of Growth: U.S. Private Domestic Economy

	Percentage Contribution to the Growth Rate of Labor Productivity			Percentage Contribution to the Growth Rate of Output per Capita			
	Capital per manhour	Factor composition	TFP (Refined)	Manhours per capita	Capital intensity	Factor composition	TFP (Refined)
I: Nineteenth Century							
1800-1855	49	-	51	55	22	-	23
1855-1890	65	-	35	28	49	-	23
1890-1927	31	7	62	-15	36	8	71
II: Twentieth Century							
1890-1927	26	7	67	-4	27	7	70
1929-1966	17	25	58	-45	25	36	84
1966-1989	46	51	3	33	31	34	2

Sources: Computed from growth rates in Abramovitz and David (1999), Tables 1:II and 1:IV.

The foregoing review points to a question, or, more precisely, to a bundle of related questions. Up to a point, the broad profile of inter-century differences delineated by this growth accounting exercise seems easy enough to accept. One can well believe that the growth of labor input per head became weaker and began to decline in the twentieth century when immigration was restricted and, when, as incomes rose, workers chose to take part of their potential gains in shorter hours and greater leisure. One can well understand that land settlement and development came to an end around the turn of the century and that after the very great nineteenth century investments in transport and in the provision of the basic infrastructures of town and city life had been made, the importance of the growth of tangible capital should decline. Indeed, the evidence supporting the view that such a change occurred is even stronger than these considerations suggest, as subsequent sections will show. Yet not everything in this historical picture is so transparent. The big questions arise mainly from the findings about the pace of TFP growth itself, the inter-century contrast and the relations between technological progress, and the contribution from capital accumulation.

On the face of the numbers, TFP growth including both technological progress proper and economies of scale seems to have been very slow during the nineteenth century. This was especially so over the long period 1855-1890: although per capita output growth then was twice as fast as in the first half, and the growth account suggests that three-quarters of that increased pace was attributable to the accelerated growth of tangible capital per manhour; total factor productivity increased at an average rate of only 0.37 percent a year during that era. That rate seems slow, absolutely, and small relative to the pace set in the twentieth century; beginning 1890, the average annual trend rate of TFP growth up to 1966 was at least 3.5 times faster. We may well believe the suggestion that technological progress was faster in the twentieth century than in the nineteenth. But was TFP really so much slower in the nineteenth, when the great investments in transportation and the introduction of steam railroads and the telegraph created local, regional and national markets and, presumably, large economies of scale, when steel replaced wood and fragile iron, when harvesting was mechanized, steam power came to factories, the machine tool industry developed and the repetitive assembly of interchangeable parts became common?

Turning to the twentieth century, one asks whether a growth account that allows only for the growth of tangible capital does not turn a blind eye to the rise of a new source of growth in the form of intangible capital. It is not quite a blind eye since our account makes allowance for the growth of labor quality by formal schooling. That, however, is hardly sufficient. There are other components of intangible capital, accumulated by on-the-job training, organized R and D and the costly organization of the administrative infrastructure of large-scale business. In what part is the omission of those factors of production responsible for the apparent acceleration of the TFP growth rate, even measured on a "refined" basis that allows for the effects of the changing composition of tangible inputs?

There remains a further, and general problem of interpreting the dynamic process that is reflected, however imprecisely, in these quantitative measures. The descriptive clarity of the growth accounting approach is gained only at a cost. They assume that the various sources of growth rise or fall and achieve their effects independently of one another. In the world of the standard growth accounts, capital, whether tangible or intangible, accumulates regardless of the pace of technological progress. The growth accounts assume that technological progress is "neutral," raising the returns and demands for labor and capital in equal proportion. They pay no attention to changes in the character of technological progress that influence the kinds of capital required: land, structures, equipment; tangible capital or intangible; nor do they consider the reverse effects that may run from capital accumulation to technological progress. We shall not understand the forces that have made the pace and proximate sources of twentieth century growth different from that of the nineteenth century until we grapple with these problems. That is the interpretive challenge taken up in the following pages.

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3. An Aggregative Growth-Theoretic Framework

Our broad interpretation is couched explicitly within an overall framework deriving from the growth-theoretic analysis of a patently fictional one-sector, closed economy. Aggregate production relations are taken to be summarized by a "well-behaved"[39] function that has the following general form:

$$\mathrm{Y}(t) = Y\{ L(t), K(t), R(t), H(t) \} \quad , \tag{1}$$

in which $\mathrm{Y}(t)$ is an appropriately defined measure of real gross output at time t, and the correspondingly dated inputs are the services of "raw labor" (L), reproducible capital (K), non-reproducible capital (R, such as land and depletable natural resources) and intangible capital (H). For the purposes of implementing this framework quantitatively we place two additional restrictions on this function. The first is that $Y\{ \bullet \}$ exhibits constant returns to

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[39] Formally, the "well-behavedness" of the function consists in it being continuous and continuously differentiable in all of its arguments. Further, we assume that the partial first derivatives with respect to each of the arguments are all positive, and the second derivatives are negative -- i.e., marginal products of the inputs are positive, but there are diminishing marginal returns in all directions.

scale, so that doubling all the inputs would result in the doubling of output. This is tantamount to specifying that the elasticities of output with respect to the inputs, denoted by ϵ_i always sum to unity:

$$\epsilon_L(t) + \epsilon_K(t) + \epsilon_R(t) + \epsilon_H(t) = 1 , \quad \text{for every } t . \tag{1a}$$

The second restriction is that the input services enter the production function measured in their respective *efficiency units*, which is to say that the input of labor services at time t is measured as the number of full time equivalent manhours (of basic quality level), $L(t)$, adjusted by an index $E(t)$ indicates the currently prevailing level of productive efficiency of those "raw" labor services relative to their efficiency level at some fixed reference date (t=0).[40] Thus the production function can be written as:

$$Y(t) = Y\{ L(t)\cdot E_L(t),\ K(t)\cdot E_K(t),\ R(t)\cdot E_R(t),\ H(t)\cdot E_H(t) \} \quad , \tag{2}$$

which is referred to as the "generalized factor-augmentation" form.[41] The latter designation refers to the assumption that technological and organizational innovations, and other unobserved temporal changes affect production by altering one or more of the input-specific indexes of average efficiency. When a particular index increases with the passage of time, the effect is a proportional "augmentation" of the productive services of the input in question when the latter is considered in its natural units.

In other words, in this model the impact upon aggregate output of a ten percent increase in the average efficiency index of our labor input measure would be equivalent to that of augmenting the physical number of manhours worked by ten percent. It should be noted that these input efficiency indexes may decline over time, rather showing only positive changes; it is quite possible for biased technological change to *lower* the efficiency index of one of the inputs while raising that of another. Such a skewing of the production isoquant field may be referred to as an "input-using" innovation -- in the case of the former, whilst it is "input augmenting" in the case of the latter. An innovation that is, say, reproducible capital-using in this sense is one that (with everything else held constant) will raise the capital-output ratio that corresponds to a given real rate of return on capital, supposing that the latter is equal to the marginal physical product of the capital goods.[42]

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[40] It should be obvious that the choice of the reference date is arbitrary and simply serves to fix the scaling of the function $Y\{\ \}$.

[41] For further discussion, see Paul A. David and T. van de Klundert, "Biased Efficiency Growth and Capital-Labor Substitution in the U.S., 1899-1960," American Economic Review, vol. 55 (3), June 1965, pp. 357-94, introduction of this general formulation in a constant elasticity of substitution (CES) model of production.

[42] The economic connotations of this terminology are further discussed below. We also may acknowledge here an additional complication that arises in our implementation of the general factor-augmenting innovation model. As a practical matter, the flow of input services can be taken to be proportional to the measured stocks of productive factors when analyzing the sources of growth in potential output, because the choice of benchmark dates is designed to eliminate significant variations in the degree of utilization of those stocks that could otherwise arise due to variations in the level of effective demand. But, it remains a possibility that some significant portions of existing stocks of productive assets may quickly be rendered economically obsolete by radical technological innovations, or sudden increases in prices of complementary inputs, or transport cost shifts that render fixed facilities at some locations uncompetitive. Since the capital stock estimates employed in this analysis are not measured net of adjustments for obsolescence, the secular effects of various sources of obsolescence may be registered as declines in the *average* efficiency of the affected stocks -- because the reduction in the proportionality between the actual input service flow and the measured gross stocks goes

It will be seen that the flexibility of the model of production with factor-augmenting technological change permits one to relax the assumptions that usually are made, sometimes implicitly, as to the effects of such innovations on the relative productivities of the inputs. Assumptions of different kinds regarding the "neutrality" of technological change figure rather centrally in formal growth theory, and provide the rationale for reading the results of the conventional growth accounting exercises. Rather than introducing one or another form of technological "neutrality" merely as a matter of theoretical or empirical convenience, it will be possible within the framework adopted here to consider quantitative estimates of the character and magnitudes of differentials in the secular rates of efficiency growth among the economy's primary factors of production.

In other words, it will be possible to see what the U.S. macroeconomic data imply about the *bias* of innovation, and the ways in which that has changed over the course of the nineteenth and twentieth centuries. We think that the importance of those questions and their centrality to our interpretation of the American growth record -- much of which turns precisely upon the identification of such changes and their long-run ramifications, justifies the extra burden that may be imposed upon readers for whom the model of aggregate production subject to factor-augmenting technological change is rather unfamiliar.

Having introduced the principal features of the production model, we can now indicate how connections may be drawn between its application for purposes of growth accounting and its uses in the context of basic neoclassical growth theory. For expositional purposes here, and also in subsequently applying the framework to the interpretation of the macroeconomic evidence for the U.S. in the nineteenth century, changes in the relationship between intangible capital inputs and inputs of labor services gauged in manhours (of varying average efficiency) may be suppressed. In other words, we start out with the familiar, one-sector neoclassical model popularized by Solow (1956), in which there is labor and reproducible capital.

3. 1 Steady-State Growth Paths and 'Traversing" in Neoclassical Growth Theory

The familiar theory of market equilibrium provides economists with a useful framework for interpreting the observed movements of the prices and quantities of specific goods between different points in time. This is referred to as comparative static analysis, for each price-quantity pair is taken to correspond to the static equilibrium fixed by the intersection of some supply and demand schedule, and the job of analysis is then to identify the extent to which it is possible to account for the observed changes in terms of inter-temporal shifts in and/or movements along those schedules. Correspondingly, neoclassical growth theory offers the macroeconomic historian a framework for comparative dynamic analysis; within that analytical framework, the aggregate economy's behavior can be read either as movement along a given steady-state growth-path, or as involving a passage between the neighborhood of one such growth-path and a different steady-state trajectory.

Steady-states can be defined with reference to a variety of criteria, for in reality the economy is a multi-dimensional entity. But here we start by considering the simplest aggregative model of a one-sector economy in which output Y is produced with inputs of raw labor, L, and reproducible capital services, K. In the paradigmatic model presented by Solow

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unmeasured until the obsolete assets are retired.

(1956), the growth of output at a constant annual rate (denoted by Y*) which equals that of the real stock of capital, and the latter's strict proportionality to growth rate of the real flow of capital services (K*), are the touchstones defining "steady state dynamics." Accordingly, a particular equilibrium growth path of this sort will be characterized by a constant level of the real capital-output ratio ($K/Y \equiv v$), and the corresponding real rental rate of capital (r, which may be defined either gross or net of depreciation, corresponding to the real output concept, Y). From this automatically follows the constancy of three other aggregate magnitudes characterizing the simple economy's dynamic path: (i) the constancy of the share of property income in total output, θ_K ($\equiv rv$); (ii) the net investment rate, and, supposing an unchanging rate of capital depreciation, δ , the ratio of real gross investment to total real income ($I_g/Y \equiv I/Y + \delta v$); (iii) the fraction of real output that is being consumed C/Y [$\equiv 1- (I_g/Y)$].

It is conventional, following the terminology of Hicks (1968) and Solow (1972), to describe an economy whose growth-path does not maintain these notional conditions of dynamic equilibrium as undergoing a 'traverse' to a higher, or a lower characteristic K/Y path. Such movements, while they are taking place, will have an effect on the average productivity of labor, and so it is quite natural to reconsider how growth accounting would proceed within this growth-theoretic context.

Growth Accounting from the Growth-Theoretic Perspective

The standard growth accounting procedure for calculating the crude TFP residual is equivalent to defining the latter as the weighted sum of the rates of growth of the average productivity of labor and the average productivity of capital inputs. Thus, employing the notation * to indicate the proportionate growth rates of each of the variables involved, we denote the TFP growth rate by A* and write:

$$A^* = \theta_K (Y^*-K^*) + (1-\theta_K)(Y^*-L^*) . \qquad (3)$$

The weights in this expression are supposed to be the respective output elasticities of the two factor inputs, and are treated as parametric for the interval over which the input and output growth rates apply; under the assumptions of constant returns and cost minimization in competitive factor markets, these elasticities are identified with the corresponding shares of the gross product: $\epsilon_K \equiv \beta = \theta_K$, in the case of the capital inputs, and $(1- \beta) \equiv \epsilon_L = \theta_L$ in the case of labor.

It has become conventional in growth accounting to re-arrange the relationship in equation (3) so as to partition the growth rate of labor productivity between the contribution made by increasing capital-intensity, i.e., increasing the ratio of capital inputs per unit of labor input, and the residual term representing the growth rate of total factor productivity:

$$(Y^* - L^*) = A^* + \theta_K (K^*-L^*) .$$

(4)

But equation (4) also may be re-written in the following form:[43]

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[43] This is most expediently done by first subtracting $(\theta_K)[Y^* - K^*]$ from both sides of eq. (3), then dividing through on both side by θ_L, and rearranging terms .

$$(Y^* - L^*) = (A^*)/\theta_L + (\theta_K/\theta_L)[K^* - Y^*]. \qquad (5)$$

The latter expression partitions the labor productivity growth rate between two “sources” in a way that related more immediately to the foregoing growth-theoretic framework. Only one further specification is needed to complete the transformation. To effect this we may begin by observing that a measured residual such as that found in equation (3), if calculated for a production system like that described by equation (2) would capture the weighted sum of all the “factor-augmenting” changes in the economy, i.e., changes that alter the respective efficiencies of each of the labor and capital inputs used in this basic production model. $A^* = \theta_L (E_L^*) + \theta_K (E_K^*) \equiv E^*$. Now, in either of these formulations, by making a suitable (but different) assumption about the way in which technical changes affect the productivity efficiency of the inputs, one may justify treating technological progress and factor input growth as distinct and separable forces, operating in an *orthogonal* manner to raise the productivity of labor.[44] The question one should ask before accepting such an interpretation of the dynamics of growth, of course, is whether the particular assumptions that are required to effect such a separation are historically appropriate.

The conventional procedure in the growth-accounting literature, following the interpretation made familiar by Solow (1957), implicitly or explicitly assumes that technological progress (or other sources of efficiency gain) is augmenting the efficiency of inputs of labor and capital at identical rates. This is the condition referred to as one in which technological innovations are “Hicks-neutral”. When this condition obtains, and the growth rates of those inputs have been properly measured, and if there are no static scale economies at the level of the aggregate economy, then the contribution made to the output growth rate by the (uniform) rate of factor-augmenting innovations is what the TFP residual measures: $A^* = E^* = E_L^* = E_K^*$.[45]

Alternatively, on *a priori* grounds one equally might suppose that such factor-augmenting changes worked to enhance the efficiency of the labor inputs *only*, without altering that of capital inputs (i.e., $E_K^* = 0$). This particular specification corresponds to the condition of ‘Harrod-neutrality’ of technological (and related organizational) innovation, which leaves the capital-output ratio undisturbed. Under that assumption the expression for the labor productivity growth rate becomes

$$(Y^* - L^*) = E_L^* + (\theta_K/\theta_L)[K^* - Y^*] \ . \qquad (5a)$$

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[44] It is important to notice that there are two aspects of the “orthogonal forces” view: conceptual separability derives from the imposition of the “neutrality” assumptions regarding the influence of technological change, whereas the additive separability of the contributions made by the two “forces” stems simply from the convention of doing the growth accounting in terms of growth rates, rather than multiples of increase. In other word, terms that enter multiplicatively into a relationship, and so may be said to “interact” algebraically, are additive under logarithmic transformation. Sometimes the conceptual point about the interactions between technological change and the growth of factor inputs is misleadingly illustrated by showing that they enter multiplicatively in a production function, but this invites confusion of the two issues. See, e.g., Richard R. Nelson, “Aggregate Production Functions and Medium Range Growth Projections,” American Economic Review, 54 (September 1964), pp. 575-606.

[45] This uniformity assumption corresponds to assuming what is referred to as “Hicks-neutrality” of technological change, so long as the elasticity of substitution between the inputs *L* and *K* in the aggregate production Y =

$Y(L, K) = F(E_L L, E_K K)$ is less than unitary.

The first term on the right-hand side of this expression, which can be found from the TFP residual as $[(A^*)/\theta_L]$, tells us the pace at which average labor efficiency, and hence labor productivity will be rising on the economy's steady-state growth path, whereas the second term represents the effect of "traversing" between one steady-state path and another. Obviously, the process of traversing to paths characterized by higher capital-output ratios works to support the growth rate of real output per (natural) unit of labor input.

Determinants of Traversing Movements in the Solow Growth Model

Given the assumption of Harrod-neutrality, in this model changes in the aggregate capital-output ratio can be brought about only by forces that in effect, alter the relative prices of capital inputs vis-à-vis labor services, and necessarily also in relation to the (numeraire) price of aggregate output. Putting the same point in a different way, because the potential disturbances created on the demand side of the factor markets by technological innovation are held in abeyance here *by assumption*, this model tells us that changes in the real rate of return on capital can come about only through those developments in the economy that impinge directly upon the dynamics of relative factor supplies. Further, because changes in the aggregate capital-output ratio along the aggregate production function would result from capital-labor substitutions induced by alterations in the relationship between the real wage and the real rental rate of capital, the supply-side determinants of the latter would appear to hold the explanation for the historical movements observed in the former.

Thus, were one to proceed strictly on this hypothesis, it would be exclusively within the latter category of forces -- those ranging from institutional and distributional conditions affecting savings behavior and the aggregate supply of loanable funds available for real capital formation, to demographic and labor market conditions impinging upon the supply of labor services -- that it would be appropriate to look for explanations of historically observed "traverses." But it should be evident from the terms in which our narrative interpretation was set out that we consider the evidence of U.S. macroeconomic experience to be at odds with that simplification, and more consistent with the view that there have been sustained departures from both the Hicks-neutrality and the Harrod-neutrality conditions as far as concerns the impact of technological and organizational innovations on the trend period behavior of the stock of conventional, tangible reproducible assets. Therefore, when seeking to account for the behavior of the capital-output ratio, we have to consider the nature and magnitude of the equilibrium-disturbing "shocks" exerted on the demand-side of the investment market by the course of technological progress, as well as the influence of developments directly shifting the supply of savings and the growth of the labor force.[46]

For those who accept the aesthetic canons of "pure" growth theory, the beauty of the Solow-type parable is found in the existence, under the assumption of Harrod neutrality, of a globally stable path of steady-state growth that is *unique.* Obviously, we are prepared to mar that beauty in some degree, sacrificing the property of uniqueness in the interests of telling a story that is more consistent with our view of the nature of the underlying forces in the U.S. historical growth process, and one can be squared with the salient macroeconomic trends. In

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[46] Indeed, it will be seen that rather than viewing the aggregate conventional savings rate as being determined predominantly by (exogenous) institutional and demographic factors, our interpretation points to mechanisms through which it has tended to be adjusted (endogenously) in response to shifts originating on the demand side of the investment market. There is in this regard a difference in interpretive emphasis here and the discussion in the Chapter by Robert Gallman of the forces responsible for the capital-output ratio's rise over the course of the nineteenth century.

practice, what that means is that the formal dynamics of growth envisaged in the Solow model will here be thought to operate conditionally on an invariant efficiency index being specified for the capital stock, which thus allows for the possibility of non-(Harrod)-neutral "shocks," that in effect reposition the relevant (stable) steady-state path towards which the macro-economy would thereafter be tending to converge.

Every such steady-state path is characterized by the equality between two calculable macroeconomic magnitudes: the reigning "natural rate of output growth" set by the growth rate of efficiency-augmented labor inputs (i.e., $L^* + E_L^*$) on one side, and on the other side, the growth rate of real output (and capital) that is "warranted" to clear the loanable funds market by setting desired savings equal to desired investment. This equilibration is brought about by the endogenous adjustments of the K/Y ratio along the economy's production function.[47] Ultimately, it is the crucial assumption of the existence of diminishing marginal returns to capital accumulation along the aggregate production function that underlies this stability property of the Solow growth-model, and so assures that when a situation of dynamic equilibrium is disturbed by a structural "shock" of one kind or another, the traverse thereby set in motion will converge to the new steady-state growth path that is implied by persistence of those altered fundamental conditions.[48]

While the transverse to a higher (lower) K/Y is in progress, the labor productivity growth rate will be accelerated (retarded) on that account. Thus, in addition to whatever changes might impinge immediately upon the Harrod neutral rate of efficiency growth during a given historical epoch, we should be able to draw upon growth theory for further insights in identifying forces that have affected the observed growth rate of labor productivity by disrupting the economy's dynamic equilibrium in ways that set in motion either "capital-deepening," or "capital-shallowing" traverses.

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[47] Obviously it is the reproducible capital-output ratio that must do the adjusting, and this should be allowed for when using empirical data to implement the model, as has been done explicitly for the US nineteenth century economy by Paul A. David in "Invention and Accumulation in America's Economic Growth: A Nineteenth Century Parable," in International Organization, National Policies and Economic Development, a supplement to the Journal of Monetary Economics, vol. 6, 1977, pp. 179-228.

[48] The term "structural shocks" in this context refers to conditions affecting the savings supply function, the growth rate of the labor supply measured in efficiency units (and also the shape and position of the aggregate production function, which is held to remain unchanged in the standard presentations of this neoclassical model). See, e.g., R.M. Solow, Growth Theory, New York: Oxford University Press, 1970. Of course, the whole discussion of stability and convergence speed in models of this kind (e.g., that reviewed by Paul A. David, "Invention and Accumulation in America's Economic Growth: A Nineteenth Century Parable," in International Organization, National Policies and Economic Development, a supplement to the Journal of Monetary Economics, vol. 6, 1977, pp. 179-228, and more recently, R.J. Barro and X. Sala-i-Martin, "Convergence," Journal of Political Economy, 100, pp. 223-251, abstracts from the more difficult question of an economy's *disequilibrium* dynamics. It should be noted, therefore, that the macroeconomic behavior of an economy whilst 'traversing' may well involve cyclical fluctuations and 'long swing' oscillations in the rate of growth that carry the system temporarily beyond the its new "target" steady state path. The secular growth trend analysis presented here has sought to abstract from such movements, of course. Yet at this point in the argument, however, it requires some suspension of disbelief -- an act of faith in the heuristic value of our proposed growth-theoretic interpretation -- to accept that the American economy's disequilibrium dynamics were not inconsistent with the supposed property of secular convergence. The latter question, however, touches upon some fundamental matters relating to the subject of path dependence, hysteresis effects and the non-ergodicity of economic growth processes (see e.g., Paul A. David, "Path Dependence: Putting the Past into the Future of Economics," Technical Report No. 533, Stanford University, 1988; Paul A. David, "Path Dependence and the Quest for Historical Economics: One More Chorus of the Ballad of QWERTY," Oxford University Discussion Paper, 1997; and S.N. Durlauf, "Nonergodic Economic Growth," Review of Eonomic Studies, 60(2), April 1993, pp. 349-66, and we comment briefly on this in the following subsection.

3.2 Augmenting the Basic Solow Growth Model

Recognition of the multiplicity of the forms of capital is central to our interpretive account of twentieth-century developments in the U.S. economy, and the forces that transformed the morphology of the growth process by expanding the relative importance of the contributions to productivity advance deriving from the accumulation of new and intangible forms of productive assets. To make explicit allowance for this central theme, we may employ the simple stylized representation of an expanded production function which was introduced by equation (1), and the corresponding formulation allowing for input-specific efficiency change, as in equation (2).[49]

In order to understand America's path of capital accumulation over the course of the nineteenth century, it is important to take explicit notice of the differentially faster expansion of the reproducible part of the tangible capital stock, of the relative growth of the non-residential vis-a-vis residential structures, and of the especially rapid growth of equipment stocks within the total during the post- Civil War decades.[50] But, for our present purpose, which focuses more closely upon distinctively twentieth century trends, it is sufficient to work with the (Divisia) aggregate K_T, and emphasize the contrast between the growth profiles of the total tangible capital stock and the stock of non-conventional and intangible capital, denoted by H. Our choice of that notation is meant to underscore the fact that the growth of the stock of "human capital," primarily brought about through investments in formal education and complementary on- the-job training, has been far and away the

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[49] The measures underlying the capital inputs estimates presented by A&D (2001), Table 1:IV for the "Nineteenth Century" panel derive from a Divisia index aggregation of the contributions of the reproducible and non-reproducible components of the tangible capital stock, including estimates for improvements made to farm land in the reproducible stock estimates. (See Robert E. Gallman, "The United States Capital Stock in the Nineteenth Century," in Long-term Factors in American Economic Growth, edited by Stanley L. Engerman and Robert E. Gallman, Chicago and London: University of Chicago Press for National Bureau of Economic Research, Studies in Income and Wealth, vol. 51, 1986, Table 4.8, and Gallman's chapter in Cambridge Economic History of the U.S., Vol.2, (forthcoming): Table 12, for the changing absolute and relative importance of capital formation in improvements to farm land during the nineteenth century.) Corresponding reproducible capital input estimates in the "Twentieth Century" panel of Abramovitz and David's Table 1:IV accept the arithmetic aggregation of those components in the case of the simple "capital stock" figures which are drawn from John W. Kendrick, Productivity Trends in the United States, Princeton, NJ: Princeton University Press for the National Bureau of Economic Research, 1961, and the U.S. Bureau of Economic Analysis as presented in Department of Commerce, National Income and Product Accounts of the United States, vol. I, 1929-1958 and vol. II 1959-1988, Washington, D.C.: Government Printing Office, 1993). The allowance estimated for the contribution of "capital quality" in Tables 1:IV, and 2:I, however, reflect the detailed Divisia-type aggregation of different categories of conventional reproducible and non-reproducible tangible assets by Dale W. Jorgenson, "Productivity and Economic Growth," in E.R. Berndt and J. Triplett, eds., Fifty Years of Economic Measurement, Chicago: University of Chicago Press, pp. 19-118, 1990.

[50] See Robert Gallman's chapter in the Cambridge Economic History of the U.S., Vol. 3 (forthcoming) for the basic statistical picture of these changes. Paul A. David, "Invention and Accumulation in America's Economic Growth: A Nineteenth Century Parable," in International Organization, National Policies and Economic Development, a supplement to the Journal of Monetary Economics, vol. 6, 1977, pp. 179-228, gives an interpretive account of those nineteenth century developments, in terms that are generally consistent with the general explanatory framework adopted here. An alternative formulation, Paul A. David, "The Mechanism of 'the Grand Traverse', 18-17-1897: A Cantrabridgian Synthesis" (Unpublished Working Paper) emphasizes the effects of the bias in innovation upon the functional distribution of income, and through that upon the adjustment of the supply of savings.

quantitatively preponderant element in the expansion of the total unconventional stock.[51]

Thus, we suppress separate notice of the non-reproducible capital inputs, *R,* that appear in equation (2), and, by total differentiation of the latter with respect to time, obtain the following growth accounting equation for the "augmented Solow model":[52]

$$(Y^* - L^*) = \quad E^*/\theta'_{L} \; + \; (\theta'_{KT}/\theta'_{L})[K_T^* - Y^*] + (\theta_H/\theta'_{L})[H^* - Y^*],$$

where
(6)

$$E^*/\theta'_{L} \quad = \quad [E_L^*] \; + \; (\theta'_{K}/\theta'_{L})[E_{KT}^*] + (\theta_H/\theta'_{L})[E_H^*] \; .$$

Two points should be noticed concerning this expression. with the equations leading to (5). First, in place of the term A*, which corresponds to the "crude TFP" residual found by the growth accounting exercises in Part I, we now implicitly have a still-more-refined TFP residual, denoted here as E*. The latter is the magnitude that would be found by explicitly extending the growth accounting to capture the contributions made by the growth of the ratio of all intangible capital relative to the corresponding aggregate output measure.[53]

A second detail is signified by the use of the prime notation in the terms representing the input elasticities, now indicated by θ'_L to represent the elasticity of output with respect to labor inputs of the minimum educational quality type. In other words, our labor input measure remains "raw" full-time equivalent manhours, but we have to recognize that the elasticity of real output with respect to the latter is not approximated by the share of payments flowing to a workforce that embodies intangible productive assets such as educationally produced human capital, and investments in on-the-job training. Similarly, members of the workforce may embody knowledge produced by investments in R&D, and their productive capabilities also may have been enhanced by expenditures for health and safety. Thus, it is appropriate explicitly to reduce the estimated elasticity parameters from the magnitudes defined for the crude growth accounting exercise, by imputing some part of the directly observable factor payment shares to the effects of the services of the national stock of intangible capital:

$$\theta'_{L} = \theta_L - \alpha_L \quad ; \qquad \theta'_{KT} = \theta_K - \alpha_K; \qquad \theta_H = \alpha_L + \alpha_K \;\; .$$

(6a)

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[51] This will be seen from closer examination of the rise of intangible capital formation (in Section 4, below).

[52] The descriptive term "Augmented Solow model" has become popular in the recent growth theory literature, following the work of N.G. Mankiw, D. Romer and D.N. Weil, "A Contribution to the Empirics of Economic Growth," Quarterly Journal of Economics, 107, pp. 407-437, and R.J. Barro and X. Sala-i-Martin, "Convergence," Journal of Political Economy, 100, pp. 223-251, and we use it here with the caution that the "augmentation" to which it refers is simply the explicit inclusion among the arguments of the production function of "factors" additional to conventional labor and capital. The usage here should not lead to confusion with the specification of the aggregate production function as subject to factor-augmenting innovations reflected by changes in factor-specific efficiency indexes, such as E_L and E_K.

[53] When we come to implement this approach, below, it is necessary to allow for the possibility that a suitably expanded concept of real gross product, the "augmented output" Y_A, may be growing at rates Y_A^* different from the conventional real gross product, Y*. Augmentation of the aggregate output concept is needs because investment in education includes the imputed real value earnings foregone, which latter must to added to the conventional total output measure. Similarly, if R&D expenditures viewed as investment, they ought to be included in the gross product originating rather than being fully expended. We have not further cluttered exposition at this point by introducing the augmented output notation in the above text.

In the following section we proceed by implementing the basic Solow Model with factor-specific efficiency growth for the nineteenth century U.S. economy, and show that the augmented Solow Model affords a parallel interpretation of the macroeconomic growth record in the twentieth century.

4. The Tale of Two "Technology-Driven" Traverses

The U.S. macroeconomic record displays a number of striking features that distinguish the morphology of long-term growth during the twentieth century from the pattern of development that had characterized the preceding century. The contrasting dynamics of those two epochs is evident from the movements of key macroeconomic ratios, and the latter therefore serve to highlight differences in the nature of the growth process that also are perceptible at the lower levels of aggregation which figure in the narrative overview of section 2. Both the patterns of change in these macroeconomic relationships particular to each of the centuries, and the contrast between the two epochs, call for explanation and interpretation. In the interpretive account offered in this section, these trends are viewed primarily as reflections of, and direct and indirect endogenous responses to underlying developments affecting the rate and direction of technological innovation, broadly conceived.

4.1 Contrasting Macroeconomic Profiles of the Nineteenth and Twentieth Centuries

Five salient points of contrast in the quantitative record may be identified and briefly characterized, as follows:

(1) The trend of labor productivity (real gross output per manhour) has been upwards throughout the whole course of the national experience, but it underwent a quickening that became evident from the mid-nineteenth century onward, and a still faster long-term rate of growth (approximating 2 percent per annum) has been maintained throughout the twentieth century.

(2) The trend in the ratio of real gross output to total factor input, or TFP (refined index), was upwards during the nineteenth century, but at an average pace that was very moderate in absolute terms until the century's closing decades, and only a fraction of the approximate 1 percent per annum TFP (refined) growth rate that has been the average maintained over the whole period from 1890 to 1989. Even so, the collapse of the TFP residual during the most recent quarter of that century (i.e., in the period 1966-1989) appears to be a phenomenon whose magnitude and duration is quite without precedent in the nation's economic history.

(3) A rising ratio of tangible capital services per manhour labor input has accompanied the rise of labor productivity, but in the twentieth century the gap between the trend rates of growth of tangible capital services and manhours has not been as wide as previously. On the other hand, since the closing decades of the nineteenth century the rise of investment in education and training, and in organized R&D activities, has meant that the ratio of the services of *intangible* capital inputs to tangible labor inputs (i.e., manhours) has been growing at a much faster pace both absolutely and relatively than previously was the

case.[54]

(4) The ratio between tangible capital (gross services) inputs and real gross output rose markedly over the whole of the nineteenth century, although its approximate doubling was concentrated within the central period c. 1835 to c. 1890. By contrast, starting soon after the beginning of the twentieth century the trend in this ratio turned downwards, and remained markedly so until early in the post-World War II era; the tangible capital-output ratio continued to drift downwards at slowing pace during 1948-1973 and has approached stability thereafter.[55] Although we presented no explicit estimates of the growth of the intangible capital stock over the course of the nineteenth century, reasons were given for surmising that it could not have been rising much faster than inputs of manhours and, consequently, must have been growing slowly by comparison with the tangible reproducible capital stock. From the late nineteenth century onwards, however, the ratio between the intangible and the tangible stock of capital has been rising rapidly, as will be seen more explicitly from new estimates that we shall introduce, below.

(5) The share of the gross private domestic product represented by the earnings of labor actually declined during the nineteenth century, whereas it has followed an upward trend in the twentieth century. It was the rising share of output represented by the gross private returns (imputed) to tangible reproducible capital that was responsible for the nineteenth century contraction in the share of labor, because the share of output represented by rental income on the stock of non-reproducible tangible wealth (unimproved land) remained essentially constant. During the twentieth century, the expansion of the labor income share has been largely concentrated in years between 1929 and 1973, and, as shall be seen, this reflected the growing portion of labor earnings that can be attributed to the relative accumulation of human (intangible) capital.

4.2 The Changing Direction of Technological Progress and the Residual's Rise

An issue that needs to be addressed at the outset is whether it is justifiable to accord such central importance to the influence of technological progress in the nineteenth century, and therefore to not view U.S. growth during the twentieth century as being fundamentally distinguishable from that in the previous epoch on the ground that technological change has come to have a far greater impact. Of course, this is a matter of what one means by "the economic impact" of technological progress. But, could it not be argued, on the basis of the very low absolute estimates we presented for the pre-1890's TFP growth rate, and the subsequent pronounced “rise of the residual,” that technological progress was really a rather insignificant factor in U.S. nineteenth century growth, and emerged as a potent force only in the twentieth century with the advent of the science-based industries and organized research and development activities?

Such a reading of the growth accounting results is one that is firmly rejected here. But, not because the occurrence of so large an acceleration in the rate of productivity growth

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[54] This last point will be brought out more explicitly, below, in the discussion of Tables 2 and 3.

[55] These trends may be inferred directly from a comparison of the growth rates for the stock of total tangible reproducible capital and real gross private domestic product shown in Table 2, or from the movements of the constant dollar tangible capital-output ratio for the U.S. domestic economy that can be calculated from the data in Table 3.

renders the underlying estimates themselves somehow suspect;[56] nor because there are good ground for doubting that advances in fundamental scientific understanding of physical phenomena have come to play an much more central role in industrial (and agricultural) process and product innovation since the end of the nineteenth century. Rather, we take the view that the pace at which technological change proceeded, and the importance of its "contribution to economic growth" cannot be directly gauged simply from the absolute growth rate of total factor productivity, or the relative importance of the TFP “residual” among the proximate sources of growth in real output per capita.

Although there are special circumstances in which such a direct interpretation of the growth accounts would be justifiable, I argue in the following that those so-called "neutrality" conditions regarding the factor-saving effects of technological innovation did not obtain for the U.S. economy during most of the nineteenth century. Nor have they obtained during the twentieth century. Yet departures of "neutrality" themselves need not take an invariant form, and it is precisely in the altered character of technology's *non-neutral* progress that I find an important key to understanding the rise of the TFP residual -- and with it the other developments that have distinguished the macroeconomic growth path taken in the twentieth century from the course along which the U.S. economy previously had been developing.

The apparent difference between the two centuries in respect to the TFP growth rate thus reflects a substantive difference, one that involved not merely an acceleration in the underlying pace of internationally shared technological advances, but a shift in “the direction of innovation” away from the very pronounced nineteenth-century bias towards *labor-saving and tangible capital-using* innovations. One way to grasp intuitively what the existence of such a “bias” would imply for our interpretation of the TFP growth rate is, first, to recall that the residually estimated measure of multifactor productivity is simply equal to the weighted average of the partial productivity growth rates of the various factor inputs, in this case full time equivalent manhours of labor and the combined services of tangible capital (in constant dollars). Since we have seen that the ratio between inputs of tangible capital and output was rising, it is evident that this must have worked against the rise in labor productivity, dragging the weighted average of partial productivity growth rates downwards.

The second step is somewhat more exacting, as it involves showing that the opposing movements in the labor and (tangible) capital productivity trends were reflecting changes in the set of technological possibilities, rather than being simply a matter of the substitution of capital for labor in response to the rising relative price of the latter inputs. For this purpose it is best that brief but nonetheless explicit reference to the hypothetical aggregate production function underlying the growth accounting framework.

We may now imagine a function -- simplified from general, multi-factor expression in equation (2), above -- specifying the relationship between real output Y(t) and labor and capital input service flows, each of which enter multiplied by its own time-varying index of productive efficiency, $E_L(t)$ and $E_K(t)$, respectively. As previously indicated, the functional relationship involving inputs measured in efficiency units will be assumed to remain invariant over time, although the relationship between output and the inputs measured in their natural units is presumed to change, as a result of the impact of technological and organization

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[56] Some allowance must of course be made for the possibility of measurement errors, but a quantitative evaluation leads to the conclusion that the gap in the long-term TFP growth rates of the magnitude indicated is too large to be dismissed as an artefact of measurement errors. See A&D (2001) Pt. Two: Endnote 10.

innovations upon the respective input-specific efficiency index.

Employing the gross income shares of the factors in lieu of the respective input elasticity weights, one may identify the (refined) residual TFP growth rate as the weighted average of the growth rates of the individual indexes of labor efficiency and capital efficiency: $E^* = \theta_L E_L^* + \theta_K E_K^*$. It then is plain that the direct impact of a *capital-using* technological bias would be to expand the demand for capital input services relative to the flow of real gross output, given the pre-existing real rate of return. That is tantamount to a negative rate of growth in the index of average capital efficiency, which would tend to offset the contribution being made to overall input efficiency growth (E^*) from concurrent *labor-saving* technical changes that were registered in the positive rate of growth of the index of average labor input efficiency, E_L^*.

This is as much as to say that the refined TFP residual (E^*) can be directly informative about the pace of technological change (or, more strictly, about pace of efficiency improvements deriving therefrom) only in the special circumstance where the direction of innovation is "neutral" : namely, when $E_L^* = E_K^* = E^*$, so that the innovation does not affect the relative mix of factor inputs. What one finds, however, is that over the course of U.S. economic history in general technological change has *not* been neutral in this sense.

Specifically, the dominant macroeconomic bias of innovation in both the nineteenth century and twentieth centuries was relatively "labor-saving", that is, $(E_L^* - E_K^*) > 0$ contributed to raising the desired ratio of tangible capital inputs per manhour. But, in the nineteenth century this bias was far more pronounced than that which has persisted throughout the twentieth century. Indeed, the former epoch was distinguished from the latter by the existence of a strong "absolute tangible capital-using" bias ($E_K^* < 0$), which imparted a marked upward trend to the ratio between tangible-capital and real output.

Tangible Capital-Using, Scale-Intensive Technology and Increasing "Roundaboutness"

The technological trajectory that emerged in nineteenth century American and persisted into the early years of the twentieth century was both tangible capital-using and scale-dependent. Exploiting the technical advances of the time demanded heavier use of machinery per worker, especially power-driven machinery in ever more specialized forms. But it required operation on an ever-larger scale the use of such structures and equipment economical. Furthermore, it required steam-powered transport by rail and ship, itself a capital-intensive and scale-intensive activity, to assemble materials and to distribute the growing output to wider markets.

Contemporary observers understood what was happening during the closing quarter of the nineteenth century in terms that were closely related to this. They spoke of technological progress as achieving gains in the productivity of labor by increasing the "roundaboutness" of production; innovations could be incorporated into production, on this view, only by the agency of raising the economy's stock of tangible capital goods in relation to the real flow of final goods and services. Or, putting the point slightly differently in the terminology of those times, "the progress of invention" was tending to raise the physical capital-output ratio that producers would choose at any given level of the real rate of interest.[57] Frank W. Taussig

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[57] This "absolute capital-using bias" also violated the condition known as "Harrod-neutrality". See A&D (2001) Pt. Two: Endnote 1 for further discussion.

(1897: 10), one of the founders of modern American economics wrote:

> In the past, those inventions and discoveries which have most served to put the powers of nature at human disposal have indeed often taken the form of greater and more elaborate preparatory effort. The railway, the steamship, the textile mill, the steel works, the gas works and electric plant -- in all of these, invention has followed the same general direction. But that it will do so in the future, or has always done so in the past, can by no means be laid down as an unfailing rule.

Here he was almost echoing the earlier views of Henry Sidgwick (1887: 133), formed more largely on European impressions:

> Though the progress of Invention -- including the developments of the great system of cooperation through exchange -- does not necessarily increase the need of capital, it has, on the whole, tended continuously and decidedly in this direction: the increase in the amount of consumable commodities obtainable by a given amount of civilized labor has been attended by a continual increase in the amount of real capital required to furnish these commodities to the consumer.

This is a view that also finds support in many modern contributions to the economic history of technology and econometric studies of American industrial production during the nineteenth and early twentieth century.[58] The quantitative evidence available to support this view at the level of the macro-economy is not conclusive, but it is enough to further strengthen the presumption in its favor. Indeed, with appropriate allowance for the changes that have occurred in the composition of the nation's stock of productive assets, changes that were responsive to the course of technological and organizational innovation, the shared vision of the classical, neoclassical and Austrian economists -- all of who saw long-term development as essentially a process of "capital-deepening"-- remains an illuminating way of interpreting the American experience in the twentieth century, as well as in the nineteenth.

4.3 The Testimony of the Macroeconomic Variables: Capital-Using Biases of Two Kinds

The growth rates for the factor input and real output measures that are assembled in Table 2 tell a tale of not one, but two successive movements toward greater "roundaboutness" in the U.S. economy's aggregate system of production system. This story is one of "unity in diversity," featuring a contrast between historical epochs that have witnessed distinctive, yet in one sense closely analogous changes in macroeconomic dynamics of the American macro-economy. Its quantitative outlines may be summarized in the following broad terms. The first of the two movements towards a high aggregate capital-output level involved the accumulation of tangible reproducible assets, and, was temporally concentrated during the middle decades of the nineteenth century, may be seen from the upper panel (Panel A) of Table 2. Yet, its force already was largely spent by the *fin de siècle* era (1890-1905), after which the trend in the aggregate tangible capital-output ratio has been continuously downwards.

The emergence of a second capital-deepening drive has shaped the economy's growth experience during the twentieth century, but, as this involved the rapid rise of the *intangible* capital inputs in relation to real output, its quantitative dimensions are not fully visible within the conventional growth accounting framework based upon the official national income and product and concepts. Therefore, the lower panel (Panel B) of the table, presents the

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[58] See A&D (2001) Pt. Two: Endnote 13.

"augmented" version of the conventional set of input and output growth rates: these reflect the inclusion of estimates for the rate of growth of the real stock of intangible productive assets. The latter is denoted by the variable H* -- since, as will be seen, (non-tangible) human capital forms the preponderant element within this part of the total U.S. domestic capital stock. For growth accounting consistency, it is necessary to consider the rate of change in a correspondingly "augmented" measure of real gross domestic product (denoted by Y_A*). These figures reflects the movements of the more comprehensive output measure that includes, *inter alia,* real gross investments directed toward human capital formation through formal education and training, and outlays for intangible non-human assets created through organized research and development.

We will come subsequently to a closer examination of the forces underlying these developments, but for the present overview it is sufficient to note that the movement towards a higher intangible capital-output ratio (H/Y_A) was especially pronounced during the decades between 1929 and 1989. The growth rate of the intangible capital-output ratio over trend periods beginning in the 1890's, and the impact of this form of capital-deepening traverse may be seen from the lower panel of Table 6-Part C. Its relative contribution to the growth of labor productivity (in the context of the "augmented" output accounts) has expanded from a mere 7 percent during 1890-1927 to almost 60 percent during 1966-1989. While impressive, the relative contribution made to labor productivity growth by the intangible-capital deepening movement alone has not matched the overwhelming proportions attributable to the nineteenth century traverse to a higher tangible reproducible capital-output ratio, which may be seen from the upper panel of Table 6-Part C.

The growth of the intangible part of the stock over the course of those six decades era was fast enough to more than compensate for the retarded pace of accumulation of tangible productive assets. This brought about a reversal of the previous "capital-shallowing" trend that had characterized the economy -- in regard to both tangible and total productive assets -- during the 1890-1927 era. But, rather than being a continuous upward trend over the entire sixty years, virtually all of the implied post-1929 rise of the total (tangible plus intangible) capital-output ratio has come about since the end of the 1960's.[59] The impact of the overall capital deepening traverse during the that period as a source of labor productivity growth may be seen (from Frame II of Table 2:IV-Part D) to have become significant only during 1966-1989, however, when the tangible capital-output ratio began rising once again.

On the Tangible Capital-Using Bias of Technological Progress in the Nineteenth Century

In regard to the proposition that the first of these capital-deepening episodes owed a great deal to the absolute tangible capital-using bias of technological innovation over the decades running from the 1830s to the 1890s, the key macroeconomic observations concern the coincident upward movement of the reproducible capital-output ratio and the expanding share of the gross returns attributable to capital in the gross (private) domestic product.

The figures in the upper panel of Table 2 reveal that a positive gap was being maintained between the growth rates of the entire capital reproducible capital stock and real output throughout period stretching from the mid-1830's to the end of the 1880's. From the underlying estimates it is evident that the growth of the reproducible capital stock was sufficiently rapid, that it soon bulked large in the total real tangible stock and was

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[59] See A&D (2001) Pt. Two: Endnote 14.

proximately responsible for the latter's rise at a rate the surpassed the annual growth rate of real output by 0.5 percentage points on average during the period stretching from 1835 to 1890.[60] Over that interval the real reproducible capital-output ratio was almost doubled, and the total tangible capital-output ratio rose by almost one-third. Just as the contemporary economists opined, the development impelling this trend was a differentially more rapid accumulation of fixed capital in the form of structures and equipment.[61] This had been plainly revealed by Robert Gallman's exacting and detailed estimates of the changing distribution of the fixed reproducible stock *inclusive of improvements made to farm land* during the period 1840-1890. Whereas at the beginning of the century (1799-1805) the stock of improvements made to farm land constituted more than 62 percent of the nation's fixed domestic stock of reproducible capital, that share had been reduced to 47 percent by 1840, and over the next half-century it dwindled to a mere 14.5 percent. Moreover, Gallman's (1992) comprehensive estimates tell us that although in 1840 fixed reproducible capital goods had represented only 35 percent of the aggregate domestic capital stock (valued in 1860 prices), that share had risen to 66 percent in 1890 and had fully doubled by 1900.

Yet, during the very same extended era, as one may see from the entries in Table 4 (Frame I), the share of gross income going to owners of reproducible capital underwent a sustained enlargement, rising from an average of 19 percent during the 1800-35 interval to almost 34 percent during the 1890-1905 period. The total property share thus rose by essentially the same (proportional) extent, from about 32 to 46 percent according to the estimates shown in Frame I for the *fin de siècle* period, and by only a little less if one consults the alternative total property share estimate shown for 1890-1905 in Frame II of the table.

The concurrence of these two trends, one in the real capital-output ratio(s) and the other the property share(s) carries a strong implication supporting out interpretation of the dynamics of nineteenth century capital-deepening growth as having been driven by technologically induced shifts in the desired capital-output ratio, and consequently in the desired real investment rate. Had the growth of the aggregate capital-output ratio been pushed upward simply by an increase in thrift, this would have had to work entirely through the induced substitution of capital for labor in production; the higher rate of savings (gross) in relationship to the growth rate of the labor supply would have led to a downward pressure on the real rental price of capital vis-à-vis the wage rate, and thereby induced the substitution of tangible capital for labor. The behavior of the share data, however, implies that the real rate of return was not being forced sharply downwards.

How far the relative return to capital would have been depressed in proportion to the consequent rise of the tangible capital-labor ratio is what is measured by the elasticity of substitution, which, for present purposes may be treated as a parametric feature of aggregate production relations in the economy during this epoch. Successive econometric investigations of aggregate production function models of U.S. private (and private business) domestic economy in the twentieth century, as well as a parallel inquiry for the nineteenth

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[60] These years of aggregate "capital-deepening" form the central period of what one of us (see Paul A. David, "Invention and Accumulation in America's Economic Growth: A Nineteenth Century Parable," in International Organization, National Policies and Economic Development, a supplement to the Journal of Monetary Economics, vol. 6, 1977, pp. 179-228) has called the nineteenth century American economy's "Grand Traverse." The term refers to the movement of the economy *between different (steady-state) growth paths*, each characterized by a constancy of the capital output ratio and the real rate of return on capital (or, equivalently, constancy in the capital share).

[61] See A&D (2001) Pt. Two: Endnote 15.

century domestic economy, and numerous sectoral and industry studies, all concur in finding that the elasticity of substitution to be less than unity.[62] Unitary elasticity would imply, of course, that the relative shares of the factors in gross output would be unchanged. But, if that elasticity was less than unity, and if technological progress had been (Hicks) neutral, tangible reproducible capital's share in gross income would have been *contracting, and labor's share would have been rising* -- as the latter was the slower growing of that pair of inputs. Yet, just the opposite happened: in the first half of the nineteenth century the share of capital rose by 19 percent, and during the second half the proportional increase was again 19 percent, for an overall 41 percent expansion (see Table 4).

The immediate implication if this is that the effects of technological change must have been "non-neutral," and have worked to counter-act the rise of the capital-labor ratio measured in "natural" units, i.e., the ratio of the constant dollar value of the flow of capital services per manhour. By raising the efficiency of labor faster than the efficiency of capital inputs, the pronounced capital-using bias of technological innovation operated so as to offset the depressing effect that the accumulation of capital goods tended to exert on the real rate of return.[63]

A further aspect of these macroeconomic relationships enables us to venture a step farther: the implied trend differential between the growth rates of the average efficiency of manhour inputs and average efficiency of the services of tangible capital during the nineteenth century turns out to have been so pronounced that one has to conclude that it was the impact of technological and other innovations in the nineteenth century which worked to push the desired aggregate capital output ratio upwards. Equivalently, we may say that in the absence of any other change in the capital-output ratio, the effect of technological progress was tending to raise the real rate of return on the existing stock. In the event, however, it served to substantially moderate its downward course over the century.

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[62] See A&D (2001) Pt. Two: Endnote 13, on econometric estimates of the elasticity of substitution.

[63] It is possible to obtain an estimate that puts the rate of capital-using technological change for the period 1835-1890 at E_K* = - 0.68 per cent per year. The corresponding rate of growth of the manpower inputs' efficiency index is found to be 1.02 per cent per year. See A&D (2001) Pt. Two: Endnote 16, for the method of estimation.

Table 2
Real Gross Output and Factor Input Growth Rates (percent per annum), 1800-1989
U.S. Private Domestic Economy

Panel A: *Frame I*	Y^*	Y_A^*	L_*	K_T^*	K_{TQ}^*	H_*	Y^*-L^*	$K_T^*-L^*$	$K_{TQ}^*-L^*$	$H^* - L^*$
1800-1835	3.84	---	3.57	3.84	---	---	0.27	0.27	---	---
1835-1890	4.02	---	3.32	4.51	---	---	0.70	1.19	---	---
1890-1905	3.80	3.81	2.41	3.64	(3.64)	4.40	1.37	1.20	(1.20)	1.94

Panel B: *Frame II*	Y^*	Y_A^*	L^*	K_T^*	K_{TQ}^*	H_*	$Y_A^*-L^*$	K_T^*-L	K_{TQ}^*-L	$H^* - L^*$
1890-1905	4.25	4.26	2.28	3.49	(3.49)	4.40	1.94	1.16	(1.16)	2.07
1905-1927	3.31	3.70	1.24	2.43	2.43	4.40	2.43	1.18	1.18	3.12
1929-1966	3.05	3.17	0.52	1.85	2.52	3.88	2.64	1.32	1.99	3.34
1966-1989	2.86	2.84	1.61	3.11	4.00	3.82	1.21	1.48	2.37	2.17

Source: See following Notes and Sources for Table 2

Notes and Sources for Table 2: Description of Growth Rate Variables and Data Sources

Panel A:

Y^*, L^*: See A&D (2001 Statistical Appendix, Sources for Tables 1:IA, and 1:IIA (Frame I), for real gross product, and manhours, respectively. (**Note:** All following citations of "Statistical Appendix" refer to material in A&D 2001].)

Y_A^*: augmented real gross product for the interval 1890-1905 is based on Y^* in that interval, adjusted by extrapolating the growth rate of (Y_A/Y) in the period 1890-1905, from the estimates underlying the entries in Panel B in this table.

K_T^*: the total real tangible capital stock (estimated as a constant price Divisia index of the reproducible and non-reproducible tangible stock). See Statistical Appendix, Sources for Table 1: IVA (Frame I).

K_{TQ}^*: total real tangible capital adjusted for (compositional) "quality change": $K_{TQ}^* = [K_T^* + q_K^*] = K_T^*$ in the 1890-1905 interval, by extrapolation of the argument in Part Two, section 2.23, based upon constant dollar stock estimates showing that the composition of the tangible reproducible stock remained virtually unchanged over the period 1910-1929. See sources for Panel B of this Table.

H^*: the real stock of intangible capital: See Panel B of this Table for sources of the 1890-1905 estimate.

Notes and Sources for Table 2: -- Continued

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Panel B:

Y^*, L^*, K_T^*: See Statistical Appendix, Sources for Tables 1:IA, and 1:IIA (Frame II).

1890-1905 and 1905-1927, based on underlying estimates in John W. Kendrick, Productivity Trends in the United States, Princeton, NJ: Princeton University Press for the National Bureau of Economic Research, 1961, Table A-XXII (for Y, and L), Table XV(for K_T); 1929-1966 and 1966-89, from Statistical Appendix, Tables 1:IA and 1: IIA, based on underlying data from U.S. NIPA (1992, 1993), for Y^* and L^*; Table 1:IVA (Frame II), from U.S. Bureau of Economic Analysis as presented in Department of Commerce, National Income and Product Accounts of the United States, vol. I, 1929-1958 and vol. II 1959-1988, Washington, D.C.: Government Printing Office, 1992 and 1993, Tables A6 and A9, for K_T^*.

Y_A^* : 1890-1905 and 1905-1927, from Y^* adjusted by the growth rate of (Y_A/Y) computed for 1905-1929 from augmented real domestic product estimates in Table 3, pt.A; 1929-1966 and 1966-1989 from Y^* adjusted by the growth rate of (Y_A/Y) computed by interpolation from the Table 3, pt.A estimates for 1929, 1973 and 1990.

$K_{TQ}^* = [K_T^* + q_K^*]$: 1929-1966 and 1966-1989 adjustments of K_T^* for (compositional) quality change, using estimates underlying Table 1:IV and 1:IVA, as described in Statistical Appendix. The growth rate estimates for q_K^* appear in the Technical Appendix Note on the Vintage Effect and the Growth Rate of Capital-Embodied Efficiency. See Sources for Panel A of this Table on the basis of the estimate of $q_K^* = 0$ in the period 1890-1927.

H^*: 1905-1927, 1929-1966 and 1966-1989 computed from Total Intangible Stock estimates in Table 3, pt. A. See Statistical Appendix Sources for Table 3.

Table 3-Part A

Real Gross Domestic U.S. Capital Stocks and Product
(billions of 1987 dollars, and ratios)

Part A: Stocks and Flows

Selected Components of Real Stock	**1900-1910**	**1929**	**1948**	**1973**	**1990**
Conventional Tangible: Total	3583	6075	8120	17490	
Structures and Equipment	2305	4585	6181	13935	23144
Inventories	300	268	471	1000	1537
Natural Resources	978	1222	1468	2555	3843
Non-conventional Non-tangible: Total	1131	3251	5940	17349	28525
Education and Training	1001	2647	4879	13564	25359
Health, Safety, Mobility	120	567	892	2527	5133
R&D	0.1	37	169	1249	2327

Alternative Measures of Real Product					
Conventional Real GDP	330	822	1300	3269	4878
Augmented Real GDP	410	1112	1715	4302	6395

Source: See A&D (1999) Statistical Appendix: Notes and Sources to Table 2:II-Part A.

Table 3-Part B

Real Gross Domestic U.S. Capital Stocks and Product, 1900 - 1990

Part B: Ratios Derived from Part A Entries

	1900-1910	1929	1948	1973	1990
Ratio of Non-tangible Stock to Conventional Tangible Stock	.316	.535	.731	.992	1.150
Ratio of Education and Training and R&D Stocks to:					
Conventional Real GDP	3.03	3.26	3.88	4.53	5.67
Fully Augmented Real GDP	2.44	2.41	2.94	3.44	4.33
Total Conventional and Non-Conventional Capital Stock	0.21	0.29	0.36	0.42	0.45
Ratio of R&D Stock to Fully Augmented Real GDP	.0002	.033	.098	.290	.364

Source: calculated from entries in Table 3-Part A.

What this means, then, is that to the extent that the supply of savings was elastic to the real rate of return, as seems quite plausible, a portion of the rise that has been observed to occurred in the proportion of the nation's aggregate income that was being channeled into net (and gross) savings in the form of tangible reproducible wealth, can be attributed to the upward pressure that biased innovation was bringing to bear on the demand side of the market for loanable funds. Some part of the rise in the fraction of income saved undoubtedly is traceable to independent supply-side shifts, stemming from altered household savings habits, institutional innovations that improved bank and non-bank financial intermediation, and other such developments.[64] But, to the extent that the aggregate supply of savings was responsive to changes in the functional distribution of income, which would be the case if the propensity to save out of the earnings of property exceeded that out of wages, the expanding share of income going to holders of tangible reproducible property as a consequence of the bias of technological change provided a mechanisms through which the upward shifts in the demand for loanable funds tended to be met by an accommodatingly high elasticity of on the supply side.[65]

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[64] These developments are summarized by Robert Gallman's chapter (in the *Cambridge Economic History of the US*, Vol. 3), which gives references to the relevant literature on nineteenth century trends affecting the supply of savings.

[65] See A&D (2001) Pt. Two: Endnote 17, for further elaboration of this point.

[1] **Table 4**
Gross Factor Shares: Input Weights for Conventional and Augmented Production Models: U.S. Private Domestic Economy, 1800-1989

	Weights for Conventional Tangible Inputs:			Adjustment Ratios:		Weights for Augmented Model:		
	Labor Man-hours	Unim-proved Land	Repro-ducible Capital	Human Intangible Inputs	Non-Human Intangibles	“Raw” Man-hours	Total Tangible Capital	Total Intang-Capital
	θ_L	θ_R	θ_K	α_L	α_{KT}	θ_L’	θ_{KT}’	θ_H
Frame I :								
1800-1835	.683	.125	.192	---	---	---	---	---
1835-1855	.623	.152	.225	---	---	---	---	---
1855-1871	.536	.162	.300	---	---	---	---	---
1871-1890	.553	.130	.317	---	---	---	---	---
1890-1905	.539	.124	.337	.092	.000	.448	.461	0.092
Frame II :	**Labor inputs:**		**Capital:**					
			(θ_R+θ_K)			(θ_L-α_L)	(θ_{KT}- α_{KT})	(α_L+α_{KT})
	θ_L		= θ_{KT}	α_L	α_{KT}	= θ_L’	= θ_{KT}’	= θ_H
1890-1905	.560		0.44	0.092	0.00	0.468	0.440	0.092
1905-1927	0.60		0.40	0.185	0.003	0.415	0.397	0.188
1929-1966	0.64		0.36	0.244	0.084	0.396	0.276	0.328
1966-1989	0.65		0.35	0.246	0.084	0.404	0.266	0.330

Sources:

Frame I. Standard Weights: See A&D (1999) Statistical Appendix, Sources for Table 1:IV and 1: IVA (Frame I) discussion of imputed factor share estimates. For 1890-1905 adjustments for intangible inputs, see Sources of Frame II estimates in this Table. Weights for Augmented Inputs are the conventional shares minus $\alpha_L$and α_K, respectively.

Frame II. Conventional gross factor shares are obtained for 1890-1905 and 1905-1927 by raising the net share estimates from Kendrick, 1961, Table A-X for 1899-1909, and the average of 1909-19 and 1919-29, by 0.09, to allow for capital consumption; for 1929-1966 and 1966-1929 see Statistical Appendix Sources for Table 1:IV and 1:IVA (Frame II), factor share estimates. Imputed estimates of $\alpha_L$and α_K, the gross returns on stocks of intangible human capital, and on the stock of (non-human intangible) R&D capital, expressed as fractions of augmented GPDP, respectively, are obtained by the procedures described in Statistical Appendix Sources for Table 2:III. Note that $\theta_H = \alpha_L + \alpha_{KT}$.

The Relative Rise of Real Stocks of Intangible Capital

Turning now to the twentieth century, we must begin by looking beneath the growth rates of those large aggregate measures of tangible and intangible capital inputs, which are reported in the lower panel of Table 2. This can readily be done by consulting the estimates in Table 3-Part A pertaining to the U.S. Domestic Economy, where estimates of the component stocks valued in constant prices of 1987 are set out for benchmark dates between 1900 and 1990. From these it will be seen that the secular rise of each of the principal categories of intangible assets -- Educational and Training, Health, Safety and Mobility (combined), and R&D -- outpaced the accumulation of conventional tangible assets in the form of commodity inventories, structures and equipment.

The main facts of the national "portfolio transformation" that this has involved stand out plainly enough from comparisons of their respective absolute 1987 dollar magnitudes: beginning from a level that was less than one-third that of the tangible capital stock in the first decade of the century, size of the real stock of intangible capital grew to match that of its tangible counterpart in 1973, and, by 1990 it already was 15 percent larger. Thus, the ratio between the non-conventional (intangible) stock and the conventional (tangible) components of total non-financial wealth (which appears in the topmost line of Part B of Table 3) increased by 3.5-fold over the 1900/1910-1990 interval as a whole, and was more than doubled between 1929 and 1990.

Two distinct sets of secular forces can be identified as having been responsible for bringing about this striking twentieth century switch in the composition of the nation's portfolio of domestic non-financial wealth. On the one hand were those forces that tended to *reduce* the desired demand for wealth in the form of tangible capital stocks at given levels of real income and the real rate of interest, and on the other were the set of forces that were tending to *raise* the desired ratio between real intangible wealth and real income. As the focus of the discussion in the following pages will rest upon the latter two, before going on it is important to take note of the emergence of a number of significant tangible-capital saving developments, especially during the first quarter of the twentieth century.

Tangible Capital-Saving Developments in the Twentieth Century

More intensive utilization of fixed capital facilities that were initially installed in large, lumpy blocks, was a prominent source of gains in tangible capital productivity, which became especially pronounced first in the railroad transportation industry and the new public utilities, particularly electricity supply and telephone networks during the 1890-1905 era.[66] But it should not be supposed that this was simply a matter of waiting until demand grew up to the levels of the capacity that had been originally installed. As Albert Fishlow[67] shows for the case of the U.S. railroads, numerous technological advances were required to permit attaining higher ton-mileage rates with reliability, and fuller utilization of the fixed capacity of roadbed, stations, marshaling yards and the rolling stock itself; these innovations ranged from the design of heavier and more powerful locomotives, to the introduction of air-brakes and automatic car coupling, as well as more reliable signaling systems to control train movements. Similar technological advances underlay the expanding generating capacity of electrical dynamos, and the integration of more extensive electricity distribution networks across with "load balancing" became possible, permitted reductions in the excess capacity that was entailed when generators were installed to meet daily and seasonal peaks in demand.[68]

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[66] See, for example, Melville J. Ulmer (1960), Capital in Transportation, Communications, and Public Utilities: Its Formation and Financing, Princeton University Press (for NBER), and John W. Kendrick (1961), Productivity Trends in the United States, Princeton University Press

[67] Albert Fishlow, "Productivity and Technological Change in the Railroad Sector, 1840-1910," in Brady (ed.), Output, Employment, and Productivity in the United States After 1800, 1966, pp. 583-646.

[68] See, e.g., Thomas P. Hughes (1983), Networks of Power: Electrification in Western Society, Baltimore and London: Johns Hopkins University Press, and Paul A. David and J.A. Bunn (1988), "The Economics of Gateway Technologies and Network Evolution: Lessons from Electricity Supply History," Information Economics and Policy, Vol. 3, pp. 165-202; Paul A. David, "Computer and Dynamo: The Modern Productivity Paradox in a Not-Too-Distant Mirror," in Technology and Productivity: The Challenge for Economic Policy,

In manufacturing industries the introduction of continuous process production and the increasing use of multiple shift-work in the years around 1915, and the diffusion of automated materials handling technologies to increase the rates of charging and discharging of batch production processes, similarly rested on technological innovations, including the growing use of electro-mechanical control systems in chemical plants, breweries, steel rolling mills, and the like.[69] Moreover, during the 1920's particularly, the introduction of the unit drive system of factory electrification in many industries completed the replacement by wires of the former mechanical means of power transmission using shafts and belting, and this brought significant savings in fixed construction costs, as well as permitting reductions in lost output during "down time" for retro-fitting of particular departments in the plant, or for reconfiguring the layout of the factory floor to accommodate product changes.[70]

Once initiated, this trajectory of development and diffusion of fixed tangible capital-saving innovations has persisted into the 1929-1966 era. Wartime pressures on capacity in the 1940s led to new methods of intensive utilization which could be introduced in conjunction with plant renewals, but it was not until the 1960's that a further notable increase in the "work-week" of manufacturing capital took place, due to structural changes that increased the importance of the continuous production industries and the extent of shift-working. According to the estimates prepared by Murray Foss, the index of intensity of utilization of industrial plant capacity rose at the average annual rate of 0.38 percentage points per annum.[71] As manufacturing is a comparatively capital-intensive sector, capital-savings from these sources carried considerable weight in the aggregate, but the share of manufacturing in gross private domestic product shrank towards the 20-25 percent range in the post-World War II period, setting a limit on their ability to raise tangible capital's productivity economy-wide.

It is therefore significant that this era also saw a similar movement towards organizational and technological changes that permitted greater fixed capacity utilization in the service sector: banks and insurance using computers moved to time-sharing of that equipment in the 1960s, while automatic teller machines reduced the demand for numerous small retail banking facilities that typically could attain only relatively low levels of transactions throughput; in retail distribution, stores catering to a rising number of women in the workforce began significant extension of their opening hours during the 1970s. The contribution of such developments towards raising the economy-wide level of (partial)

Organization for Economic Co-operation and Development, Paris, 1991, pp. 315-48; Sam H. Schurr, et al., Electricity in the American Economy: Agent of Technological Progress, New York: Greenwood Press, 1990.

[69] See Harry Jerome (1934), Mechanization in Industry, New York: National Bureau of Economic Research; Claudia Goldin and Lawrence F. Katz (1998), "The Origins of Technology-Skill Complementarity," Quarterly Journal of Economics, 113, pp. 693-732.

[70] For discussion of the implications of these developments for reductions in the capital-output ratio, and the acceleration of average labor productity, as well as TFP growth during the interwar period, see Paul A. David and Gavin Wright, ""General Purpose Technologies and Surges in Productivity: Historical Reflections on the Future of the ICT Revolution," (with Gavin Wright), Ch. 4 in The Economic Future in Historical Perspective, P.A. David and M. Thomas, eds., Oxford University Press for The British Academy, 2003.

[71] Murray F. Foss (1997), Shiftwork, Capital Hours and Productivity Change, Boston, Dordrecht, and London: Kluwer Academic Publishers, 1997.

productivity of tangible capital during these years is difficult to quantify with any precision.[72] But, if the average yearly rate of rise in the long-term utilization rate of fixed capital overall matched that estimated for the manufacturing sector during the years 1929-73, this alone would have accounted for roughly two-thirds of the concurrent 0.61 percentage point per annum average rate of increase in the ratio between augmented real gross domestic product and the real stock of fixed reproducible tangible capital.[73]

A second major contributor to the differentially faster pace of accumulation of the intangible portion of the aggregate domestic capital has been the growing difference between the average service lives of tangibles and intangibles, and, the fact that the latter difference has also reflected the shifting internal make-up of those broad classed of assets. Consider first the non-conventional intangibles: from the estimates of the absolute 1987 dollar magnitudes in Table 3-Part A it is seen that education and training has remained the overwhelmingly dominant element within the intangible stock. Indeed, the rise of this particular form of human capital has been the development that must be assigned proximate responsibility for driving the secular shift towards intangible asset formation. Because the real capital stock figures we are considering are estimated gross of depreciation (and obsolescence), the assumed average service life of the intangible component reflects the dominance of the comparatively long-lived humans in whom educational, training (and health) investments have been embodied; even though its share of education and training in total intangible capital drifted downwards, from 88 percent to 77 percent between the first and the final decade of the century, this was not sufficient appreciably to shorten the extended average service life of the entire class of intangible assets.

By contrast, however, the average service life of newly installed tangibles has fallen appreciably, in part as a consequence of the rising relative importance of equipment relative to structures especially from 1929 onwards, but also due to the shortening of the average service life of equipment itself.[74] Taken in conjunction with the longevity of educational and training investments embodied in the labor force, this shift towards a higher average rate of depreciation on tangible reproducible assets has meant that even if a constant comprehensive rate of real gross savings had been allocated in an unchanged way between tangible and intangible capital formation, the intangible component of the total U.S. real gross capital stock would have been growing at a differentially rapid pace -- at least since 1929.

But it is evident also that these preliminary considerations cannot be the main part of the story of the relative rise of the intangible stock, which, in any case, can be seen to have been underway since the beginning of the century.[75] Demography also has had a hand in this development. On turning the problem around so as to consider the historical evolution of an

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[72] See Foss (1997).

[73] See Table 3-Part B, for the estimates underlying the latter calculation. Robert J. Gordon (1964) argued that industrial facilities built by the government during WWII (such as the aluminum plants on the Pacific Coast) were transferred to the private sector at values well below reproduction cost, resulting in an underestimate of the growth of the real tangible stock over the interval 1929-1948. But, more recently, Robert Higgs (2003) contends that these "defense production" facilities by-and-large were poorly suited for civilian production, in which case a reproduction cost valuation would not be appropriate.

[74] See A&D (2001) Pt. Two: Endnote 18 for discussion of service lives of tangible assets and estimates of the changing composition of the real tangible stock .

[75] See A&D (2001) Pt. Two: Endnote 19 on the assumptions underlying the intangible capital stock growth rate estimates in Table 2 for the pre-1929 era, and the extrapolation of the real stock figures in Table 3 back to 1900-1910.

education-health care nexus from the prospective viewpoint of the late nineteenth century, it is evident that the advance of scientific knowledge in the fields of medicine, including public health, contributed substantially in the late nineteenth and early twentieth centuries to lengthening adult life expectancy. It did so first by reducing the incidence of diseases such as tuberculosis, which are economically very costly because they debilitate if not abbreviate the lives of young adults, and subsequently by prolonging the potential working lives of mature adults.[76]

These demographic developments may be seen to have had two entwined effects. On the one hand, by extending the prospective "service lives" of human capital investments, they worked to raise the anticipated rates of return on formal education and training. An illustrative set of calculations conveys some idea of the magnitude of the impact upon the demand for further educational that this consideration alone may have entailed. Starting from a representative age-earnings profile of U.S. male workers ages 15 to 60 who had a grade school education, and the corresponding profile (with earnings starting at age 25) for those who completed four years of college, one may ask what would be the effect on a rational assessment of the economic return to opting for college completion of an improvement in adult life expectancy such as that which actually occurred between 1870 and 1960. Using the age-specific mortality schedules for the U.S. white male population at those two dates, the corresponding expected values of the (1960) alternative education-associated earnings profiles can be obtained, and the present value of those may then be evaluated and compared by positing alternative time-discount rates. What a counterfactual exercise of this kind reveals is that the impact of the historical improvement in male survival probabilities in the U.S. was sufficient to raise the expected present value of a college education by 25% if the discount rate were as low as 5 percentage points per annum, and by 60% if the discount rate was as high as 15 percentage points per annum.[77]

At the same time one should notice the implications of the tendency for the age distribution of the U.S. workforce to shift upwards over the period 1890-1940 -- both as a consequence of the early twentieth century continuation of the fall in fertility rates until the late 1940s, and the subsequent reductions in adult mortality levels. This meant that the accelerated pace in the advance of knowledge and its translation into new techniques of production and work routines increased the problem of obsolescence in the human capital stock. Taken by itself, that would have contributed to depressing the *average* index of the human capital stock's efficiency, whilst raising the marginal rate of return to gross investment in intangible capital formation through the education and training of young workers. As shall be seen, the movements of the observable macroeconomic variable in the twentieth century are consistent with the existence of such a secular bias towards *intangible capital-using* efficiency changes.

Intangible Capital-Deepening and the Growth Accounts for the U.S. in the Twentieth Century

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[76] On the shift in mortality schedules and the effects of public health especially, see Samuel H. Preston, Mortality Patterns in National Populations, New York: Academic Press, 1976; on infant and child mortality conditions in the U.S. around the turn of the century, see Samuel H. Preston and Michael R. Haines, Fatal Years: Child Mortality in Late Nineteenth Century America, Princeton, NJ: Princeton University Press, 1991.

[77] The results reported are based upon Paul Taubman (1971): unpublished seminar notes, Stanford University Department of Economics, 11 January. They make use of the earnings functions for the two educational attainment categories from G. Hanoch, "An Economic Analysis of Earnings and Schooling," in B.F. Kiker, Investment in Human Capital, 1971.

The first point to be considered is that the rise in the intangible capital-output ratio was accompanied by a rise in the share of total intangible capital in the augmented gross product, as may be seen by comparison of the positive growth rates of the (real) ratio H/Y_A indicated for the U.S. Private Domestic Economy by Table 2 (Panel B), with the trend in the share θ_H that appears in the lower panel of Table 4. Over the whole of the 1905-1989 interval the rate of increase of the former ratio averaged 0.74 percentage points per annum, but the pace quickened perceptibly from the late 1960's onwards and during 1966-1989 was running at 0.95 percentage points per annum. Thus, by 1989 the intangible capital-output ratio stood at 190 percent of its 1890 level, a proportionate rise that was approximately the same as that recorded over the nineteenth century by the *tangible* (reproducible) capital-output ratio.[78]

There is a further parallel to be noted between the experience of the two centuries in the behavior of the corresponding gross factor shares, for, the share of augmented gross product that is imputed here to total intangible capital inputs was rising along with the intangible capital-output ratio. From Table 4 (Frame II) it is evident that the rising imputed returns on intangible *human capital* were the quantitatively important development of during the period 1890-1927, reflecting the labor force impact of the High School education movement. When those returns are subtracted from the total labor earnings, the resulting estimate of the share of "raw labor inputs" in gross (augmented) output shows no rise during the twentieth century; indeed, the essential constancy of the share at the 40 percent level after 1890-1905 can be viewed as the eventual bound reached by the secular contraction that had begun early in the nineteenth century.

Privately and publicly financed expenditures for research and development began to rise rapidly from initially negligible levels in relationship to national output during the 1920's, and the sustained rise in this ratio over the next three decades produced the almost ten-fold rise in the ratio of the real R&D capital stock to gross (augmented) product occurred between 1929 and 1973, according to the estimates presented in Table 3–Part B. That movement underlay the rapid expansion of the share of gross product imputed to the non-human component of intangible capital inputs, an increase of approximately 8 percentage points between the immediate post-World War I and post-World War II years. Subtraction of this component from the imputed gross earnings of all capital results in a sharper contraction of the gross share of tangible assets (in augmented output) between the first quarter and the following part of the twentieth century. Thus, the share of all tangible inputs (human and non-human) is seen to have decreased from approximately 90 percent at the turn of the century (1890-1905) to the 67 percent level that has been maintained over the 1929-89 period.

The input growth rates and estimated factor shares are brought together in Table 5-Part A to provide a more comprehensive growth accounting for the U.S. Private Domestic Economy in the three long periods since 1890. These figures incorporate the adjustments for the changing composition of tangible assets, previously introduced as a "capital quality improvement" in Table 1:IV (see Appendix). But, they make no corresponding adjustment in the labor inputs, inasmuch as the estimates of the growth of the stock of intangibles directly and indirectly reflect compositional shifts in the expenditures and foregone earnings flowing into investments in human capital. Because the contributions of the growth of intangible

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[78] These average annual growth rates are computed as $(H^*-Y_A^*)/(1+Y_A^*)$ from the entries in Table 2.

inputs per (full time equivalent) manhour exceed the previously estimated contributions of improved “labor quality”, the resulting multifactor productivity residuals are smaller in each of the periods than the corresponding entries in Table 1:IV-Part A (see Appendix). The reduction is quite minor for the pre-1929 period and moderate in the 1966-1989 interval, but quite pronounced for the 1929-66 period. Consequently, the new, “super-refined” TFP estimate (E_A*) is found to have declined from the 1.3 percentage point per annum high point that have been attained during the first quarter of the century (it stood at 1.375 percentage points per annum in the sub-period 1905-27, slightly above its average for 1890-1927).

If we accept the estimate of 1.00 percentage points per annum for the “refined” TFP growth rate in the long period 1871-90 (from Table 1:IVA in the Appendix) as roughly comparable with these figures, the picture that emerges is one of acceleration to a peak rate of growth of multifactor productivity during 1905-27, followed by a return to the same (1 percentage point per annum) rate during 1929-1966, before the protracted shrinkage of the residual that marked the 1970’s and 1980’s. The final row in Table 5-Part A shows that the

Table 5-Part A

The Sources of Labor Productivity Growth: Augmented Accounting Framework for U.S. Private Domestic Economy

(Growth rates in percentage points per annum)

Long Periods	Growth Rate of Augmented Real Output per Manhour: $[Y_A^* - L^*]$	Contribution of Tangible (Quality-Adjusted) Capital per Manhour: $\theta'_{KT}[K_{TQ}^* - L^*]$	Contribution of Intangible Capital per Manhour: $\theta_H[H^* - L^*]$	Contribution of Total Capital Inputs per Manhour:	Contribution of Refined Multifactor Productivity: E_A^*
1890- 1927	2.21	0.484	0.424	0.908	1.302
1929-1966	2.64	0.549	1.096	1.645	0.995
1966-1989	1.21	0.630	0.716	1.346	-0.136
"*The Slowdown*": from 1929-1966 to 1966-1989	- 1.43	+ 0.081	-0.380	-0.299	-1.131

Notes and Sources to Table 5:

For cols. (1), (2) and (3) the growth rates and input weights from Table 2 (Panel B), combining entries for 1890-1905 and 1905-1927 rates, geometrically averaged with appropriate relative weights for lengths of sub-periods. Col. (4) is the sum of cols. (2) and (3). For col.(5): EA* is obtained as a residual from col.(1) minus col.(4).

Table 5-Part B

The Relative Contributions to Labor Productivity Growth and the MFP “Slowdown”:

Augmented Accounting Framework for U.S. Private Domestic Economy

	Growth Rate of Augmented Real Output per Manhour:	**Relative**	**Contributions**	**in Percentages**	**of Column1:**
		Tangible (Quality-Adjusted) Capital per Manhour:	Intangible Capital per Manhour:	Total Capital Inputs per Manhour:	Refined Multifactor Productivity:
1890- 1927	.0221=100	21.9	19.2	41.1	58.9
1929-1966	.0264=100	20.8	41.5	62.3	37.7
1966-1989	.0121=100	52.0	59.2	111.2	-11.2
"*The Slowdown*": from 1929-1966 to 1966-1989	-.0143=100	-5.7	26.6	20.9	79.1

Sources: Calculated from entries in Table 5-Part A.

In Table 5-Part B the relative contributions of tangible and intangible capital-intensity growth, and of multifactor productivity change are calculated. The steadily mounting relative importance of intangible capital per manhour, and, consequently, of total capital inputs per manhour forms a decided contrast with the picture presented by the standard accounting in Part One. From this perspective the decreased importance of multifactor productivity growth in the most recent period appears less of an anomaly, and more a continuation of previous developments. The resurgent relative role of tangible capital-intensity growth after 1966, which parallels the increased absolute size of the contribution to labor productivity growth, is seen now as an accompaniment to the relative growth of the contribution of rising intangible capital-intensity.

Although the explanation of the post-1966 productivity "slowdown" is not my main concern here,[79] one may note in passing that by considering the role of intangible inputs some headway has been made in that direction: whereas the standard growth accounts indicate that more than the entire reduction of the labor productivity growth rate should be attributed to the shrinkage of the refined TFP growth rate, the results from Table 5-Part B assign 21 percent of the decrease in (augmented) output per manhour to the diminished rate

Although the explanation of the post-1966 productivity "slowdown" is not my main concern here,[80] one may note in passing that by considering the role of intangible inputs some headway has been made in that direction: whereas the standard growth accounts indicate that more than the entire reduction of the labor productivity growth rate should be attributed to the shrinkage of the refined TFP growth rate, the results from Table 5-Part B assign 21 percent of the decrease in (augmented) output per manhour to the diminished rate of increase of total capital-intensity growth, leaving 79 percent to be "explained" by the contraction of the

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[79] See A&D (2001) Pt. Two, Section 3 for treatment of this issue, especially Table.

[80] See A&D (2001) Pt. Two, Section 3 for treatment of this issue, especially Table.

multifactor productivity residual. All of the diminished contribution from capital-intensity growth since the late 1960's, however, is traceable to the reduced contribution made by intangible capital-intensity, so that the movements in that component may be rightly said to have played the pivotal role in both the acceleration of labor productivity growth between 1890-1927 and 1929-1966, and its subsequent deceleration.

Table 5-Part C

Specific "Capital-Deepening" Impacts on Labor-Productivity Growth: U.S. Nineteenth and Twentieth Century Experiences Compared

	Manhours Productivity (percent per annum)	"Capital-Deepening"	Relative Weight	Effect of "Capital-Deepening" (percent rate per annum)	Percentage Contribution to Labor Productivity Growth Rate
Frame I: The Nineteenth Century: Tangible Reproducible Capital-Deepening					
Periods	$[Y^* - L^*]$	$[K^* - Y^*]$	(θ_K / θ_L)	$(\theta_K / \theta_L)[K^* - Y^*]$	$\frac{(\theta_K/\theta_L)[K^*-Y^*]}{[Y^*- L^*]}$
1800-1835	0.26	0.68	.281	0.193	73.9
1835-1890	0.68	1.21	.487	0.589	86.7
1890-1905	1.37	0.14	.625	0.087	6.3
Frame II: The Twentieth Century: Intangible Capital-Deepening					
	$[Y_A^*- L^*]$	$[H^*-Y_A^*]$	(θ_H / θ'_L)	$(\theta_H / \theta'_L)[H^*-Y_A^*]$	$\frac{(\theta_H/\theta'_L)[H^*-Y_A^*]}{[Y_A^*- L^*]}$
1890-1927	2.21	0.46	.342	0.156	7.1
1929-1966	2.64	0.69	.828	0.570	21.6
1966-1989	1.21	0.95	.743	0.708	58.6

Note: The entries shown for “1800-1835”, “1835-1890” ,“1905-1927" refer, as previously, to the terminal year averages: 1799/1800, 1834/36, 1888/1892, 1903/07, 1925/29; for post-1929 periods the underlying terminal year data are those for 1929, 1966, 1989.

Source: See Table 2 entries for growth rates (and data underlying Table 2 for K*); Table 4 for input shares.

Table 5-Part D

Absolute and Relative Impacts of "Traversing" on Labor-Productivity Growth: U.S. Nineteenth and Twentieth Century Experiences Compared

	Manhours Productivity (percent per annum)	"Capital-Deepening" (percent per annum)	Relative Weight	Effect of Total "Capital-Deepening" (percent per annum)	Percentage Contribution to Labor Productivity Growth Rate
Frame I: The Nineteenth Century: Total (Tangible) Capital-Deepening Traverse					
Periods	$[Y^* - L^*]$	$[C^* - Y^*]$	$\{(1-\theta_L)/\theta_L\}$	$\{(1-\theta_L)/\theta_L\}[C^* - Y^*]\}$	$\frac{\{(1-\theta_L)/\theta_L\}[C^*-Y^*]\}}{[Y^*- L^*]}$
1800-1835	0.26	0	.464	0	0
1835-1890	0.68	0.49	.745	0.320	47.0
1890-1905	1.37	- 0.15	.855	- 0.128	- 9.4
Frame II: The Twentieth Century: Total (Tangible and Intangible) Capital-Deepening Traverse					
Periods	$[Y_A^* - L^*]$	$[C'^* - Y_A^*]$	$\{(1-\theta'_L)/\theta'_L\}$	$\{(1-\theta'_L)/\theta'_L\}[C'^* - Y_A^*]$	$\frac{\{(1-\theta'_L)/\theta'_L\}[C'^*-Y_A^*]}{[Y_A^*- L^*]}$
1890-1927	2.21	- 0.51	1.291	- 0.660	- 29.9
1929-1966	2.64	0.08	1.525	0.127	4.8
1966-1989	1.21	0.59	1.475	0.873	72.1

Notes:

In Frame I: $C^* = K_T^* = [(\theta'_K)K^* + (\theta_R)R^*] / (1-\theta_L)$;underlying shares are θ_K, $\theta_{KT} = (\theta_K+\theta_R) = 1- \theta_L$

In Frame II: $C'^* = [(\theta'_{KT})K_{TQ}^* + (\theta_H)H^*] / (1-\theta'_L)$: underlying shares are θ'_L, θ_H, $(\theta'_K + \theta_H) =1- \theta'_L$.

Source: See Notes to Table 5-Part C; Tables 2 and 5-Part A for growth rates; Table 4 for shares.

Whereas the growth of intangibles per manhour and tangible capital per manhours were roughly on a par during 1890-1927, in terms of their contributions to labor productivity growth, the former has been seen to have become more important in absolute and relative terms after 1929. This shift, brought out clearly by Table 5, reflected the underlying influence of demand-side forces favoring the accumulation of intangible rather than tangible assets. Evidently, the rise of the intangible capital stock in relationship to both the tangible stock and to real gross product during the twentieth century evidently did not depress the real gross rate of return on intangible enough to prevent the expansion of those assets earnings share; indeed, the proportionate increase in the latter share over the course of the century was actually greater than the near doubling of the intangible capital-output ratio. On the face of it the implication would appear to be clear: there must have been powerful forces offsetting the tendency for the relative accumulation of intangibles to lower the marginal productivity of such assets.

The style of the argument that the opposing force in question was an overall intangibles-using bias of innovations, however, is a little involved. quite as straightforward.

At least it is not quite so straightforward as the one that I previously advanced to support the inference that technological progress in the mid-nineteenth century must have been strongly biased in the tangible capital-using direction. This is the problem: although there is still ample basis for supposing that the elasticity of substitution between "raw manhours" and tangible capital inputs is less than unitary, the same cannot be said for the elasticity of substitution between the "raw manhours" and the intangible (human capital) components of labor inputs. Since the elasticity of substitution between "skilled " (or higher education attainment) labor and unskilled labor inputs has been found to exceed unity in many econometric studies,[81] it is possible that the rapid growth of intangible (human) capital per manhour bore some responsibility for the increasing share of intangible capital in (augmented) gross output.

In other words, with three (main) factor inputs to consider, and no clear basis for supposing that the elasticity of substitution between intangibles and the other (tangible) inputs was less than unitary, inferring the existence of a intangible capital-using bias of innovation requires establishing the quantitative relationships among the several input-specific rates of efficiency growth, and their collective relationship to the residual measure of multifactor productivity, when intangibles as well as tangible inputs are included among the inputs.[82] The detailed results need not concern us here, but their general qualitative import is quite clear and bears directly on the point at issue: throughout the era since 1929 the index of average efficiency of intangible inputs has trended downwards, and the rate of that decline was much more pronounced during 1966-89 than it had been during 1929-66. This worked to raise the real rate of return on intangible assets, given the ratio of intangibles to other, tangible inputs (and real output). It thereby supported the continuing relative accumulation of that broad class of assets. Prior to 1929, however, the trend in the efficiency of intangibles appears to have been upwards at a pace and not very different from that of the efficiency of tangible capital; other things being equal, this operated to lower the real rate of return on intangible assets.[83]

The bias of technological and organizational changes towards intangible capital-using innovations has been seen to have encouraged the extension of capital formation activity to include new classes of productivity assets, and so contributed to the growth of overall capital intensity among the sources of rising labor productivity. Indirectly, these interrelated developments in technology and input growth also affected the magnitude of their impact upon labor productivity because the share of the most rapidly growing input -- intangible capital services -- was not depressed, but grew larger especially between 1890-1927 and 1929-66. These "interactions" show the limitations of attempting to parse out the supply side of the long-run development process into cleanly separable "contributions" that reflect the influence of forces affecting the supplies of inputs, on the one hand, and the advance of technological knowledge, on the other. That message will be seen to be more fully borne out

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[81] See Technical Appendix Note 1, footnote 5 for references to this recent literature in the labor economics field, from which it appears that the elasticity of substitution between skilled (educated) and unskilled (low educational-attainment) workers in the post-World War II period lay between 1 and 2.

[82] The methodology and resulting estimates are set out in Appendix Note 2: Estimates of Trend Growth Rates of Efficiency of Intangible Inputs.

[83] The latter effect combined with that of the rapid rise in of the real stock of intangibles per manhour over the period 1890-1927 to exert downwards pressure on the rate of return on intangibles relative to the remuneration of unskilled ("raw") labor services. The discussion below of "the course of real rates of return on intangibles capital" notices corroborative evidence of a decline over the period from 1895 to 1939 in the differential in wage rates between education-associated skilled labor and unskilled workers.

by a closer examination of the determinants of the supply of savings, the subject to which I turn briefly in the following section.

5. The Behavior of Private Saving: Binding Constraints or Adaptive Responses?

Rising flows of investment in intangibles and a diminished rate of net capital formation in tangible assets bear proximate responsibility for the differentially faster growth of the real stock of intangibles. Mainstream thinking regarding U.S. macroeconomic growth in the second half of the twentieth century has focused upon the retarded pace of tangible capital accumulation as a consequence of decisions about the allocation of (conventional) income between present and future consumption, and has analyzed the phenomenon a declining rate of private domestic investment (conventionally defined) rate without reference to the rise of intangibles. The explanation has been sought by considering such developments in the U.S. economy that could have adversely affected capital formation by constraining the supply of savings. Our view of the matter, however, is rather different. In emphasizing the interconnected influences operating upon the demands for tangible and intangible capital, our interpretation suggests that it is more illuminating to examine saving behavior within a broader framework that considers the financing requirements of non-conventional as well as conventional productive assets.

The post-World War II era has seen the expansion of demand for new productive assets that are not particularly well suited for financing through the mechanisms that are available in organized capital markets and private financial institutions. The financing of investment in general forms of human capital, through education, through private capital markets, is virtually impossible in a society of free men and women. Such investments carry very significant risks, arising from the asymmetric distribution of information about the intellectual capabilities and motivations of the student, as well as problems of moral hazard and debt default. It has proved possible to mobilize substantial amounts of private capital for "student loans" only through a combination of highly selective screening in the case of leading to finance professional training, and the government intermediation in the form of guarantees of the principle and interest. Health investments are even more imperfectly served by private capital markets, and so must be paid for out of current incomes either directly, or through the purchase of insurance. Likewise, intangibility and the uncertainties that surround the research and development activities, mean that R&D performance cannot be debt-financed to any very large extent, and so must compete for external equity financing, or be funded internally through the retention of corporate earnings.[84]

The financing problems posed by this secular development in the U.S. economy have exacerbated the rather more transient effects of government fiscal operations affecting the flow of funds available from domestic sources for conventional capital formation. Yet, in our view, there remains no persuasive evidence that the rate of tangible capital formation has been reduced by an increasingly binding constraint imposed by the increased unwillingness of Americans to forego current consumption. This much may be concluded from even a cursory review of private savings behavior over the course of the twentieth century, and secondly, from the absence of any long-term upward trend in the real net rate of return on investment.

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[84] See A&D (2001) Pt. Two: Endnote 12.

The Supply of Savings in the Long-run: Is there a Problem?

A recurring theme in discussions about capital formation and long-term economic growth since World War II has been the worry that structural changes in the U.S. economy may have reduced the private sector's propensity to save. Indeed, the view that the savings rate has been the active, quasi-exogenous element to whose behavior the tangible capital-output ratio and the pace of capital accumulation have passively responded, antedated the widespread adoption of neoclassical growth theory among macroeconomic analysts. It had been articulated clearly by Simon Kuznet's historical survey *Capital in the American Economy* (1961). Kuznets regarded the falling rate of net national savings as the consequence of the combination of tightened constraints on the supply of private savings and growing government deficits. Both were depicted as developments that had restrained the pace of conventional capital accumulation and productivity growth, especially after 1929; and such views have continued to be influential in recent debates over U.S. macroeconomic policy.[85]

Although the notion of secularly tightening savings-supply constraint formed a background of concern for the specific worries that began to be voiced with greater urgency during the 1980s in regard to the effects of federal government fiscal policies upon net national savings, it properly should be distinguished from the latter.[86] Ballooning federal deficits undoubtedly were a matter for serious concern, but the supposed profligacy of the household sector, which some analysts have read in the downward secular trend in the personal savings rate that appears in the national income and product accounts, has been the more enduring theme. Yet, the "official" personal savings rate is a seriously inadequate indicator of the behavior of the overall rate of private savings in the US economy.

Secondly, the apparent decrease in personal savings rates is an artifact of the official national income accounting conventions, which fail to register the marked changes that were taking place after WWI in the forms in which households were actually accumulating assets. An increasing proportion of income was flowing into expenditures on consumer durables -- the range of which had been widened dramatically during the 1920s with the introduction of radios, phonographs and a variety of household appliances similarly powered by electricity, as well as private automobiles. Thus, between the pre-World War I and the Interwar periods, the personal savings rate out of DPI fell by almost 2 percentage points, whereas the ratio of consumer durables expenditures to DPI had increased by 5 percentage points. This appears to have been a once-and-for-all shift in household behavior, rather than the first step in a steady enlargement of the share of durables spending in income. A comparison between the period 1898-1916 and the post-World War II period shows changes of just about the same magnitudes (the personal savings fraction in DPI moves from 0.0804 to 0.0627, whereas CED/DPI increases from 0.0657 to 0.0970).[87] The shift seems to have been a response to the dramatic fall in the supply prices of the new range of durable goods, and the new and more

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[85] See, e.g. Michael J. Boskin, "Macroeconomics, Technology, and Economic Growth: An Introduction to Some Important Issues," in The Positive Sum Strategy: Harnessing Technology for Economic Growth, Ralph Landau and Nathan Rosenberg, Eds., Washington, D.C.:National Academy Press, 1986: pp. 33-56, for an expression of this argument. It predates the "new growth theory" view that a higher rate of capital formation could in itself increase the rate of efficiency growth in the economy.

[86] See A&D (2001) Pt. Two: Endnote 13.

[87] See A&D (2001) Pt. Two: Endnote 14.

attractive installment credit arrangements that were introduced during the 1920s.[88]

Stability in the Comprehensively Measured Gross Private Savings Rate

When this is taken into account by defining gross private savings more comprehensively to include consumer expenditures on durables, and augmenting GNP by adding the flow of gross rental services on the stock of consumer durables, one arrives at the GPSRA measure shown in the second row of Panel A.[89] Strikingly, the level of this savings rate in the post-World War I era turns out to be essentially identical to the 23-24 percent rate that prevailed in the pre-1916 era. Indeed, as may be seen from the first column of Table 2:VI, the temporal constancy of the average augmented gross private savings rate has characterized the entire century from 1869 to 1969.

The remarkable nature of that stability during the twentieth century is brought out by probing beneath the aggregate savings relationship known as "Denison's Law," which holds that the level of the GPSR in the U.S. remained in the neighborhood of 15-16 percent for years of "full employment" from the 1920s up to 1969.[90] This story continued, with only minor deviations, during the following two decades. Although during the 1970s the personal savings rate out of DPI shot up to a level not seen since the pre-World War I era, and this combined with a slight rise in the gross business savings rate out of gross after tax business income to boost the GPSR temporarily to 16.8 percent, by the end of the 1980s, the latter had returned to its long-term trend level of 15.4 percent.

The pattern of opposing movements in the underlying business and personal savings rates has suggested that American households' personal savings behavior in the twentieth century may have been affected by the increased attractions of accumulating wealth indirectly, via ownership of the corporate sector. Equity holders might thus be seen to have tolerated an increase in the rate of retention of corporate after tax earnings, and accepted the relative expansion of capital consumption allowances, in exchange for the escape this provided from double taxation of income from property. The contention that households have no trouble in peering through the "corporate veil", and so take account of the net worth changes in the enterprises whose equity they own, has prompted many empirical studies and generated a distribution of findings on both sides of the question. On balance, the hypothesis that personal and business savings are linked by some such a mechanism has found empirical support from macro-level analyses for the U.S. in the post-World War II era.[91] Still, one cannot accept as a literal description of that mechanism the theoretical model of a super-rational representative household -- one that has maintained an essentially constant

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[88] See A&D (2001) Pt. Two: Endnote 15.

[89] For productivity studies, it is more satisfactory to move towards the private domestic business concept, excluding the imputed returns on residential structures and consumer durables from output. Nevertheless, we include savings in the form of durables expenditures here in order to make the point that there has been remarkable stability in the private sector's savings rate across the whole of the twentieth century.

[90] The entries in Panel A of the table were obtained (in Paul A. David and John L Scadding, "Private savings: Ultrationality, aggregation and Denison's Law," Journal of Political Economy, 82 (March-April), 1974: pp. 225-49, see Table 1) from regression estimates based upon annual data for years when the unemployment rate for civilian workers was below 6.1 percentage points, within the various periods shown. The differences between the GPSR rates for sub-periods 1921-1940 and 1948-1969 are not statistically significant.

[91] See, e.g., James M. Poterba, "Dividends, Capital Gains, and the Corporate Veil: Evidence from Britain, Canada, and the United States," Ch.2 in National Saving and Economic Performance, B. Douglas Bernheim and John B. Shoven, Eds., Chicago: University of Chicago Press for N.B.E.R., 1991: pp. 49-71.

consumption rate out of gross income while opportunistically adjusting its forms of consumption and its asset portfolio.[92] The nature of the mechanism that has maintained the long-term stability of the U.S. gross private savings rate remains very much a mystery, but, the obtrusive empirical fact is that it is not possible to blame the slowed rate of growth of the domestic capital stock on the private sector's supposedly rising current consumption propensities. What should be said, instead, is that the U.S. private sector's gross savings rate has not been rising to accommodate the secular increase in the share of aggregate output that is claimed by capital consumption allowances. Nor did it rise to offset the public sector dissaving that occurred when the federal government deficit mushroomed in the 1980s.

The stability of the GPSR ("Denison's Law") is not, however, the only striking long-run constancy that appears in the record of U.S. aggregate saving over the course of the twentieth century. Furthermore, it may be pointed out that the persisting readiness of the private sector to forego current consumption is greatly understated by the statistics we just have reviewed. Actually, a 23 percent rate of gross savings has been maintained since the first post-Civil War decade. This fact is brought out by the first column of Table 76, which shows an augmented GPSR that takes into account savings in the form of consumer durables); and the figures in the second column of that table presses the point even farther by presenting a still more comprehensive measure of the gross private savings. The latter has been formed by adding the total resource costs of investments in education to gross private savings inclusive of expenditures on consumer durables, and expressing that total as a fraction of GNP augmented by inclusion of the estimated gross rental services from the stock of consumer durables (the same denominator as used for the rates in Column 1). This shows that a comprehensive savings rate in the near neighborhood of 27-28 percent has been maintained throughout the period stretching from the 1880s to the early 1960s.[93]

Thus, there is thus a very substantial margin of gross domestic capital formation taking place in the U.S. economy, over and above conventional gross private savings flows directed to tangible capital formation. This observation inveighs strongly against the notion that the aggregate supply of savings is inadequate to maintain the former growth rate of the tangible capital stock. Rather, it suggests that there are other, more attractive investment uses, and that these have continued to absorb the large share of America's growing productive capacity that the private sector continues to divert from current consumption.

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[92] One would have to envisage this "household" as shifting its sources of current utility between public and private consumption, and altering the corporate retentions rate (via its control of corporate policy), as well as the balance between its holdings of financial and real (tangible) wealth, in response to technologically driven changes in real rates of return, as well as in government tax policies and other exogenous developments. Such an "hypothesis" was put forward by Paul A. David and J.L. Scadding, ["Private Savings: Ultra-Rationality, Aggregation and 'Denison's Law,'" Journal of Political Economy, 82 (2, Pt. 1), March/April, 1974] in a tongue-in-cheek manner. At best this fantasy could be regarded as merely another parable, but, in this case, one that served primarily to call attention to the absence of a more satisfactory explanation of the data.

[93] We have chosen to use the same denominator in columns 1 and 2 of Table 6-Part B, so that the magnitude of the relative total resource costs of education can be inferred directly by subtracting column 1 from column 2. If one expresses the comprehensive measure of gross private savings as a ratio of the "fully augmented GNP" estimates (which form the denominator of the rates shown in column 4 of the same table) the result is to lower the level slightly, without materially disturbing its long-term stability.

Table 6
U.S. Educational Investment and Capital Formation Rates in the Nineteenth and Twentieth Centuries

(Current Dollar Ratios)

Year or Period	Gross Private Savings Including Consumer Durables as a Fraction of: *Durables-Augmented GNP*[a]	Gross Private Savings Including C- Durables and Education Costs, as a Fraction of: *Durables-Augmented GNP*[a]	Total Educational Resource Costs as Fraction of : *GNP Augmented by Students' Earnings Foregone*[b]	Total Educational Resource Costs as Fraction of: *Fully Augmented GNP*[c]
1869-1878	.225	.247	.027	.025
1879-1888	.239	.268	.036	.034
1889-1898	.245	.282	.046	.043
1899-1908	.237	.280	.047	.044
1923-1929	.217[2]	.287[3]	.030	.027
1940	.205	.253	.050	.046
1948	.235	.272	.055	.040
1956	.234	.278	.053	.048
1962	.224	.283	.069	.063

Notes: [a] Augmented GNP includes imputed rental flow on stock of durables.
[b] GNP plus foregone earnings costs of education.
[c] GNP plus imputed rental flow on stock of durable plus foregone earnings costs of education.
[1] Period averages for educational investment costs based on terminal Census years, e.g., 1899-1908 uses the value of numerators in columns 3 and 4 uses average of 1900 and 1910 estimates..
[2] Estimated average GPSRA for full employment years (1923-29) in the 1921-1940 interval, from Table 6-Part A.
[3] Weighted average of 1920 and 1930: for col. 3, (.021) and (.045); for col. 4. (.020) and (.041).

Sources: Estimates of augmented gross private savings inclusive of consumer durables, and GNP plus rental flow on consumer durables from underlying data for P.A. David and J.L. Scadding, "Ultra-Rationality, Aggregation and "Denison's Law," Journal of Political Economy, 82(2, Pt.1), March/April, 1974. Estimates of direct costs and foregone earnings cost of schooling from M. Abramovitz and P.A. David, Appendix 8-B to "Economic Bases of the Rise in Labor Quality" (unpublished MS., Stanford University), and underlying worksheets (June 1974/ November 1997). See text for discussion of conceptual basis of estimates.

The Growing Burden of Financing Education and Training Investments

The extension of secondary education of some form throughout the population, and the opening of colleges' doors to more than half of high school graduates, rank among the great social and economic achievements of American society during the twentieth century. But these have not come cheaply. The annual resource costs of this educational effort have grown enormously in absolute volume and in proportion to the size of the national economy. When one considers not only the direct expenditures by households, nonprofit organizations and government, but also the foregone earnings of students, it must be recognized that at the beginning of the twentieth century it was still legal in many states for children to enter regular work at age 11 or 12. Consequently, even at the beginnings of this movement, the earnings foregoing by the families of the youngsters sent to school, already bulked quite large in comparison with their relative proportions in modern times. It is estimated that even as early as the last two decades of the nineteenth century (see entries for 1879-1898 in Table 7, col. 3) the average total educational resource cost stood as high as 4.6 percent of GNP adjusted to include the imputed value of the foregone earnings of students.

The beginnings of the rise in high school enrollments in this period entailed an upward step in the national educational investment rate from the level a bit under 3.0 percent that had prevailed in the immediate post-Civil War decade. That the share of augmented GNP being devoted to sending Americans through grade school and elementary school already was so big at this time was due primarily to the large costs estimated for the foregone earnings component of the total, reflecting the fact that the opportunity costs of school attendance had yet to be curtailed by compulsory schooling laws and restrictions on the employment of juveniles, and that in many states where schooling was compulsory this did not extend through high school.[94] By the 1920s, however, the situation had changed, and the lowered level of the rates estimated for that decade in the central row of Table 7 (cols. 3 and 4) are accordingly lower, although they would show a further rise over those at the beginning of the century were they to have been made on the same basis.[95]

The point just noted, regarding the effect of shifting social regulations affecting school attendance and the opportunity for juvenile employment, means that the level of the educational investment rates shown for 1940 onwards is not immediately comparable with those for earlier periods except as measuring educational resource costs within the legal and institutional context that has prevailed more or less unchanged throughout the second half of the twentieth century. Focusing attention on the estimates for that period (the lower panel of the table), the beginnings of a second and more pronounced rise of the educational investment rate are visible. As the post-World War II "higher education boom" got underway, the absolute resource costs soared: in real (constant price) terms the U.S. total resource costs devoted to formal schooling expanded 10-fold between 1948 and 1962, as increasing college attendance contributed strongly to a 6-fold rise in real resource costs per student.

By the early 1960s, the relative national burden represented by the total resource costs of these educational investments had been pushed upwards from the neighborhood of 5 percent in the 1950s, to reach 7 percent of GNP inclusive of foregone earnings. An upward shift of similarly substantial proportions is seen when total educational resource costs in current prices are expressed as a ratio of the corresponding current value of *GNP fully augmented* (that is aggregate productive potential including both the gross rental services of consumer durables and foregone earnings of students): this measure of relative national burden rose from approximately 4.4 percent in the 1950s to 6.3 percent in the early 1960s. But that was just the beginning; by 1981 the corresponding proportional burden had been fully doubled and stood at 12.7 percent.[96]

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[94] See A&D (2001) Pt. Two: Endnote 17.

[95] See A&D (2001) Pt. Two: Endnote 18.

[96] See A&D (2001) Pt. Two: Endnote 19.

Viewing the private costs of schooling in relationship to the flow of income available to American households provides another perspective on the massive scale of the income reallocation which has been entailed just in financing the growth of human capital formation through formal education. Leaving aside the direct costs that have been paid for by tax revenues, and financed by state and local bond issues secured by the prospect of future taxes, and netting out scholarships and grants received by college students, virtually all the private costs of high school education and approximately 80 per cent of the private costs of college education take the form of foregone earnings. Considering the ratio of the latter to the level of disposable personal income *plus* foregone earnings thus provides a lower-bound estimate of the rising relative claims made upon households' potential income by private investments in schooling. Starting at an average of 6 percent in 1889-1908, the share was reduced to 4 percent during the prosperous 1920s, partly as a result of the markedly reduced birth rate in the early years of the century. By 1962, however, the minimal size of the proportional educational burden had risen to 11 percent, and by 1981 it represented 20 percent of disposable personal income plus foregone student earnings. Allowing for the swelling direct private costs of college attendance, the full extent of the burden moved into the range upwards of 25 percent during the 1980s.[97]

Over the course of the twentieth century the education investment component has not been the only component of intangible capital formation that has claimed a growing share of the U.S. gross savings potential, but has been far and away the dominant claimant. According to recent estimates made by John Kendrick (1994), by 1990 the share of educational investment in total tangible conventional *plus* non-tangible investment, which adds R&D to the educational component, had reached the neighborhood of 35 percent.[98] The corresponding share (as calculated from the estimates in Table 3-Part A) had been 22 percent in 1962, and was around 16 percent in 1900-10.

Thus, although the twentieth century has seen appreciably more than a doubling in the proportional claims made for education upon the comprehensively measured gross flow of savings in the U.S. economy, during the past three decades the relative expansion of that share has been particularly rapid. It has far exceeded the long-term growth of the claims on savings for the other significant intangible investment form, R&D, although it is the latter that has been claiming more and more theoretical and empirical attention from economists in recent years. To be sure, R&D expenditures and the estimated real stock of (cumulated) R&D have been growing at a spectacular rate from their negligible pre-1929 levels. But, even so, according to the available estimates for 1990 (in Table 3- Parts A, B) the volume of investment in organized R&D remained merely a tenth of the concurrent educational resource costs, and the ratio between the R&D stock and fully augmented GDP was only one-twelfth of the corresponding ratio for education and training capital.[99]

In large measure the emphasis that the foregoing discussion has given to human capital formation within the class of intangible investments, follows from the preponderant weight that the latter carries within the accounting framework of our augmented Solow-model. Yet it should be borne in mind that the continued strength of the derived demand for investment in human capital itself reflects consequences that have flowed from the other,

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[97] See A&D (2001) Pt. Two: Endnote 20.

[98] See, John W. Kendrick, "Total Capital and Economic Growth," Atlantic Economic Journal, 22(1), 1996.

[99] See A&D (2001) Pt. Two: Endnote 21.

quantitatively minor component of intangible capital formation. The significance of the rapid rise of investment in organized R&D following World War II lies less on the input side than on the output side of the growth accounts; it is seen in the persistingly high private and social rates of return that have come to be expected from the generation of designs for new goods and services, production methods, and modes of organization.

As the "new growth theorists" lately have been seeking to model,[100] there are great externalities from the fruits of investments in scientific knowledge, in the engineering of ways to realize economies of scale and scope, and in the development of new products that enhance consumers' sense of well-being -- even though the full extent of such benefits may not be fully recorded in the official national product accounts. Ideas of those kinds, especially when they have been codified and validated, are likely to generate effects that readily "spill over" among individuals, firms and industries; they can be repeatedly used and re-used by successive generations, and thereby contribute to maintaining the economy-wide marginal rates of return on tangible and intangible factors of production alike.

The Course of Real Rates of Return on Intangible Capital

What has been the effect of the massive formation of educational capital, and the accompanying accelerated growth of the total stock of education and training assets relative to manhour labor inputs, upon the average real rate of return to these intangible assets? The central and striking fact is that the differentials in the average earnings rates of college graduates relative to high school graduates have remained remarkably stable, despite an enormous increase in the population's educational attainments, and particularly in the face of the tremendous pace of increases in average educational attainments during the post-1929 era.

It would indeed be remarkable, had there been no compression whatsoever in education-associated earnings differentials during the earlier part of the century, especially at the higher educational attainment levels which initially were so thinly populated. This expectation is confirmed by the findings of Claudia Goldin and Lawrence Katz's recent systematic survey of the available wage data bearing on this question: the schooling premium for male clerical and office workers did indeed decline between 1895 and 1939.[101] Nevertheless, when -- during the era that followed --the rise of the educational capital stock would have been exercising its most powerful depressing effects on the differential rate of return to human capital formation, that downwards pressure appears to have been offset entirely by the forces that we have identified as operating on the demand side of the labor market. For white male workers there has been a remarkable degree of stability during the 1940-80 period in the ratios of lifetime earnings between high school and elementary school graduates, and between college and high school graduates, save for a still puzzling collapse in these differentials during the 1950s. Furthermore, in Table 8 one may examine the results of some rather careful calculations of the private rates of return to educational investment, based on corrected earnings data for educational groups reported in U.S. census samples, which show that these inducements remained remarkably stable over the period up to 1960 in the U.S.

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[100] See, e.g., Paul M. Romer, "Endogenous Technological Change," Journal of Political Economy, 98(5), October, 1990: pp. S71-S102; Charles I. Jones, "The Upcoming Slowdown in U.S. Economic Growth," Department of Economics Working Paper, Stanford University, (September) 1997; Charles I. Jones, Introduction to Economic Growth, New York: W. W. Norton & Co., 1997, esp. Ch. 5.

[101] See A&D (2001) Pt. Two: Endnote 22.

These findings carry two direct implications. The first and rather transparent point is that economic gains from high school and college completion were sufficiently high to mobilize political support in the electorate for public programs to subsidize schooling at all levels, and to induce families to meet heavy private costs, including the foregone earnings of their young college-bound youngsters. The second inference is that the stability of the education-associated earnings differentials in the face of the relative growth in the shares of the (male) civilian labor force who had completed high school and college during the decades of the 1940s and 1950s was most likely due to favorable demand-side shifts.[102] In the same way, the constancy of the educational rates of return in the face of a rapid rise in the ratio of the stock of education and training capital to real gross product (augmented by educational production) is most plausibly explained for the period in question on the supposition that technological and related innovations, and organizational changes were working to raise the demand for the stock of educated workers.

A further important indicator of the human capital-using bias that operated in this era is to be read in the change in the occupational composition of the workforce.[103] Using a grouping by broad occupational classes and the schooling levels of the different occupations observed from the 1950 Census, one may calculate by how much the average level of schooling of the whole work force would have increased simply as a result of the shift in occupational composition. This is a crude measure but it alone accounts for approximately half the actual rise in the average school level of the workforce that occurred between 1900 and 1960. Of course some of the occupational shift, especially that between 1900 and 1929, can be thought to have been induced by the reduced earnings differentials paid for workers who held high school diplomas, so on that score rather less than half the observed increase might more properly be attributable to a demand shift affecting the compression in educational premia, and the gaps between the earnings of high school and college graduates were widening just in the period when significant increases in college completion rates were beginning to affect the labor force.

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[102] This is supported by the analysis of the detailed pattern of increases and decreases in the age-education composition of the labor force for these decades in Moses Abramovitz and Paul A. David ("Technological Change and the Rise of Intangible Investments: The US Economy's Growth-Path in the Twentieth Century," in D. Foray and B.-A. Lundvall (eds.), Employment and Growth in the Knowledge-Based Economy, London: Edward Elgar," 1996: Table 8) and the accompanying discussion.

[103] See Moses Abramovitz and Paul A. David, "Technological Change and the Rise of Intangible Investments: The US Economy's Growth-Path in the Twentieth Century," in D. Foray and B.-A. Lundvall (eds.), Employment and Growth in the Knowledge-Based Economy, London: Edward Elgar, 1996: Table ; and Stephen R. Barley, "The Rise of the Technical Labor Force in the United States, Canada and the United Kingdom," Working Paper from the Department of Industrial Engineering and Engineering Management, Stanford University. November, 1994.

Table 7
Rates of Return on U.S. Investment in Education and on Tangible and Intangible Capital Stocks

Part A :
Private Internal Rates of Return for Different Levels of Schooling: U.S. Urban White Males (Percent per Annum)

Years of Schooling	1939	1959
9-11	10.3	10.2
12: High School Grads	12.9	14.5
13-15	9.4	10
16+: College Grads	14.6	13.4

Part B :
Average Gross Social Rates of Return on Gross Capital Stocks by Major Category: U.S. Private Domestic Business Economy (Percent per Annum)

	1929	1948	1981
Aggregate Intangible Stock Embodied in Humans (excluding R&D capital)	4.6	5.5	4.2
Aggregate Tangible and R&D Capital Stock (Nonhuman)	8.3	10.5	8.7

Notes and Sources:

Part A: Moses Abramovitz and Paul A. David, "Technological Change and the Rise of Intangible Investments: The US Economy's Growth-Path in the Twentieth Century," in D. Foray and B.-A. Lundvall (eds.), Employment and Growth in the Knowledge-Based Economy, London: Edward Elgar, 1996: Table 7.

Part B: Gross returns on the Intangible Stock (comprising Education and Training, and Health, Safety and Mobility) were computed from data in Kendrick (1994), Table 7, for the total (Tangible and Intangible) Human stock earnings, adjusted by the average ratios of (α_L / θ_L), from data in Table II.3.1A: $\alpha_L / \theta_L = 0.388$, 0.431, and 0.431 were the averages for periods centered approximately on 1929, 1948 and 1981 respectively. Gross rates of return for the "Nonhuman" aggregate stock are those given by John W. Kendrick, "Total Capital and Economic Growth," Atlantic Economic Journal, 22(1), March, 1994: pp. 1-18, Table 7.

The stability in the earnings premium for education in itself is not conclusive evidence that the relative marginal *social* product of schooling was tending to be raised, in the absence of a responsive increase in the supply of educated workers.[104] If employers view education as a signal that workers have other desirable qualities – such as high IQ, ambition, energy, a capacity for absorbing codified instructions and a toleration of organizational

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[104] See the discussion accompanying Figures 1A and 1B in Moses Abramovitz and Paul A. David, "Technological Change and the Rise of Intangible Investment: The US Economy's Growth-Path in the Twentieth Century," in D. Foray and B.-A. Lundvall (eds.), Employment and Growth in the Knowledge-Based Economy, London: Edward Elgar, 1996.

discipline – the demand for schooled workers may rise with the extension of education regardless of its contribution to "labor quality" viewed as the possession of cognitive skills.

The interpretation of U.S. labor market developments in the pre-1960 era is also broadly applicable to the subsequent American experience: the upward trend of education-associated earnings differentials over the period since the 1960s, and especially the explosion of those differentials that began in the 1980s, was driven by net shifts in derived labor demands that were shaped primarily by technical change. That is to say, it represented the latest phase of a long-standing process, involving deep and powerful forces arising in the biased character of modern technological change, and the changes in the industrial composition of employment associated with the growth of aggregate and per capita income in the economy at large. This view of the factor-market impacts of the intangible (human) capital-using bias of technological innovation during the period 1966-89 is consistent with the implications of a related argument, namely, that skill-technology complementarity effects – presumptively associated with the introduction of new, computer-based information technologies – have been working also to widen wage differentials within age, occupational, and educational attainment groups in the U.S. labor force.[105]

This particular question remains far from conclusively settled. Nevertheless, the evidence assessing various suggested causes of the growth of wage and earnings inequalities in the U.S. points to the preponderant of the influence coming from demand-side shifts stemming from the introduction of new technologies and their complementarity with certain skills and capabilities for problem-solving that are likely to develop with increased educational attainments. The consensus of recent expert opinion is that during the period from the mid-1980s to the mid-1990s, the intensification of this biased form of "technological change" has resulted in a greater premia being paid to workers with the appropriate qualifications *within* each of a wide range of industrial sectors and broad occupational categories. This trend, rather than decline of unionization and industry-wide wage bargaining, or the increased intensity of international competition, that appears to have been the dominant factor responsible for the widening of differentials within the upper half of the distribution of earnings among male high school graduates, although it must be acknowledged that this, in its nature, is something of a residual explanation.[106]

The evolution of modern wage structures has been characterized by the economist Jan Tinbergen (1975) as "a race between technological development and access to education."[107] The insightful nature of that remark is amply borne out by the long-term experience of the U.S. during the twentieth century. That experience might be described more specifically if less succinctly as a race between the human-capital using bias of technological and organizational innovation, on the one hand, and, on the other, the accumulation of intangible capital through education and training investments. Major changes in the economic circumstances and behaviors of American households, and critical public measures affecting

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[105] See Moses Abramovitz and Paul A. David, "Technological Change and the Rise of Intangible Investments: The US Economy's Growth-Path in the Twentieth Century," in D. Foray and B.-A. Lundvall (eds.), Employment and Growth in the Knowledge-Based Economy, London: Edward Elgar, 1996 for discussion of the literature on increasing wage inequality in the post-1967 period.

[106] See A&D (2001) Pt. Two: Endnote 23.

[107] See Jan Tinbergen, Income Differences: Recent Research, Amsterdam: North-Holland, 1975; also, on this theme, Jan Tinbergen, "Substitution of Academically Trained by Other Manpower," Weltwirtschaftliches-Archiv, 111(3), 1975: pp. 466-76.

access to and financing of education, were entailed in the process that kept this race an approximately even one for most of the century. But, the untoward resurgence of earnings as the century draws to its close points to the possibility that the inherited infrastructure of institutions, public programs, and financing mechanisms, may no longer be adequate to enable the U.S. economy to fully exploit the potential synergetic interaction between technological developments and the formation of complementary productive assets.

6. Conclusion: American Historical Experience and Growth Theory, Old and New

The broad perspective presented here is one that long has informed my collaborative work on American economic history with Moses Abramovitz (and presentations of this view found their way into the individual and joint publications that emerged in the context of that collaboration).[108] Nevertheless, it is a view that until very recently has remained unorthodox from the vantage point of growth-theorists working within the neoclassical tradition. The latter typically eschew readings the macroeconomic record that are not compatible with the assumption of Harrod-neutrality, and the consequent stablity of steady state growth paths. But, the view advanced here will have been seen also to diverge in some important regards from the characteristic points of emphasis in the literature devoted to "new growth theory."

Of course, this interpretation is fully in sympathy with the emphasis lately being given (by economists in quest of wholly endogenous models of long-term growth) to the role of advances in knowledge flowing from investments in organized research and product development; no less with the renewed attention to the dynamics of specialization and division of labor, and the latter's connections with the realization at the macroeconomic level of economies of scale and scope deriving from access to widened markets.[109] While those themes certainly do figure importantly in the present narrative, its subscription to some distinctive features of the applied macroeconomics literature inspired by "new growth theory" remains decidedly qualified. Several reasons for holding to "a different view" may now be indicated, by way of a conclusion.

Firstly, mention should be made of a technical matter that is perhaps of greater

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[108] In addition to joint publications by Abramovitz and David cited in footnote 1,above, see Moses Abramovitz and Paul A. David, "Economic Bases of the Rise in Labor Quality," Ch. 8 of *Economic Growth in the US*, Appendix 8-B, Unpublished MS, Stanford University, 1968; A&D (2001), Part Three; also, Moses Abramovitz, "Resource and Output Trends in the United States since 1870," in Thinking about Growth, and Other Essays on Economic Growth and Welfare, New York: Cambridge University Press, 1989; Moses Abramovitz, "The Search for the Sources of Growth: Areas of Ignorance, Old and New," (Presidential Address), Journal of Economic History, 53(2), June 1993, n. 21; David (1975), Ch.1; Paul A. David, "Invention and Accumulation in America's Economic Growth: A Nineteenth Century Parable," in International Organization, National Policies and Economic Development, a supplement to the Journal of Monetary Economics, vol. 6, 1977, pp. 179-228.

[109] See, e.g., Robert E. Lucas Jr., "On the Mechanics of Economic Development," Journal of Monetary Economics, 22(3), June 1988, pp. 3-42; Paul M. Romer, "Increasing Returns and Long-run Growth," Journal of Political Economy, 98(5, part 2), October 1986, S71-S102; Paul M. Romer, "Endogenous Technological Change," Journal of Political Economy, 98(5), October 1990: pp. S71-S102; P. Aghion and P. Howitt, "A Model of Growth Through Crative Destruction," Econometrica, 60, 1992, pp. 323-51; Elhanan Helpman (ed.), General Purpose Technologies and Economic Growth, Cambridge, MA: MIT Press, 1998. See also Steven N. Durlauf and Danny T. Quah, "The New Empirics of Economic Growth," Santa Fe Institute Economics Research Program Working Paper, 1998, for careful discussion of the empirical implications of this literature, and an examination of the international comparative data relating to the post-World War II era.

interest for time-series analysts than for most readers of descriptive economic history. Nevertheless, it concerns the key notion in our interpretative parables of successive capital-deepening "traverses" that were initiated by non-neutral technological and organizational innovations. Underlying that part of the discourse is an assumption of local dynamic stability, and of consequent convergence to the next steady-state growth path in the historical sequence. That, however, is directly at variance with the spirit of the "new growth" models which endogenize all the proximate sources of rising labor productivity, including the growth of knowledge, and thereby escape the constraints of diminishing marginal returns to capital formation. Such models carry the theoretical implication that their dynamic behavior is not *convergent*. The empirical plausibility of adopting our analytical framework is therefore intimately related to the econometric question of the existence or non-existence of unit roots, and other statistical indicators of the persistence of shocks in the extended historical record of aggregate production.

Macroeconomic time-series analysts have been much occupied lately with the latter question. From some of their more recent finding for the U.S. over the period 1870 - 1990 it appears that within secular epochs that can be distinguished by major trend breaks, the empirical relevance of unit root hypothesis can be rejected by econometric tests. In other words, within the identified epochs – whose durations are of the same order as the "Long Periods" that figure in our account – the dynamic process at the macro level therefore may be treated as essentially convergent.[110] This lends at least a measure of technical statistical support for the assumptions that are embraced implicitly by the particular style of growth-theoretic parable that we find, on other counts as well, to have considerable heuristic value in interpreting of the American economy's long-term performance.

The next point on which the claims of the "new growth theory" to historical relevance might well be qualified concerns the differentiation between the successive American "traverses," a matter that has been central in the argument of the preceding pages. Any pretensions that the popular formulations of endogenous growth theory might possess empirical validity of a historically general and universally valid sort, simply fails to find support in the American experience. In particular, the key role in raising labor productivity and per capita real income that is now accorded to *increases* in average educational attainment and the growth of human capital-intensity more broadly, cannot be squared with the quantitative picture of U.S. economic progress throughout much of the *nineteenth* century. Maintenance of a high level of literacy in important sections of the population may

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[110] See, e.g., the work of C. D. Romer, "The Pre-War Business Cycle Reconsidered: New Estimates of GNP, 1869-1908," Journal of Political Economy, 97, 1989, pp. 1-25, and other contributions reviewed in D. Greasley and L. Oxley, "Explaining the United States' Industrial Growth, 1860-1991," Bulletin of Economic Research, 48, 1996b, pp. 65-82. The latter report on their own analysis of the annual industrial production series for the U.S. from the 1860s onwards, derived from W.G. Nutter's series (Growth of Industrial Production in the Soviet Union, Princeton, NJ: Princeton University Press for the NBER) based on the Frickey index, which they spliced with the Federal Reserve index of industrial production in 1919. When dummy variables are introduced to allow for structural discontinuities affecting the trend, significant "breaks" are found c. 1901 and c.1973, the former being the most pronounced. If that is treated as exogenous, Greasley and Oxley's (1996) statistical tests reject the existence of a unit root in U.S. industrial production. They point out that C. R. Nelson and C. I. Prosser's ("Trends and Random Walks in Economic Time Series," Journal of Monetary Economics, 10, 1982, pp. 139-162) contrary finding of "difference stationarity" in the U.S. industrial production data for the century preceding 1965 was based on an analysis that assumed trend stationarity. These findings are thus broadly consistent with the interpretation here, for we contend that the 1890-1905 era marked a watershed between two structurally distinct epochs of U.S. macroeconomic growth, and implicitly assume that convergent traverses were underway during the more extended periods before and following that interval, i.e., c.1835- c.1890, and c.1905 - c.1989.

have had a good bit to do with establishing a growth path characterized by high levels of labor productivity and per capita consumption. But, that says nothing directly about education's contributions to a faster rate of growth in economic well-being. Furthermore, quite a number of studies of the nature of schooling and the extension of basic literacy and numeracy in antebellum America have raised substantial doubts about the immediate relevance of the cognitive content of education to the processes through which the productivity of the workforce was being enhanced in that era.[111] By comparison, the accumulation of workplace experience appears to have been a more important determinant of differential earnings rates.[112]

Continuing further in this vein, it would seem that there is a greater measure of empirical support -- from detailed studies of the transformation of industrial technology at the plant and firm level during the nineteenth century -- for putting major emphasis upon learning-by-doing as a source of increasing industrial efficiency. This, it might be recalled was the main message imparted by the pioneering economic growth literature on endogenous sources of technological advance, long before the current popularity of mathematical models of “endogenous growth.”[113] More recently, Gavin Wright (1998) has elaborated the idea of

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[111] On the consistency of this view with evaluations of the role of human capital formation through formal education in the industrial revolution in Britain, see Peter Mathias, The First Industrial Nation, London: Methuen, 1984. On the relevance of the cognitive content of the formal school curricula in the US during the nineteenth century, see e.g., Albert Fishlow, “The American Common School Revival, Fact or Fancy?” in Henry Rosovsky (ed.), Industrialization in Two Systems, New York: John Wiley and Sons, 1966; on nineteenth century investment in education see Albert Fishlow, “Levels of Nineteenth Century American Investment in Education,” reprinted in Fogel and Engerman (eds.), The Reinterpretation of American Economic History, 1971, pp. 265-73. Journal of Economic History, 1966: pp. 418-36; on education, “socialization” of the work force, and factory discipline in mid-century, see A. J. Field, “Educational Expansion in Mid-Nineteenth Century Massachusetts: Human Capital Formation or Structural Reinforcement?” Harvard Educational Review,46(4), November 1976; A.J. Field, “Economic and Demographic Determinants of Educational Commitment: Massachusetts, 1855,” Journal of Economic History, 39(2), June 1979, pp. 439-59. For quantitative studies showing the absence of strong, or even weak statistically significant education-associated wage differences among manufacturing employees in northern and southern cotton textile mills in the nineteenth century, see Harold S. Luft, “New England Textile Labor in the 1840s :from Yankee Farmgirl to Irish Immigrant,” Harvard Business School, unpublished working paper, 1971; Thomas Dublin, Women at Work: The Transformation of Work and Community in Lowell, Massachusetts, 1826-1860, New York: Columbia University Press; Cathy McHugh, Mill Family: The Labor System in the Southern Cotton Textile Industry, 1880-1915, New York: Oxford University Press, 1988. But see also, Susan A. Matthies, Useful Children: An Economic Study of Child Workers in the Cotton Textile Industry, 1900-1910, Unpublished Ph.D. Dissertation, Stanford University, 1991, Ch.5, for findings of positive schooling effects on earnings rates among child workers in the southern states, and northern states (separately), early in the twentieth century.

[112] In addition to the qualitative indications, there is also some econometric evidence pointing to the significant role of experience-based "learning-by-doing" among the microeconomic sources of rising labor productivity, and real earnings rates reflecting the accumulation of individual worker experience, particularly in textiles manufacturing. See, e.g., Paul A. David,"Learning by doing and tariff protection: a reconsideration of the case of the United States cotton textile industry,” Journal of Economic History, 30(3), September 1970; Paul A. David, "The Use and Abuse of Prior Information in Econometric History, A Rejoinder to Professor Williamson on the Antebellum Cotton Textile Industry," Journal of Economic History, vol. 32 (3), September 1972, pp. 706-727; Paul A. David, "The ‘Horndall Effect’ in Lowell, 1834-1856: A Short-Run Learning Curve for Integrated Cotton Textile Mills," Explorations in Economic History, vol. 10 (2), Winter 1973, pp. 131-150. Significant experience effects on differential worker earnings are reported for the cotton textile industry by Luft, “New England Textile Labor,”(1971), McHugh, Mill Family (1988), and Matthies, Useful Children (1991).

[113] A. Alchian, “Reliability of Progress Curves in Airframe Production,” Econometrica, xxxi (October 1963), pp. 679-73; Kenneth J. Arrow, “The Economic Implications of Learning by Doing,” Review of Economic Studies, 29(2), 1962; Robert M. Solow, “Investment and Technical Progress,” in K.J. Arrow et al. (Eds.), Mathematical Methods in the Social Sciences, 1959, Stanford: Stanford University Press, pp. 89-104, 1960; Robert M. Solow, “Perspectives on Growth Theory,” Journal of Economic Perspectives, 8(1), Winter 1994, pp.

learning-by-doing in social network environments, and argued that the formation and transmission of particular design traditions, and characteristic approaches in industrial and mineral engineering, constituted a “social learning process” that was national in its scope, and which, by the early twentieth century, had created a technological culture that was distinctively American.[114]

Considering the matter from the perspective of the nineteenth century U.S. economy, then, the particular mechanisms seen by "new growth theory" as driving the process of productivity improvement and rising real per capita income appear at best to have very little explanatory power. Perhaps not surprisingly, this assessment accords with the overall judgement reached by N. F. R. Crafts' (1993) evaluation of these endogenous growth models’ relevance in accounting for Britain’s growth experience during the epoch of the Industrial Revolution.

But what of the more recent past, the modern experiences of the U.S. and other already advanced industrial societies, experiences that are more likely to have informed the “new” growth theory? Here the previously noted qualifications are no longer appropriate. The emphasis accorded to intangible capital formation through education, and investment in organized R&D certainly is warranted, as is the insistence that the mobilization of resources for those purposes has been at it base a response to perceived economic payoffs. But the need to register some other qualifications remains. Among these we should note doubts regarding the implicit, and sometimes explicitly formalized assumption that there exists a global stock of technologically relevant knowledge, the pace of additions to which remain highly elastic to the input of national research efforts.

Studies of the determinant of company investment in R&D in the post-World War II era repeatedly have pointed to the importance of "science-based opportunities" as well as to conditions affecting private appropriability of economic returns in affecting the pattern of research intensities across industrial sectors. But what these investigations of inter-industry differences also reveal is that where the positive statistical association between high ratios of R&D to sales and the growth rate of input efficiency emerges, the latter is largely accounted for by the indicators of strong "science-based opportunities."[115]

45-54 are classics among the more theoretical contributions in this vein. In addition to much richly detailed descriptive material in standard historical sources for the period, such as Clark (1929) and Kirkland (1955), a number of econometric findings identifying "learning effects" in integrated cotton textile production (power spinning and weaving mills), mechanized shoe factories, and blast furnace and rolling mill operations, may be mentioned in this regard. See Paul A. David,"Labour Productivity in English Agriculture1850-1914: Some Quantitative Evidence of Regional Differences," Economic History Review, vol. 23 (3), December 1970, pp. 504-514; Paul A. David, Technical Choice, Innovation and Economic Growth: Essays on American and British Experience in the Nineteenth Century, Cambridge and New York: Cambridge University Press, 1975, Chs. 1, 4. (Second Edition forthcoming in Fall 1999 from Cambridge University Press); Peter Berck, “Hard Driving and Efficiency: Iron Production in 1890,” Journal of Economic History, 38(4), December 1978, pp. 879-900, and Ross Thompson, The Path to Mechanized Shoe Production in the US, Chapel Hill: University of North Carolina Press, 1989.

[114] This view is not unrelated to the theme of American economic exceptionalism having contributed to shaping technology in ways that were “congruent” with national market characteristics and resource endowments that were not replicated elsewhere during the nineteenth and early twentieth centuries. See Moses Abramovitz and Paul A. David, “Convergence and Deferred Catch-Up: Productivity Leadership and the Waning of American Exceptionalism,” Ch. 2 of Ralph Landau, Timothy Taylor and Gavin Wright (eds.), The Mosaic of Economic Growth, Stanford, CA: Stanford University Press, 1997.

[115] See e.g., F.M. Scherer, “Firm Size, Market Structure, Opportunity, and the Output of Patented Inventions,” in Innovation and Growth, Cambridge MA: The MIT Press, 1984, Chap. 9; Richard R. Nelson and Edward N.

In other words, whereas the burden of the macroeconomic formulations of the "new growth theory" has been to tell us that rapid technological advances can be endogenously generated by the investment of resources in R&D which does not encounter diminishing marginal returns, the available indications at the industrial and line-of-business level suggest that this is more true of the long-run than it is over the near term; "opportunities" for profitable investment are more constrained by the slow, incrementally transformed and path-dependent state of the existing fundamental scientific and engineering knowledge-base.

Furthermore, the growth of that knowledge-base, although surely substantially subject to economic forces over the long run, cannot usefully be portrayed – as it is in many formal models of the "new" genre -- as being determined "endogenously" by the behaviors of individual agents and organizations working wholly within the context of a particular, informationally insulated (and isolated) national economy. It is, rather, a construction of the larger international systems of knowledge generation and dissemination, to which public and privately-funded research activities taking place under a variety of economic and political conditions have been contributors. This may pose a more daunting challenge than the new growth theory has accepted thus far. Yet, for some long time the way forward in theorizing about economic growth has tended to lie along the trail blazed, however roughly, by students of quantitative economic history. It would seem fruitful to continue further along that path by explicitly modeling the interactions among the knowledge-intensive economies.

Lastly, we come to a point on which the perspectives of "new" and "neoclassical" growth theorists tend to coincide, namely, in the undertaking to apportion responsibility for the growth of an economy's productive capacity among distinct contributory factors, or "proximate sources of growth." Taken at face value as an exercise in "growth accounting" there is nothing in this enterprise to which one could object in principle (the accuracy of the assumptions underlying the measurement procedures employed is another matter, to be sure). Yet there is something vaguely self-contradictory about emphasizing the importance of seeing all aspects of the growth process -- technological innovation included -- as "endogenous" economic processes, while carrying out calculations that seemingly accept the standard accounting approach as an informative explanatory framework.

Such clarity as the latter are able to achieve by assigning quantitative measures of absolute and relative "importance" to the various sources of the growth of real output (whether on an aggregate or a per capita basis) derives in reality from the growth accountant's willingness to hew to a particularly simplified view of the workings of the economy: namely, to treat the identified set of "proximate sources" as though they operated quite independently of one another. That procedure rests on notions of the "neutrality of innovation" as constituting the typical state of affairs. By contrast, we have sought to put those notions firmly aside in favor of a more throughly "endogenous" interpretation of U.S. macroeconomic history, one that recognizes the shifting complex of forces which continue to make novelty and structural change the essence of long term economic progress.

Wolff "Factors Behind Cross-Industry Differences in Technical Progress," NYU Economics Department working paper, 1996.

APPENDIX

Technical Note

Estimates of Trend Growth Rates of Efficiency of Intangible Capital Inputs

The interpretation of twentieth century macroeconomic trends as having been shaped in significant part by the emergence of a bias towards technological and organizational innovations that were intangible capital-using can be supported by numerical estimates of the growth rate E^*_H. The latter designates that rate of "intangible capital augmenting" innovation, and should carry a negative sign when the changes in efficiency are such as to raise the desired ratio (H/Y), given the same rate of return on the real intangible stock, H. Therefore, finding the sign condition ($E^*_H < 0$) to be fulfilled for the U.S. private domestic economy from 1929 onwards therefore is an important point of quantitative substantiation for the argument we advance.

For the reasons given by the text of Part 2, Section 2.3, it is not possible to infer the sign of E^*_H immediately from the behavior of the input ratios and their shares in total product. Hence, a direct computation is required. This requires solving the whole system of relationships describing the input specific rates of efficiency change.

These are: E^*_L, E^*_{HL}, E^*_L for the inputs of pure tangible manhours, intangible human capital, and tangible and intangible labor, respectively;

E^*_{KT}, E^*_{HK} and E^*_K, for inputs of tangible capital, intangible, non-human capital and tangible and non-human, intangible capital combined;

and E^*_H itself.

We thus have seven unknowns, and the following directly measurable magnitudes: K^*_T, H^*, E^*_A, θ_L, θ_K (= $1-\theta_L$), θ'_L(= $\theta_L - \alpha_L$), θ'_{KT} (= $\theta_K - \alpha_K$), $\theta_H = \alpha_L + \alpha_K$ and q^*_K, from Appendix Note 2.

Given seven equations in these magnitudes, the system can be solved from the seven unknowns. Beginning with the residual, from Appendix Note 1, equation (7), we first write the definitional identities:

(i) $E^*_A \equiv \theta'_L E^*_{L,} + \theta'_K E^*_{KT} + \theta_H E^*_H$;

(ii) $E^*_H \equiv (\alpha_L / \theta_H) E^*_{HL} + (\alpha_K / \theta_H) E^*_{HK}$;

(iii) $E^*_L \equiv (\theta'_L / \theta_L) E^*_{L'} + (\alpha_L / \theta_L) E^*_{HL}$;

(iv) $E^*_K \equiv (\theta'_{KT} / \theta_K) (E^*_{KT} + q^*_K) + (\alpha_K / \theta_K) E^*_{HK}$.

Then, from the specification that the bias of innovation is a time invariant parameter, we have

(v) $\lambda = (E^*_L - E^*_K)_t$, for all t.

which, under suitable separability conditions, can be obtained by regression estimation for the constant elasticity of substitution production function:

$$(\theta^*_{L'} - \theta^*_K)_t = [(1-\sigma) / \sigma] [K^* - L^*]_t - [(1-\sigma) / \sigma] \lambda .$$

From the specification based on the strict skill-technology complementarity hypothesis, in Appendix Note 2, we have:

(vi) $E^*_{KT} = H^* - (K^*_T + q^*_K)$.

Lastly, we specify a proportionality constant $\beta \geq 0$ in the relationship

(vii) $E^*_{HK} = \beta E^*_H$.

A little algebra is needed to solve for E^*_H in terms of the known magnitudes and the parameter β. One may first substitute from definitions (iii) and (iv) into equation (v) and solve for E^*_{L}'; next substituting (vi) in (i), we can solve for E^*_H in terms of E^*_L' and the other known magnitudes, whence we can eliminate E^*_L' and obtain:

(viii) $E^*_H = \{\lambda - (E^*_A / \theta_L) - 2(\theta'_{KT} / \theta_H) [H^* - K^*_T - q^*_{KT}]\} / [1 - (\theta_H / \theta_L) - \beta\delta]$,

where $\delta \equiv [(\alpha_K / \theta_H) + (\alpha_K / \theta_{KT})]$.

Referring back to equation (vi), we directly obtain E^*_{KT}. Using (ii) and (iii) to eliminate E^*_{HL} , and (iv) and (v) to eliminate E^*_L, one obtains:

(ix) $E^*_{L'} = \{(\lambda + E^*_{KT})\, \theta_L + E^*_H [\theta_H - \alpha_K \beta]\} / \theta'_L$.

Substitution of the values of $E^*_{L'}$ from (ix) back into (ii) and (iii) provides us with E^*_{HL}, and thence E^*_L**,** whence using (v) we obtain E^*_K; and using (iv) we can find E^*_{HK}, to complete the solution.

The following Table shows the solutions for E^*_H obtained from equation (viii) using the indicated values for q^*_K, E^*_{KT} and β, as well as the E^*_A estimates from Part Two, Table 2.IV-Part A, and applying the invariant parameter estimate $\lambda = .007$ obtained by David and van der Klundert (1965) for the whole period 1899-1960. The magnitude of the shares, θ_i, are those shown for the relevant intervals in Table 2.III, with the 1890-1927 interval value found as the weighted average of the sub-periods 1890-1905 and 1905-27.

Given the heroic specification assumptions, and the use of "speculative" magnitudes obtained in Appendix Note 2, we can do no less than caution the reader by labelling the results frankly as "speculative".

Table A:1
Speculative Input Specific Efficiency Rates (Per Annum): PDE, 1890-1989

	E^*_A/θ_L	q^*_K	E^*_{KT}	$[1 - (\theta_H/\theta_L) - \delta\beta]$		E^*H	$E^*_{L'}$
Periods				**Assuming: β = 1**			
1890-1927	.0223	.0026	.0120	0.744	(0.742)*	.0116	.0293
1890-1905	.0221	0	.0079	0.834	(0.833)*	.0008	.0179
1905-1927	.0228	.0046	.0146	0.682	(0.679)*	.0193	.0400
				Assuming: β = 2			
1929-1966	.0155	.0067	.0081	- 0.491		- .0079	.0212
1966-1989	- .0021	.0089	.0010	- 0.492		- .0215	.0027

***Note:** Values in parentheses are found with β = 2, essentially identical to those for β = 1 in these sub-periods.

The computed rates in Table A.1 for E^*_H and E^*_L' are *conditional* on the specification used in

Appendix Note 2 to find E^*_{KT}, and consequently the share-weighted sum of these two rates is not constrained to yield the same value as will be found by subtracting $[\theta'_{KT}\ (E^*_{KT})]$ from the residual estimates shown for E^*_A in Table 2.IV-Part A. To insure consistency of the full set of input specific efficiency growth rates, we normal the computed values of E^*_H and $E^*_{L'}$ by multiplying each by the normalizing ratio $n = [E^*_A - \theta'_{KT} E^*_{KT}] \,/\, [\boldsymbol{E}^*_A - \theta'_{KT} E^*_{KT}] = n$, where $\boldsymbol{E}^*_A = \theta'_L E^*_{L'} + \theta'_{KT} E^*_{KT} + \theta_H E^*_H$, using the values entered in Table A3.1. The final estimates are shown in Table A2.

Table A:2
Normalized Speculative Efficiency Growth Rates

Periods	**N**	**$nE^*_{L'}$**	**nE^*_H**	**E^*_{KT}**
1890-1929	0.534	0.156	.0062	.0120
1929-1966	0.307	.0277	- .0103	.0081
1966-1989	0.273	.0007	- .0059	.0010

Appendix: Statistical Table

Note: The following tables reproduced for convenient reference corresponds to A&D (2001), Part One: l:IV. The latter source should be consulted for underlying sources.

Table 1:IV The Source of Labor Productivity Growth, Private Domestic Economy, 1800-1989, Sources in Percentage Points Measures Across Long Periods

	I Nineteenth Century			**II Twentieth Century**		
	1800-1855	**1855-1890**	**1890-1927**	**1890-1927**	**1929-1966**	**1966-1989**
1. Output per manhour	0.39	1.06	2.01	2.00	2.52	1.23
<u>Sources</u>						
2. Capital stock per manhour	0.19	0.69	0.62	0.51	0.43	0.57
3. Crude total factor prod.	0.20	0.37	1.39	1.49	2.09	0.66
4. Labor quality	-	-	0.15	0.15	0.40(0.30)	0.31(0.16)
5. Capital quality	-	-	-	-	0.24	0.31
6. Refined total factor prod.	0.20	0.37	1.24	1.34	1.45(1.55)	0.04(0.19)
<u>Addenda</u>						
7. Gross factor share weights						
a. Labor	0.65	0.55	0.54	0.58	0.64	0.65
b. Capital	0.35	0.45	0.46	0.42	0.36	0.35
8. Vintage effect	-			-	0.04(0.05)	0.00(0.01)
9. Age-neutral refined total factor prod.	-			-	1.41(1.50)	0.04(0.18)

[1] Revision of the text entered on 16.ix.98 by PAD begin here.