Interpreting the "One Big Wave" in U. S. Long-term Productivity Growth

Robert J. Gordon

Northwestern University,
National Bureau of Economic Research,
and Centre for Economic Policy Research

April 22, 2000, revision of paper forthcoming in
Bart van Ark, Simon Kuipers, and Gerard Kuper, eds.,
Productivity, Technology, and Economic Growth, Kluwer Publishers, 2000

This research has been supported by the National Science Foundation. I am grateful for helpful suggestions to Moe Abramowitz, Zvi Griliches, and participants in several NBER seminars. I am indebted to Stuart Gurrea for his excellent work as research assistant. The data in this paper do not reflect the October, 1999, revision of the U. S. National Income and Product Accounts. A summary version of this paper, based on an earlier iteration of data analysis, appeared as Gordon (1999a).

Interpreting the "One Big Wave" in U. S. Long-term Productivity Growth

ABSTRACT

This paper assesses the standard data on output, labor input, and capital input, which imply "one big wave" in multi-factor productivity (MFP) growth for the United States since 1870. The wave-like pattern starts with slow MFP growth in the late 19th century, then an acceleration peaking in 1928-50, and then a deceleration to a slow rate after 1972 that returns to the poor performance of 1870-1891. A counterpart of the standard data is a mysterious doubling in the ratio of output to capital input when the postwar era is compared with 1870-1929.

Three types of measurement adjustments are applied to the standard input data. Following the lead of Denison and Jorgenson-Griliches, adjustments for the changing composition (or "quality") of labor and capital, currently published by the BLS back to 1948, are estimated for 1870-1948. These composition adjustments take into account the shifting mix of the labor force along the dimensions of education and age-sex composition, and of the capital stock between equipment and structures. Further adjustments are made to capital input data to allow retirement to vary with gross investment rather than to follow a fixed pattern depending only on age, and to add types of capital owned by the government that are particularly productive in the private sector. A new MFP series taking account of all these adjustments grows more slowly throughout, and the "big wave" phenomenon is both flatter and extends back further in time to 1891. However, there is no solution to the post-1972 productivity slowdown, and in the new data MFP growth during 1972-96 proceeds at a pathetic 0.1 percent per year. A byproduct of the measurement adjustments is to solve completely the previous puzzle of the jump in the output-capital ratio; in the new data this ratio is actually lower in 1996 than in 1870.

The primary substantive explanation for the big wave lies in the timing of inventions. MFP growth during the "big wave" period benefited from the diffusion of four great clusters of inventions that dwarf today's information technology revolution in their combined importance. A complementary hypothesis is that the partial closing of American labor markets to immigration and of American goods markets to imports during the big wave period gave an artificial and temporary boost to real wages which fed back into boosting productivity growth, followed by a reopening that contributed to the post-1972 productivity slowdown.

Robert J. Gordon
Department of Economics
Northwestern University
Evanston IL 60208-2600
(847) 491-3616
rjg@nwu.edu

TABLE OF CONTENTS

"The change in trend that came after World War I is one of the most interesting facts before us. There is little question about it. . . . the rate of growth in productivity witnessed by the present generation has been substantially higher than the rate experienced in the quarter-century before World War I." (Solomon Fabricant, introduction to Kendrick (1961, p. xliii).

I. INTRODUCTION

It is now more than 25 years since the growth rate of labor productivity and of multi-factor productivity (MFP) decelerated sharply both in the United States and in most other industrialized nations.[1] This slowdown in productivity growth, or "productivity slowdown" for short, has eluded many attempts to provide single-cause explanations, including fluctuations in energy prices, inadequate private investment, inadequate infrastructure investment, excessive government regulation, and declining educational test scores.[2] The wide variation in productivity slowdowns and accelerations across individual industries also argues against a single-cause explanation.[3] The slowdown has also been immune to multi-faceted explanations, including those of the late Edward F. Denison (1962, 1979, 1985) to quantify the role of a slowdown in the growth of inputs and specific

---

1. The data in this paper end in 1996, because this was as far as the U. S. Bureau of Labor Statistics had extended its data on labor and capital composition, and multi-factor productivity, at the time the conference draft of this paper was written. During the 1996-99 period the quarterly data on output per hour indicate a modest acceleration when growth over the recent 1995:Q4-1999:Q1 interval is compared with the slowdown interval 1972:Q2-1995:Q4. Gordon (1999b) argues that this acceleration can be entirely explained by (1) improved measurement of price deflators, (2) normal procyclical effects, and (3) the production of computer hardware, with nothing left over to indicate a structural revival in productivity growth in the 99 percent of the economy engaged in activities other than the manufacture of computers.

2. Given that the productivity growth slowdown has continued over the period 1973-96, energy prices are ruled out as a cause, since by the early 1990s real energy prices had returned almost to their 1972 levels. Private investment is ruled out in that the productivity slowdown has occurred not just in output per hour but also in multi-factor productivity, which takes into account the growth of capital input. If private investment in equipment has "super-normal" returns, as argued by DeLong-Summers (1991), then a recalculated MFP exhibits an even more severe slowdown than in the official data. The infrastructure hypothesis proposed by Aschauer (1989) in research on the aggregate economy has been criticized on the grounds of reverse causation and for failing to explain cross-country productivity differences (Ford-Poret, 1991). Environmental regulation provides only a partial explanation of the productivity slowdown, and only for a few specific industries, e.g., electric utilities. Baily-Gordon (1988) use Bishop's earlier work to argue that declining test scores can explain at best 0.2-0.3 percentage points of the overall productivity growth slowdown.

3. See Gordon (1998), Tables 3 and 4.

qualitative factors such as the movement out of agriculture and the spread of crime.

Explaining the "Big Wave"

When an important problem so completely eludes explanation, other possibilities are suggested. Perhaps we have been asking the wrong question. A basic theme of this paper is that slow productivity growth in the past 25 years echoes slow productivity growth in the late nineteenth century. Perhaps both were normal, and what needs to be explained is not the post-1972 slowdown but rather the post-1913 "speedup" that ushered in the glorious half century between World War I and the early 1970s during which U. S. productivity growth was much faster than before or after.

The timing of the productivity "golden age" is different in the U. S. from that in Europe and Japan, where there is no novelty in suggesting that the 1948-73 "golden age" may have been unsustainable, particularly insofar as it contained an element of catching up from lost opportunities during the previous dismal decades of the two world wars and the Great Depression.[4] However, the United States is another story. The low level of productivity and per-capita income in Europe relative to the U. S. in an early postwar year like 1950 reflects not only Europe's poor performance but also the rapid advance of the U. S. prior to that point.[5] Although most casual observers assume that 1948-73 was the "golden age" of U. S. productivity growth as it was in Europe and Japan, the data

4. Nordhaus (1982) christened his pessimistic interpretation the "depletion hypothesis," that we were running out of resources and ideas. Abramowitz (1986, 1991) regards the first 25 years after the war as a unique period when simultaneously the production possibility frontier expanded rapidly and as well the possibility of "realisation" of this potential was unusually favorable.

5. Abramowitz (1991, Table 2, col. 1) shows that mean productivity in Maddison's sample of 15 countries (Europe and Japan) fell from 77 percent of the U. S. level in 1870, to 61 percent in 1913, to 46 percent in 1950, and then recovered to 69 percent by 1973 and 76 percent by 1986.

compiled in this paper suggest that the American golden age began much earlier, around the time of World War I, and that a substantial part of the great leap in the level of multi-factor productivity had already occurred by the end of World War II.

Unlike the common image of a step function, with steady MFP growth through 1973 and a post-1973 step down to a lower level, this paper shows that another image is more appropriate, that of "one big wave." Starting the record at 1870, MFP growth was slow until 1890, then accelerated and reached a crescendo in the five or six decades starting around World War I (1913-72), and then decelerated until in 1972-96 it reached a rate similar to that in 1870-1913.

The big wave image raises at least two big questions, (1) "is it real?" and (2) "what caused it?" Was there indeed a "golden age" of economic growth that spanned the half century between 1913 and 1972, in contrast to a more normal situation of slow growth before and after?[6] If so, why did the big wave occur? Was there a happy coincidence of particular innovations that created unusually rapid MFP growth during this period? If so, are we forced to conclude pessimistically that slow growth since 1972 has been normal and that we may never return to the earlier years of glory?

This paper is about both questions, "is it real?" and "what caused it?" We establish the existence of the big wave in the official U. S. data and then examine numerous measurement issues which could either cut down the peak of the wave or boost its post-1972 wake. We construct and extend previous estimates of changes in the *composition* of labor and capital inputs, which depending on semantics could be considered as errors in the measurement of inputs or explanations of the

---

6. Abramowitz (1991, Table 1) cites his own earlier research as indicating that MFP growth was only 0.45 percent per year over the entire nineteenth century, 1800-1905.

growth rate in MFP, and in addition make corrections to the quantity of capital input. In explaining the big wave, we give primary attention to the many great inventions of the late 19th and early 20th centuries. Compared with these, the information technology (IT) "revolution", which dates back to the first commercial mainframe computer in 1954, is smaller-scale and less important than the real revolution caused by the earlier cluster of "great inventions." Other hypotheses are also examined, including the idea that immigration and flexible markets made labor cheap both before World War I and in the past two decades, thus driving down real wages and labor's marginal product, whereas during the "big wave" period controls on immigration and the growing influence of labor unions worked in the opposite direction.

Plan of the Paper

The paper begins in Part II by examining data since 1870 on the growth rates of output, labor input, and two types of capital input, namely structures and equipment. We examine some critical relationships that have not received much attention, including the relationship between the big wave in MFP growth and the jump between the 1920s and 1950s in the output/structures ratio. Part III turns to existing postwar data on secular changes in the quality of labor and capital and then attempts to extend backwards before World War II estimates of changes in labor quality using a consistent methodology. Part IV examines several issues in measuring the quantity and composition of capital that relate equally to the interwar and postwar period, and Part V provides new quantitative estimates of the secular growth in labor and capital input and in MFP itself. Part VI provides an an overview of several hypotheses that together are promising in providing an explanation of the big wave. The most important of these is the concurrence of five great clusters of inventions in the late nineteenth and early twentieth century. Complementary explanations involve the closing off of the U. S. economy to immigrant workers and to imported goods between the 1920s and 1960s. Part VII concludes.

II. BASIC DATA ON OUTPUT AND INPUTS

Data Sources and their Main Features

While there are many sources of data on output and input growth in the U. S. economy over the last 125 years, three basic sources remain paramount. The U. S. National Income and Product Accounts (NIPA) provide a consistent set of accounts on the income and product side since 1929. For gross product originating (or value added) by industry the accounts are more difficult to use, since the current methodology has been extended back only to 1977, and previous estimates back to 1948 are based on a methodology that differs in many major and minor aspects. The NIPA also include data on employment and hours of labor input on a consistent basis, and the agency that produces the NIPA (Bureau of Economic Analysis, or BEA) also maintains data on capital stocks by industry since 1925.

Another complementary data set on aggregate output and input, available annually for 1948-96, is maintained by the Bureau of Labor Statistics (BLS).[7] While the BEA is the basic source for the output and capital input data used by the BLS, and the BLS is the basic source for the labor input

7. Since the conference version of this paper was written, the data set described here has been extended to 1997 and will soon be extended to 1998.

data used by the BEA, there are two important differences. First, the BLS data are available only for three sectors — private business, private nonfarm business, and manufacturing. In contrast, the BEA data set is available for roughly 60 two-digit industries.[8] Second, the BLS data incorporate for the period since 1948 the results of extensive research on the composition of labor and capital, inspired in large part by the work of Denison on labor input and of Dale W. Jorgenson and Zvi Griliches (1967) on both labor and capital input, whereas the BEA data contain no information at all on the composition of labor or capital input.

The third data set is the classic work by John Kendrick (1961) which provides time series on output, labor input, and capital input for major (one-digit) industry divisions over the long period between 1870 and 1953. The best match to extend the Kendrick data to the present on a consistent basis is the BEA data set, because it has much more disaggregated detail than the BLS data. Like the Kendrick data, the BEA data contain no compositional adjustments. We will turn in the next section to the BLS composition adjustments and how much they explain of the growth in the Kendrick/BEA MFP series. Subsequently we will explore the possibility of extending back before 1948 similar composition adjustments for labor and capital input.

MFP Growth and the Output-Capital Ratio Puzzle

This paper ignores inputs of energy and imported materials and considers only inputs of labor and capital. In this context it is obvious that the growth rate of MFP *(m)* is a weighted average of the growth of average labor productivity *(y-n)* and of the average product of capital *(y-k):*

8. BEA data on hours of labor input are only available at the one-digit industry level while output, employment, and capital stock data are available at the two-digit level.

$$m = y - \alpha n - (1-\alpha)k$$

$$= \alpha(y - n) + (1-\alpha)(y - k). \qquad \textbf{(1)}$$

Here α is the share of labor and reflects the standard joint assumptions of constant returns to scale and competitive factor pricing.

In the 1960s, largely as the result of data then newly published by Kendrick (1961) and Kuznets (1961), economists became aware of the puzzling behavior of the output-capital ratio. If one ignored the years within the 1929-48 interval in which economic relations were distorted by the Great Depression and World War II, it was clear that between the 1920s and 1950s there had been a sharp one-time leap in the output-capital ratio, i.e., the average product of capital. In terms of equation (1), the growth rate *(y-k)* was much faster during the decades of the 1930s and 1940s than in any other two-decade period in recorded U. S. history. Clearly, if the average product of labor grew steadily, then measured MFP growth *(m)* would be unusually high during the period of the spurt in *(y-k)*.[9]

Figure 1 begins our examination of the "standard" data on output and labor input based on splicing the Kendrick and BEA data sets at their intersection point of 1929. Details of data collection for the standard data are provided in the Data Appendix. Sectoral capital stock data come from Kendrick before 1925 and from the BEA capital stock study since 1925. As discussed below, there

9. The jump in the output-capital ratio intrigued me sufficiently to devote my Ph. D. dissertation (Gordon, 1967) to explaining it. This paper represents a return to several themes that remained unresolved at that time. My attention to the big wave was drawn by Duménil and Levy (1990), who call attention to this "rupture" in technical change without decomposing it by sector nor providing any link to the several aspects of capital input mismeasurement that in substantial part are responsible for it.

is a "rupture" in the BEA data source on capital, in that several data series previously compiled (e.g., capital retirements) have been discontinued, and this has required some improvisation to achieve a consistent historical record.

Figure 1 displays the output/capital ratio separately for equipment and structures in the top frame and for the total capital stock, i.e., equipment and structures together, in the bottom frame. The jump in the output/equipment ratio observed during 1936-44 was transitory; by 1966 the ratio had returned to its level of 1929, and the ratio declined steadily after 1966. But the jump for the output/structures ratio was huge and permanent. The average ratio for 1960-96 (1.13) was almost double the 1929 ratio of 0.59 and more than 2.5 times the average ratio for 1890-99 of 0.42. The ratio of output to total capital (equipment plus structures) in the bottom frame is dominated by structures (which were 5.0 times the constant-dollar value of equipment in 1929).

As shown in the top frame the jump in the ratio for structures was permanent but that for equipment was temporary. A corollary is that the ratio of equipment to structures, as shown in Figure 2, exhibits a steady and relentless increase beginning in the mid-1930s from an average of about 0.18 for 1870-1913 to an average of 0.62 for 1990-96. This dramatic feature of the historical record has received surprisingly little attention; clearly there has been a continuous bias toward space-saving innovation in the development of new equipment as compared to the equipment that was in place in the late 1920s.

Figure 3 compares average labor productivity (output per hour, or ALP) with MFP over the full period since 1870. While both ALP and MFP exhibit a high degree of cyclical volatility, the loglinear trends drawn through selected years reveal several features of long-run trends.[10] The first is that the big wave phenomenon is evident for both ALP and MFP, with faster growth during the middle period (1913-72) than in either the early or late periods. The second is that the big wave phenomenon is more pronounced for MFP than for ALP, and in the framework of equation (1) above this is the counterpart of the jump in the output-capital ratio in the middle period.

Several dimensions of the "big wave" phenomenon evident in Figure 3 are quantified more precisely in Table 1. Here are presented annual (logarithmic) percentage growth rates for output, inputs, and MFP in the non-farm non-housing private business sector. The top section of the table exhibits growth rates for nine medium-term intervals, the same as those used to draw the log-linear trends in Figure 3. The bottom section identifies long-term trends by dividing the full period into three intervals split at 1913 and 1972. The middle period has not only the fastest growth rate of MFP but also the slowest growth rates of labor and capital.[11] We note that the "big wave" is roughly symmetric, in that the final 1972-96 period has about the same rate of MFP growth as the initial period 1870-1913. This is also true for ALP, where the growth rates in the three long-term periods are 1.18, 1.86, and 1.04 percent, respectively. The medium-term trends in the top part of Table 1

10. The use of piecewise loglinear detrending implicitly involves the same method of separating trend and cycle as the more formal approach of Blanchard and Quah (1989), and this is to assume that the unemployment rate is stationary in the long run, that output is not, and that demand disturbances can be represented by shocks that occur in common to unemployment and to deviations of output from trend. The years used to identify trends are 1870, 1891, 1913, 1928, 1950, 1964, 1972, 1979, 1988, and 1996. These are "cyclically neutral" years chosen to smooth out the effects of recessions, depressions, and wartime booms. All the years chosen for the postwar have roughly the same unemployment rate, close to 5.5 percent. The long time span between 1928 and 1950 is intended to eliminate the impact of the Great Depression and World War II; while 1941 would be a possible interim year, distortions in output and labor markets (with rapid inflation, excess demand, and continuing residual unemployment) might create misleading results.

11. The tendency for input growth and MFP growth to be negatively correlated over long time intervals was observed in P. Romer (1987).

display a more continuous version of the "wave" phenomenon, with MFP growth steadily accelerating to a peak in the 1928-50 period and then decelerating after that until 1972-79, with a minor reacceleration after 1979.

III. COMPOSITION ADJUSTMENTS FOR LABOR AND CAPITAL

Dating from the pioneering work of Denison (1962) and Jorgenson-Griliches (1967), it has been conventional to explain part of the growth in MFP as the result of an improvement in the quality of labor. The BLS has adopted the framework of Jorgenson (1990) and publishes its indexes of labor and capital input, and of MFP, *after* correcting for changes in labor and capital composition.

In the rest of this paper, we shall use the word "composition" in preference to the somewhat misleading alternative label "quality" to describe the resulting adjustments to the growth of inputs. The increased growth in labor input that results from placing greater weight on more highly educated workers, in proportion to the incomes earned by those with higher educational attainments, clearly warrants labelling as an increase in labor quality. However, a decline in the growth rate of labor input, as in the 1970s, that results from rapid growth in the share of females in the labor force and the lower earnings weights attributable to females should not be called a "decline in quality" — this is not only inaccurate but even offensive. Similarly, the adjustments to the growth in capital input reflect primarily the higher depreciation rate and hence rental price of equipment relative to structures, yielding a faster growth rate of capital input than in the dollar-weighted capital stock when the share of equipment is increasing relative to structures. Again, it is misleading to refer to this as an "increase in capital quality" instead of labelling it for what it is, a "shift to shorter-lived assets."

The Postwar Impact of Changing Input Composition

The labor composition adjustments are obtained by the BLS by developing Tornqvist-weighted aggregates of the hours worked by all persons, classified by education, work experience, and gender. Weights are shares of labor compensation in each group. Thus an increase in the share of higher-educated or more experienced employees will be interpreted as a positive change in labor composition, whereas an increase in the share of less-experienced teenagers would represent a negative change in labor composition.

The capital composition adjustments are obtained by weighting four types of capital (equipment, structures, inventories, and land) separately within each of 53 industries using estimated rental prices for each asset type. Since the rental price includes both the net return to capital and depreciation, any shift toward short-lived assets would be interpreted as an increase in the composition of capital. As we have seen in Figure 2, there has been a continuous shift from structures to equipment since the 1930s, and this emerges in the Jorgenson-BLS method as implying a continuous upward movement in the composition of capital.

The Kendrick and BEA data used to construct Table 1 do not contain any adjustments for labor or capital composition. Now we turn to Table 2 which indicates the magnitude of the composition adjustments. The top line of Table 2 displays growth rates of output, which in the BLS data are more rapid than the BEA data used in Table 1 for 1950-88 but slower for 1988-96. The next section distinguishes the growth rates of composition-unadjusted hours of labor input (as used in Table 1) from the composition-adjusted growth rates that include the effects of changing composition across education, experience, and gender categories. During 1964-79 it appears that the benefits of increasing educational attainment were cancelled out by a shift toward less experienced teenagers and the rapid inflow of females into the labor force. After 1979 the share of teenagers declined and the female labor force participation rate levelled off, allowing the positive impact of increasing educational attainment to be augmented by a slight increase in workforce experience.

The next section provides the composition adjustments for capital. Somewhat surprisingly, in view of the growing importance of short-lived computer capital, the compositional adjustment for capital grows more slowly in the most recent period (1988-96) than in any of the earlier periods. As a result of this phenomenon and of slower growth in the capital stock, the growth rate of composition-adjusted capital input falls by half when the most recent period is compared to the middle three periods. This helps to explain why composition-adjusted MFP growth ("based on L and J") in the next section of Table 2 is slightly faster in 1988-96 than in 1979-88, despite the fact that ALP growth measured by either Y/H or Y/L declines sharply in the final period.

Because the combined effect of the composition adjustments is greatest in the final two periods, the growth rate of MFP slows more sharply over the postwar period when the composition adjustments are included than when they are excluded, and indeed composition-adjusted MFP growth is barely positive over 1979-96. Similarly, the bottom section of Table 2 shows that ALP growth slows somewhat more from 1950-64 to 1988-96 when the effects of the labor composition adjustment are included. We also note in the bottom section of Table 2 that the output-capital ratio that takes account of capital composition change (Y/J) declines at about one percent per year after 1964. This decline in the average product of capital and the accompanying decline in capital's marginal product may raise a question as to the priority of increasing national saving and investment as a "cure" for the productivity slowdown.[12]

Changes in Labor Composition, 1913-50

Further to understand the "big wave" phenomenon, we must develop measures of changes in labor composition for years prior to the postwar coverage of the BLS composition adjustments. Fortunately the elements of such adjustments back to 1909 have already been developed in Denison's seminal initial book (1962) on the sources of economic growth. However, Denison's techniques and assumptions are not consistent with the current BLS methodology, so in this section we lay out Denison's calculations and compute the changes needed to make them consistent with the BLS data discussed above for the postwar period.

Denison made two controversial assumptions in developing his labor composition adjustments. First, he did not use hours as his basic measure of labor input, but rather assumed that effort per hour increased as hours per week decreased from 52.0 in 1909 to 39.8 in 1957. Second, he adjusted downward by 40 percent the effect of increased educational attainment for the assumed contribution of ability to earnings differentials across educational categories. That is, if a college graduate earned 100 percent more than that of a high school graduate, Denison assumed that only 60 percent of this differential represented the contribution of higher education and the remaining 40 percent represented the contribution of the higher assumed innate ability of college graduates.[13]

---

12. The decline in the marginal product of capital was noted in this context by Baily and Schultze (1990).

13. Partly stimulated by Denison's assumption, there was a vast outpouring of reseach on education and ability in the 1960s. As summarized by Griliches (2000), this research found no consistent or significant influence of ability on earnings differentials by educational category.

Table 3 displays the ingredients in Denison's calculations and the changes needed to create a series that is consistent with BLS methodology. Since Denison's adjustments are presented as annual time series, we can calculate logarithmic percentage growth rates over the same intervals that are defined in Tables 1 and 2.[14] Line 1 lists the growth in total employment, while line 2 shows the negative rate of change of "potential" hours per employee (here "potential" is used in the sense of eliminating the effect of the business cycle). Growth in hours of labor input are then computed in line 3 as the sum of the first two lines and contrasted with Denison's computation of total labor input in line 4. The difference between line 4 and line 3, displayed separately in line 5, represents Denison's adjustment for the assumed effect of shorter hours per week on output per hour.

Denison made the assumption that at or above the hours per week prevailing in 1929 (48.6) a given percentage decrease in hours per week would increase productivity per hour by the same amount, e.g., he assumed an elasticity of productivity to weekly hours of -1.0. At the lower level of weekly hours (39.8) reached in 1957, he assumed an elasticity of -0.4, and he interpolated between the 1929 and 1957 values of weekly hours. Stated another way, Denison's approach assumes that a reduction from the 1929 level of weekly hours per employee has no impact on output per employee, while a one percent reduction from the 1957 level of weekly hours per employee reduces output per employee by 0.6 percent. The effect of Denison's approach can be seen in the shifting elasticity of productivity to reductions on hours per employee — the ratio of line 5 to line 2 — which amounts

14. Denison's 1962 book contained data through 1958 and projections through 1965 and later years. His 1985 book contained data for 1929 through 1982. As stated in the notes to Table 3, we use the 1962 data to cover our 1913-28 period and the 1985 book for 1928-79, backcasting the 1929 data in the 1985 book to 1928 using 1928-29 data as presented in the 1962 book.

to -1.03 for 1913-28, -0.56 for 1928-50, -0.50 for 1950-64, -0.30 for 1964-72, and -0.23 for 1972-79.[15]

Denison's adjustment for education involves two changes from the standard Jorgenson/BLS technique of using observed wages by educational attainment category to attribute a productivity gain to increasing educational attainment over time. Denison multiplies the results of this compositional adjustment by 0.6, reflecting his assumption that differences in ability rather than educational attainment explains 40 percent of observed differences in earnings across educational attainment categories. Thus the estimated effect in the first column, line 11, of 0.30 percent per year represents the multiplication of the compositional adjustment of 0.5 by 0.6 to reflect the 40 percent deducation for the assumed ability contribution. Then on line 12 Denison boosts his estimate by assuming that any percentage increase in the number of school days per year has the same effect on productivity as a like percentage increase in the number of school years per person. The total education effect calculated by Denison for decadal intervals is listed on line 13 and translated into an annual series for individual years on line 6.[16]

Denison's final calculation is a compositional adjustment for age and sex, with an additional adjustment for the increased relative earnings of females. This age-sex adjustment as listed on line 7 makes only a small contribution to his final composition adjustment for labor input listed on line 8. Clearly, the Denison methodology leads to a very large labor composition effect, much larger than

15. The description here of Denison's procedure refers to his first (1962) book. His procedure in his 1985 book is more complex, treats different age-sex cohorts of part-time and full-time workers separately, and chooses somewhat lower elasticities than in the 1962 book..

16. The 40 percent ability offset used in Denison's 1962 book was reduced to 20 percent in the 1985 book, and it is this later figure that is relevant in the columns of Table 3 covering the post-1928 period.

the BLS composition effect in Table 2 for the overlapping periods of 1950-79.

However, Denison's large adjustments do not correspond to the methodology currently used by the BLS, which does not make any adjustment for the effect of changing hours per week on productivity, any adjustment for changes in school days per school year, nor any adjustment for ability in calculating the impact of increasing educational attainment. To compute a new set of labor composition adjustments for 1913-79 using Denison's data, we eliminate the composition adjustment for changing hours per week. Then for the educational adjustment, we take only the impact of increasing school years per person (line 11) and ignore the impact of increasing school days per year (line 12), and subsequently divide the resulting composition adjustment by 0.6 for 1913-28 and 0.8 for 1928-79 to eliminate the assumed ability adjustment. The resulting "alternative" labor composition adjustment as displayed on line 10 is substantially smaller than the Denison concept on line 8, although the difference shinks through time. The alternative labor composition adjustment is only slightly higher than the BLS adjustment for 1950-64 but much higher for 1964-79.

Claudia Goldin (1998, p. 346) provides some additional perspective on changes in education as an explanation of the "big wave": "Human capital accumulation and technological change were to the twentieth century what physical capital accumulation was to the nineteenth century — the engine of growth." She documents the revolution in secondary education attendance in the three decades after 1910, with enrollment rates rising from 18 to 73 percent between 1910 and 1940 and goes further in attributing to the secondary school revolution a substantial part of America's productivity advantage over European nations.[17] Goldin goes further by creating new estimates of graduation rates for 1910 that are substantially lower than implied by the 1940 Census of Population, implying a more rapid growth rate of educational attainment than in the official data. We do not pursue this bias further, because Denison was already aware of this bias and made an adjustment for it; whether or not Denison's bias correction is consistent with Goldin's new results is a complex issue that lies beyond the scope of this paper.[18]

Changes in Labor Composition, 1870-1913

Denison's treatment of labor quality begins in 1909 but the current paper computes MFP starting in 1870. In this section we shall ignore changes in age-sex composition, which in table 3 are negligible prior to 1964 and focus on changes in labor composition attributable to education. What information is available to compute a labor quality adjustment for the period 1870-1909? Goldin (1988, Figure 1, p. 348) shows that during the 1890-1910 interval the percentage of those aged 14-17 graduating from secondary school increased only from about 4 to 9 percent and thus had a much smaller effect on the quality of the labor force than the increase from 9 to 52 percent that occurred between 1910 and 1940. Was there an equivalent explosion in elementary school enrollment during 1870-1910 that would have implied an increase in educational attainment comparable to that after 1910?

---

17. "But the countries whose per capita incomes were closest to that of the United States in 1910 did not undergo an equivalent transformation at that time. Rather, their high school movements did not materialize for another thirty or more years. . . Not only was the high school movement from 1910 to 1940 a uniquely-American phenomenon, the secondary school as we know it today was a uniquely-American invention" (Goldin, 1998, pp. 349-50).

18. See Denison (1962), pp. 70-71.

Two measures of educational attainment prior to 1910 are displayed in Table 4. The first line displays enrollment in elementary schools (kindergarten plus grades 1-8), which can be compared with the population aged 5-14, as displayed on the second line. The percent of the population enrolled is displayed on the third line and displays remarkably little increase over the 60 years shown, only from 90 to 97 percent. Consistent with this evidence that elementary education was already standard by 1870 (at least for the white population) is the final line which shows the illiteracy rate for the same years, implying that literacy for whites was already 88.5 percent in 1870, reaching 97.0 percent in 1930.

It remains to translate this information into an estimate of the change in educational attainment. Goldin (1988, Table 1, p. 346) provides a distribution of educational attainment that distinguishes between the percentage distribution in each grade interval (8 or below, 9-11, 12, and over 12) and the mean years of attainment in each interval. This is presented for three cohorts, those born, respectively, in 1886-90, 1926-30, and 1946-50. To estimate years of educational attainment forty years earlier for the cohort born 1846-50, we take Goldin's attainments for the 1886-90 group, cut the percentage in each of the higher three intervals (9-11, 12, and over 12) in half, redistributing them to the 8 and below group, and then cut mean years for the elementary school group by half a year. This yields average attainment for our early cohort of 6.23 years, compared to Goldin's three cohorts of 7.58, 11.46, and 12.82, respectively.

The annual growth rate between the our cohort and Goldin's earliest is 0.49 percent per year, compared with annual growth between Goldin's three cohorts of 1.03 percent and 0.56, respectively. If we take a person aged 42 to be in the midst of working life, then the implication is that the growth rate of educational attainment for adult workers was 0.49 percent per year between 1890 and 1930, 1.03 percent between 1930 and 1970, and 0.56 percent per year between 1970 and 1990.[19] There is a puzzling conflict between Denison's education adjustment (either line 9 or 11 of Table 3), which is most rapid in his final period of 1972-79, and Goldin's attainment series, which reaches its peak growth rate (when applied to the working-age adult population) around 1950 and then falls by half between 1950 and 1980.

The best we can do with our available information is to estimate that the growth of educational attainment in the late nineteenth century was about half that of the mid-twentieth century, which would reduce Denison's 0.54 percent for 1950-64 (Table 3, line 9) to 0.27 percent per annum. However, there is one additional step, which is to convert changes in educational attainment into changes in labor quality by applying earnings differentials across education-attainment groups. Translating changes in the growth rate of educational attainment directly into changes in labor quality would be valid only if the rate of return to increase in education had remained constant over time, which it clearly has not. In fact, Goldin and Katz (1999, Figure 4) estimate that the returns to high school education fell by half between 1914 and 1949, before recovering almost to their previous level. Since the rate of return on increases in high school enrollment were much higher around 1910 than in the middle of the century, this would appear roughly to cancel out the slower growth of educational attainment in the earlier period. As a result, we shall assume in the rest of this paper that

19. For instance, the first growth rate of 0.49 percent per year is between cohorts with a mean birth year of 1848 and 1888, who would be 42-year-old adult workers in 1890 and 1930, respectively. The final growth rate of 0.56 percent per year is between birth cohorts with a mean birth year of 1928 and 1948, who would be 42-year-old adult workers in 1970 and 1990, respectively.

labor quality increased during 1870-1913 at 0.5 percent per year, roughly the same as Denison's educational adjustment (Table 3, line 9) over the entire period 1913-64).

IV. ISSUES IN THE MEASUREMENT OF CAPITAL INPUT

In addition to the questions raised in the previous section about techniques for computing labor composition adjustments, questions can be raised as well about output and capital input data in every interval. As we go back in time, price deflators on which output and capital input data are based become more problematical, as they rely on thinner and thinner samples of the final products actually sold at the time.

Here we concentrate on issues involving the growth of capital input. The close relationship of capital to the one big wave phenomenon is clear in comparing Figures 1 and 3 as discussed above, where the spike in the growth rate of MFP in the 1928-50 interval (the level of which is shown in the lower frame of Figure 3) corresponds to the period when the output-capital ratio (shown in the lower frame of Figure 1) made its one-time permanent jump. In addition to showing that the timing of the big wave and of the sharp jump in the output-capital ratio is identical, Figures 1 and 3 (and the Y/J ratio in Table 2) also show that the period of slow productivity growth since the mid 1960s has also been a period of a falling output-capital ratio. The latter phenomenon has been interpreted by Martin Baily and Charles Schultze (1990) as evidence of diminishing returns to capital, supporting the traditional Solow growth model against claims by Paul Romer (1990) and others that measured income shares understate the contribution of capital to output growth.

The purpose of this section is to consider several issues in the measurement of capital that, taken together, may help to explain the sharp jump in the output-capital ratio displayed in the bottom frame of Figure 1. These are the shifting composition of different types of capital, retirement patterns, and the role of government-owned capital in contributing to private production. The following sections of Part IV introduce each issue and discuss the results of an attempt to provide a step-by-step remeasurement of capital input that deals with each issue in turn.

Adjustment for Changing Composition

Jorgenson and Griliches (1967) pioneered the use of service price weights for capital, based on the argument that the marginal product of each type of capital, e.g., structures and equipment, is equal at the margin to its service price, and a more refined version of their approach has been adopted by the BLS in the capital composition adjustments displayed in Table 2 above. For instance, the service price of equipment is the relative price of equipment (p^E) times the sum of the real interest rate and depreciation rate $(r+\delta^E)$, and similarly for structures. Since the depreciation rate for equipment is roughly four times that for structures, the use of service price weights substantially raises the share of equipment in capital input and diminishes the share of structures. Since the big wave in MFP growth is related to the 1928-50 jump in the structures-output ratio (Figure 1), a reduction in the weight on structures indirectly dampens the big wave. Thus our task in this paper is to develop an adjustment for the shifting equipment-to-structures ratio (Figure 2) that applies to the period prior to the BLS postwar capital composition adjustments.

Already introduced in Table 2 and repeated in Table 5, column (2), are the capital composition adjustments provided by the BLS for the 1948-96 interval. These are obtained, as stated above, by weighting four types of capital (equipment, structures, inventories, and land) separately within each of 53 industries using estimated rental prices for each asset type. To extend these prior to 1948, our only information is on two types of capital, equipment and structures. Our approach is to create a crude composition index based only on reweighting equipment and structures for 1870-1996 and then compare it to the BLS capital composition index for the overlap period, 1948-96. Our crude index is the ratio of an index (1992=100) of the capital stock of equipment with a weight of three and structures with a weight of one (the "3:1 index") to a standard capital stock index which weights equipment and structures dollar-for-dollar (the "1:1 index"). The growth rate of this ratio is displayed in column (1) of Table 5.

Our capital composition index, that is, the ratio of the 3:1 to the 1:1 index displayed in column (1), grows steadily throughout the postwar period but more slowly than the BLS index shown in column (2) for the period after 1950, presumably because the BLS index contains additional reweighting within categories of equipment and across industries that has the effect of shortening the average lifetime of equipment and raising its service price. For the three intervals between 1950 and 1979, the growth rate of our crude composition index is slightly more or less than one-half the growth rate of the BLS capital composition index for various subperiods, averaging out to 0.56 for the full 1950-79 period.[20] Accordingly, we shall extrapolate the BLS composition index backwards before 1948 by dividing the growth rate of our crude composition index in column (1) by 0.56. Moving backwards, the BLS composition index in Table 2 grows by 1.29 percent per year in 1964-72 and

---

20. We omit the post-1979 period because it is most affected by the growing importance of computers, which play no role prior to 1948. It would make little difference to our results if we were to base the backcasting exercise only on the 1950-64 period; this would change our 0.56 backcasting factor to 0.49.

0.85 percent per year in 1950-64, and our extrapolated BLS index grows at 0.68 in 1928-50, 0.21 in 1913-28, and and mere 0.07 percent per year during 1870-1913. Thus the capital composition factor becomes important only after 1928, unlike changing labor composition which, at least along the educational dimension, is important throughout the 1870-1996 period. Subsequently we shall examine graphs which display the effects of the capital composition adjustment on the annual behavior of capital input and of MFP over the 1870-1996 period.

Variable Lifetimes

The single most important error in measuring capital input may be the inadequate allowance for quality change, the topic of my book on durable goods prices (1990). Unfortunately, a consistent set of new estimates of investment goods prices is available only for the period covered in that book, 1947-83, and only scattered evidence is available for earlier or later years. In particular, there is no readily available evidence that the bias in the growth rate of official price indexes for investment goods is higher or lower before or after the 1947-83 period than during that period. For the purposes of this paper, a continuous drift in measured price indexes relative to true prices does not have a major impact on the timing of MFP growth by decades. Even if the measurement error were different across decades, this would not skew our MFP calculations in a major way, simply because deflation errors affect both output and capital input growth in the same direction.[21]

---

21. For instance, I estimated for the 1947-83 period that the growth rate of capital input had been understated by 1.60 percent per year, but that this caused an overstatement of MFP growth by only 0.17 percent per year over the same 1947-83 period (Gordon, 1990, Table 12.14, column 5). Jorgenson (1966) showed theoretically that the impact of price measurement errors on MFP growth depend on the relative size of the share of investment in GDP and the share of capital in total income.

Much more important in affecting the timing of capital input and MFP growth across decades is the universal assumption in standard capital data that service lifetimes and retirement patterns are constant. Yet Feldstein and Rothschild (1974) have argued that from a theoretical perspective a fixed retirement pattern is not optimal, and Feldstein and Foot (1971) showed on the basis of firm-level data that retirement patterns are variable and depend on firm cash flow and the state of the economywide business cycle. An "eyeball test" suggests that for both structures and equipment retirements occur when new investment occurs. Gross private investment was unusually low between 1930 and 1947 because of the Great Depression and World War II, and standard capital measures assume that buildings were being torn down on schedule during this period (leading to the implication that the annual growth rate of the capital stock dropped to nearly zero during 1928-50).[22] Yet Chicago's Loop and New York's Midtown were not littered with vacant lots during the 1930s and 1940s; the old buildings were still there.[23]

A simple way to allow for variable retirement patterns is to make the retirement rate depend on gross investment. This relationship can be derived from the empirical equation estimated by Feldstein-Foot (1971):

---

22. Our standard capital stock series summarized in Table 1 grows at only 0.04 percent per year between 1929 and 1945. All of its growth rate for 1928-50 shown in Table 1 occurs during 1928-29 and 1945-50.

23. A vivid example of the cessation in office building construction in the 1930s and 1940s occurs in Chicago, where the tallest building from 1930 to 1957 was the Board of Trade, but after 1957 the title for tallest building changed every year or two until 1973. The story is similar in other cities.

$$\frac{R}{K} \;=\; \beta_0 \;+\; \beta_1(\frac{F}{K}) \;+\; \beta_2(\frac{N}{K}) \;+\; \beta_3 U\,. \qquad \textbf{(1)}$$

Here *R/K* is the ratio of retirements to the capital stock, i.e., the retirement rate, *F/K* is the cash flow ratio, *N/K* is the net investment ratio, and *U* is the unemployment rate. To simplify this equation for use here, we assume that both the cash flow ratio and unemployment rate depend on the ratio of gross investment to capital:

$$\frac{F}{K} \;=\; \alpha_0 \;+\; \alpha_1\left(\frac{G}{K}\right)\;; \qquad U \;=\; \gamma_0 \;+\; \gamma_1\left(\frac{G}{K}\right)\,. \qquad \textbf{(2)}$$

Using the identity that

$$\frac{N}{K} \;\equiv\; \frac{G}{K} \;-\; \frac{R}{K}\,, \qquad \textbf{(3)}$$

we can combine (2) and (3) and write a relationship between the retirement rate and the gross investment ratio:

$$\frac{R}{K} \;=\; A_0 \;+\; A_1\left(\frac{G}{K}\right)\,. \qquad \textbf{(4)}$$

To convert equation (5) into a specific adjustment in the capital stock series, we begin with

BEA data on retirements and the ratio of gross investment to capital, available from 1925 to 1988.[24] No adjustment is performed before 1925, but this omission is not important since the motivation for the adjustment is the delay in retirements in the 1930s and 1940s caused by unusually low gross investment during that period. The adjusted retirement rate *(R/K)** is computed from the BEA data as follows:

$$\left(\frac{R}{K}\right)^{*}_{t} = \left(\frac{R}{K}\right)_{t} \frac{\left(\frac{G}{K}\right)_{t}}{\left(\overline{G/K}\right)} \qquad \textbf{(5)}$$

Thus we simply multiply the BEA's retirement rate by the ratio of *G/K* in each year to its sample mean over 1925-88.[25] This procedure implies that retirements are reshuffled among the years between 1925 and 1988, but the average retirement rate over the entire period is maintained at the same level as in the BEA data.

The effect of the variable retirement adjustment is shown in Table 5 for equipment in column (3), for structures in column (4), and for the sum of equipment and structures in column (5). The effect is to make capital input grow faster over the 1928-50 period, as expected, and to grow slower

24. The basic computation was carried out on BEA gross investment and retirement data for the period 1925-88, as stated in the text. After these computations were carried out in 1992, the BEA changed the format of its historical capital stock data and no longer publishes gross investment or retirements. The current paper is based on the new BEA net investment data and bases its estimate of the effect of variable retirement on the previous results developed from the previous BEA gross investment and retirement data available for 1925-88.

25. An extension to 1996 will be performed in the final version of this paper.

during 1950-79. Over the entire 1925-96 period the effect of this adjustment is negligible, as is intended.

The adjustment is shown for the entire 1925-96 period in Figure 4, with the adjustment displayed for equipment in the top frame and for structures in the bottom frame. The shift to a variable retirement pattern substantially boosts the stock of both equipment and structures between 1929 and 1965 (for equipment) and 1970 (for structures). The ratio of the fixed-retirement capital stock for equipment reaches its low point relative to the variable retirement equipment stock in 1943-44 and for structures in 1945-50. As would be expected, the variable retirement pattern reduces the stock of both equipment and structures after 1975, since there was more capital existing in 1930-65 to be retired.

Omitted Capital

Part of the sharp rise in output during World War II was made possible by plants and equipment that were owned by the government but operated by private firms to produce goods and services. When the output-capital ratio puzzle was first discussed in the 1960s, the official statistics on capital input in the private sector did not keep track of this government-owned privately-operated (GOPO) capital, and thus the 1940-45 increase in the output-capital ratio (and hence in MFP) was exaggerated. After I studied this phenomenon and estimated its magnitude (1969), the BEA began to keep track of GOPO capital and includes it now as a separate category in its capital stock data bank. Thus we can show the impact of including GOPO capital, as in column (6) of Table 5, which is to boost the growth rate of capital input during 1928-50 (all of this occurs in 1940-45) and to reduce it after 1950.

A related issue is that a substantial part of government-owned infrastructure serves as an unmeasured input to production in the private sector. In particular, there has been a gradual shift over time in the transportation sector from privately owned railroad capital to publicly owned highways, airports, and air-traffic control facilities. Sufficient data are available to allow us to add to private capital input two types of government capital, GOPO in column (6) and highway capital in column (7) of Table 5, relying on Fraumeni's (1999) recent estimates of the latter. The effect of adding highway capital is to boost the growth rate of capital input in both the 1928-50 and 1950-64 periods but to reduce it thereafter, which has the effect of explaining a small part of the "big wave" of MFP growth during 1928-64 and a small part of the post-1972 MFP growth slowdown.[26]

The combined impact of changing from fixed to variable retirement, and of adding GOPO and highway capital, is illustrated for the 1925-96 period in Figure 5. Instead of declining by 7.4 percent between 1930 and 1944, total capital input actually increases by 28 percent (not counting the capital composition adjustment). This is clearly an important finding and highly relevant to the puzzle of how the United States succeeded in producing so much during World War II. Subsequently we will take a broader look at the revised input series over the entire 1870-1996 period.

---

26. Highway capital data are included only beginning in 1925. To avoid an artificial jump in total capital between 1924-25, the total capital measure including highway capital is ratio-linked in 1925 to avoid having any impact on the growth rate of capital from 1924 (or any earlier year) to 1925.

V. SUMMARY OF INPUT DATA REVISIONS AND IMPLICATIONS FOR MFP

Corrections to Labor Input Data

We now take a tour of several graphs and tables that summarize the implications of our labor and capital composition adjustments, and of our capital quantity adjustments, for the full 1870-1996 period. The tables provide summary information on growth rates over the same intervals specified in Table 1, and the figures provide additional information by displaying all the years individually.

The effects of the labor composition adjustments on the level of labor input is shown in Figure 6 — the more rapid growth of composition-adjusted labor input combines the BLS composition series back to 1948, the Denison series adjusted to correspond with the BLS concept back from 1948 to 1913, and a guesstimate back to 1870 based on scattered evidence on enrollment rates, illiteracy, and the rate of return to high school education. The effects on growth rates over our standard intervals are shown in Table 6, where in column (3) the labor composition adjustment is shown to have about the same impact in raising labor input growth by about 0.5 percent per year in all periods except 1964-72 and 1972-79.

Columns (4) through (6) of Table 6 compare standard capital input with composition-adjusted capital input and with capital input adjusted both for composition and the three quantity adjustments quantified separately in Table 5 and Figure 5, namely the shift from fixed to variable retirement, the addition of GOPO capital, and the addition of highway capital. Unlike the labor composition adjustment, which has a similar effect in all intervals but 1964-79, the effect of the capital composition

and quantity adjustments differ radically across intervals. By far the greatest impact is in 1928-50, the core period of the "big wave"
in MFP growth, where there is a substantial impact of capital composition and where the other three adjustments (variable retirement, GOPO capital, and highway capital) all have sizeable effects. The combined capital adjustments also have substantial effects of close to one percentage point per year in three of the five postwar intervals, but virtually no impact prior to 1913. Thus the combined capital adjustments have the effect of reducing MFP growth after 1913 relative to pre-1913 MFP growth and reduce MFP most of all in 1928-50, 1964-72, and 1979-96. Figure 7 shows the same adjustments for each year back to 1870 and emphasizes that the quantity adjustments had their greatest proportional effect in the 1940s while the composition adjustment made the most difference between 1964 and 1988.

Implications for MFP Growth

We have now seen that the timing of our three types of input adjustments is quite different. The labor composition adjustment has a uniform effect in boosting labor input growth and reducing MFP growth across all periods except 1964-79. The capital composition adjustment is negligible before 1913 and has its largest effect in boosting capital input growth and reducing MFP growth during the postwar period, especially between 1964 and 1988. We have seen that several quantity adjustments made to the standard capital series have the effect of substantially raising the growth rate of capital input during the 1928-50 "big wave" interval relative to subsequent intervals, and indeed these adjustments reduce the growth rate of capital input in every interval but 1988-96, thus partly offsetting the positive impact on capital growth of the capital composition adjustment.[27]

The effects of these adjustments on MFP are displayed in Table 7 and Figure 8. Comparing the growth rates of MFP based on standard inputs in column (1) with the alternative growth rates of MFP based on fully adjusted inputs in column (4), we see that MFP growth is reduced in every period but by quite a different amount. The capital quantity adjustments have their biggest impact in 1928-50, the period in which MFP growth is reduced the most. The labor composition adjustments are close to zero in 1964-72 and 1972-79, the periods when MFP growth is reduced the least. And the capital composition and quantity adjustments are negligible prior to 1913, when the reduction in MFP is also relatively low. Overall, looking at the long-term trends in the bottom of Table 7, the middle period still has the most rapid MFP growth, although its margin of victory over 1870-1913 is substantially reduced. However the reduction in the growth rate of MFP after 1972 is almost as great as in 1913-72, and thus the contrast between the "big wave" period and the post-1972 "slowdown" period remains intact.

Figure 8 exhibits the same alternative MFP series for which the growth rates are displayed in Table 7. The input adjustments do create an important change in timing in contrast to MFP based on standard inputs. Instead of exhibiting a distinct acceleration in 1928-50 as compared to the periods immediatley before or after, fully adjusted MFP growth appears as nearly a straight line all the way from 1891 to 1972, and indeed Table 7 shows that the growth rates over the five sub-periods within 1891-1972 vary only between 0.77 and 1.17 percent, a range of 0.40 percentage points compared to the range over the same sub-periods of more than twice as much, 0.87 points, when

27. Recall that the capital quantity adjustments do not extend before 1918 due to the absence of comparable data.

MFP is based on standard inputs as in column (1) of Table 7.

Implications for the Output-Capital Ratio

This paper began by pointing to the permanent doubling in the output to capital ratio between the prewar and postwar eras, as depicted in Figure 1. Does this mysterious jump in the ratio survive the composition and quantity adjustments developed in this paper? Figure 9 compares the output-capital ratio based on standard and adjusted capital input, while retaining the same measure of real output. It appears that the composition and quantity adjustments to capital input completely eliminate the permanancy of this jump, a long-standing feature of the data that has previously resisted a coherent explanation.[28] Indeed when both output and capital input are expressed in 1992 prices, the output/capital ratio is lower in 1996 (0.64) than in 1870 (0.71), in contrast to the doubling that occurs with the standard capital input date (0.37 to 0.74).

Two further differences stand out between the adjusted and standard data when shorter periods aare examined. First, the increase between 1926 and 1953 in the output- capital ratio is substantially less with the adjusted than with the standard data, 9 percent (from 0.89 to 0.97) instead of by 65 percent (from 0.49 to 0.81). Second, there is a pronounced downdrift in the postwar period in the adjusted data, with the output-capital ratio declining from 0.97 in 1953 to 0.64 in 1996 (a 34 percent decline) in contrast to a much milder decline from 0.81 in 1953 to 0.74 in 1996 (a 9 percent decline). The radical difference in the historical behavior of the output-capital ratio combines the influence of the steady increase in capital growth created by the composition effect after 1928 with

28. The jump in the output-capital ratio depicted in Figures 1 and 9 using the standard capital series was the original motivation for my 1967 Ph.D. thesis on problems in measuring real investment.

the boost to capital growth in the 1928-50 interval created by the quantity adjustments.

VI. SUBSTANTIVE HYPOTHESES

Now we turn to the task of explaining the "big wave" in U. S. growth in MFP, now expressed with the new data as the much faster growth between 1891 and 1972 than before or particularly after 1972. In discussing substantive explanations of the big wave, we begin with the timing of the great inventions and then proceed to other complementary hypotheses.

The Great Inventions

In related research (Gordon, 1998) I have argued that the current information-technology revolution does not compare in its quantiative importance for MFP with the concurrence of many great inventions in the late nineteenth and early twentieth century that created the modern world as we know it. There are four major clusters of inventions to be compared with the computer, or chip-based IT broadly conceived. These are:

(1) The first great invention in the "Group of Four" is electricity, including both electric light and electric motors. As shown by Nordhaus (1997), electricity drastically reduced the true price of light. Electric motors, after a developmental period of two or more decades emphasized by David (1990), revolutionized manufacturing by decentralizing the source of power and making possible flexible and portable tools and machines. After a somewhat longer lag, electric motors embodied in consumer appliances eliminated the greatest source of drudgery of all, manual laundry, and through refrigeration virtually eliminated food spoilage and through air conditioning made summers enjoyable

and opened the southern United States for modern economic development.[29]

(2) Sharing the title with electricity for the most important invention that had its main diffusion in the twentieth century is the internal combustion engine, which made possible personal autos, motor transport, and air transport. Grouped in this category are such derivative inventions as the suburb, interstate highway, and supermarket.[30] Gradually eliminated or greatly reduced were many of the ills of the late nineteenth century, from manure to unplowed snow to putrid air to rural isolation.

(3) The third group of great inventions includes both petroleum and all the processes which "rearrange molecules," including petrochemicals, plastics, and pharmaceuticals. These are largely an independent invention, but some of the innovations were induced by the demands of motor and air transport. They helped to reduce air pollution created by industrial and heating uses of coal, and they made possible many new and improved products, as well as conquering illness and prolonging life.

(4) The final member of the "Group of Four" is the complex of entertainment, communication, and information innovations that were developed before World War II. This set of inventions that made the world smaller can be traced back to the telegraph in 1844 and includes the telephone, radio, movies, television, recorded music, and mass-circulation newspapers and magazines. Television, which was invented in the 1920s and 1930s, is the only one of these innovations that was diffused after World War II. Otherwise, all the rest were well established before World War II and

29. The acceleration of manufacturing productivity growth in the 1920s and the role of electrification in achieving it are studied by David and Wright (1999).

30. Bresnahan and Gordon (1997) in their introduction provide a formal analysis of how complementary inventions like supermarkets, suburbs, and highways increase the consumer surplus contributed by new inventions like the internal combustion engine and the motor car.

created a quantum leap in the standard of living when a year like, say, 1939 is compared with fifty years earlier.

The "Group of Four" inventions, in turn, created an increase in per-capita income and wealth that allowed an improvement in living standards even in those aspects of consumption where inventions did not play a major role, particularly the ability of families to afford many more square feet of shelter (and in the suburbs more land surrounding that shelter) than at the turn of the century.

Has the information revolution spawned by the computer created as great a change in living conditions as any of the four major complexes of early twentieth- century inventions? While retrospective exercises are inevitably subjective, it is interesting to play an expanded version of what I like to call the "New Yorker game." A few years ago the *New Yorker* commissioned a critic to sit in front a television set for an entire week and record his impressions. He had many reactions, but the one most relevant for us is that he was surprised from the reruns of 1950 TV shows how similar were the living conditions of the 1950s Ozzie and Harriet families in comparison to those of today. Clearly living conditions were far better in the 1950s than in the 1890s, in large part because of the "Group of Four" inventions. We can surmise that a hypothetical critic revisiting the 1890s through a time machine would not have the same reaction as the *New Yorker* critic visiting the 1950s from the 1980s. For our purposes, it is a moot point whether life changed more between the 1890s and 1920s or between the 1920s and 1950s. What does seem sure is that society had cured most of the ills of late nineteenth century living conditions by the 1950s and 1960s without any help from computers.

To understand at a deeper level why the computer revolution does not measure up to the earlier great inventions, it is useful to consider some of the ways in which the great inventions created productivity growth. Electric light was a unique invention that extended the length of the day for reading, entertainment, and other pursuits. Both the electric motor and internal combustion engine created faster and more flexible movement, directly raising the productivity of factory workers, housewives, truck drivers, and airline pilots as the machines they powered could rotate ever faster. Petroleum refining, chemicals, plastics, and pharmaceuticals all involve the physical rearrangement of molecules in ways that change materials into more productive forms. The complex of electric and electronic entertainment and information industries arrived in a void in which nothing comparable existed and had, one may safely conjecture, a greater impact on everyday life of the average family than the second and third generation developments, e.g., VCRs, CDs, the first generation of color TV, and ever-larger TV screens, which provided merely better or more convenient ways of performing the same basic functions.

Some of the output of computers is, in principle, as productivity-enhancing as that of electric motors or motorized transport. From the earliest punch-card sorters, some applications of computer technology have involved movement and speed. Numerically controlled machine tools, robots, and other computer-driven machinery has the same potential for productivity improvement as the earlier great inventions and doubtless accounts for the robust rate of productivity growth still apparent in some (but not all) manufacturing industries. The use of ever-faster computers and peripherals to churn out securities transactions, bank statements, and insurance policies should enhance productivity growth in the finance/insurance sector. And, just as the motor car enormously increased personal mobility and flexibility, so the computer has spawned inventions whose main output is convenience, most notably the ATM machine.

These productivity enhancing aspects of computers suggest that MFP performance in the past two decades would have been even worse than the dismal record of Table 7 without the benefits of computers. Yet the benefits of computers have not been strong enough to bring us back to the rapid rates of MFP advance enjoyed before 1972. In my analysis (1998), the rapid price declines of computer power have resulting in diminishing returns to computers operating with unparalleled force. Just as the elementary textbook example explains diminishing returns as resulting from the application of additional units of labor to a fixed supply of land, so the computer revolution has resulted in the application of vastly multiplied units of computation power to a fixed supply of time and mental power for any given computer user. The computer revolution did not begin with the earliest PCs in the 1980s but with mainframes in the early 1950s; after more than four decades the greatest benefits of computers have been achieved. The newest aspect of the computer revolution, the internet, can be viewed largely as a source of information and entertainment that substitutes for other forms of information and entertainment.

An intriguing connection of the time path of technical innovation with the "big wave" is Kleinknecht's (1987) count of "radically new products," which rises from six during 1850-1920 to 29 during 1920-1950 and then falls to five during 1950-70.[31] Kleinknecht's count is reproduced in Table 8.

31. See Freeman (1984) for a collection of suggestive papers on long swings in design and innovation.

Other Substantive Hypotheses

1. **Immigration and the co-dependence of Productivity and Real Wages.** Given the timing of the "big wave," it is striking that productivity growth was slow in the late nineteenth century when immigration was important, and then again in the 1970s and 1980s when the baby boom and renewed immigration created rapid labor-force growth. This observation is related to Romer's (1987, Figure 1) demonstration that productivity growth and labor-force growth in U. S. history is negatively correlated over 20-year intervals since 1839. Thinking about immigration may be helpful in explaining why the U. S. MFP growth slowdown in the 1970-90 period has been concentrated in nonmanufacturing. My idea (further developed in Gordon, 1997) is that new entrants (teens and adult females in the 1970s and legal and illegal immigrants in the 1980s) have mainly gone into unskilled service jobs and have held down the real wage in services, in turn promoting the lavish use of unskilled labor in such occupations as grocery baggers, busboys, valet parkers, and parking lot attendants, jobs that barely exist in high-wage European economies. In contrast, immigrants in the 1890-1913 period were disproportionately employed in manufacturing, and their prescence probably dampened real wage increases and delayed the introduction of labor-saving equipment.[32] The "big wave" period of rapid productivity growth coincides roughly with the shutting off of mass immigration in the 1920s and the slow labor-force growth of 1930-65.

2. **Real wage convergence and divergence.** Goldin and Margo (1992) have recently studied the sharp convergence, i.e., reduction in inequality, of real wages in the 1940s and subsequent

32. On the industrial and occupational composition of successive generations of immigrants, see Borjas (1994). On migration and economic development in an international context see Hatton-Williamson (1992) and Williamson (1992).

divergence, and Goldin and Katz (1999) have shown the same type of V-shaped behavior for the rate of return to both high school and college education. If relative labor scarcity coincided with a technology that created a high demand for unskilled and semi-skilled workers, then the relatively high wages for low-skill work in the 1940s may have in turn stimulated efficiency improvements that boosted productivity. Wages started diverging after 1950, with a sharp increase in inequality in the 1980s and 1990s that is reflected in a big jump in the rate of return to college education, mainly because the real wages of high school graduates fell. This process is the outcome of a complex process in which changing technology, an increased supply of cheap imported manufactured goods, and immigration interacted to erode the rents previously earned by union members with high school educational attainment. This, in turn, may have reversed the stimulus to higher efficiency that took place in the 1940s. The immigration and convergence stories are related, since Borjas (1992) shows that immigration in 1880-1913 introduced much of the inequality in skills and real wages that Goldin and Margo (1992) show was substantially eliminated in the 1940s.[33]

3. **Growing openness to trade.** Trade theory teaches that trade in goods, not just labor mobility, can lead to convergence of incomes. This idea that trade simultaneously promotes convergence but also generates a slowdown of income growth in the leading country is closely related to several recent models, particularly that of Johnson and Stafford (1992). In this context a contribution to the "big wave" may have been a movement away from free trade in the Fordney-McCumber tariffs of 1922 and Smoot-Hawley Act of 1930. This movement away from trade may

---

33. David and Wright (1999) also emphasize the shutting off of mass immigration as a factor which stimulated faster real wage growth in manufacturing, which in turn "provided a strong impetus to changes in workforce recruitment and management practices" (title page).

possibly help to explain some of the "big wave" and also the temporary cessation of convergence among nations in the 1913-1950 period previously noted by Abramowitz (1986, 1991) and many others.[34]

4. **"Heavy" and "Light" Technology and the Upsurge in the Equipment-Structures Ratio.** One of the most striking (and as yet little noticed) features of the historical record appears in the ratio of the capital stock of producers' equipment to that of nonresidential structures. This ratio (shown in Figure 2 above) remains constant between 1870 and 1945 and then rises rapidly and steadily by a factor of almost four through 1996.[35] I believe this phenomenon is related to Wright's (1990) emphasis on the raw-materials intensity of U. S. technology in the late nineteenth century, which favored "heavy" and space-intensive machinery (steel mills, railroad stock and track, etc.) Technological innovation beginning with the electric motor allowed a shift to lighter and less space-intensive equipment, so that more and more equipment could be stuffed into a given number of square feet of structures. Space-saving may have been an important part of the big wave, but this particular trend has continued throughout the period of slow MFP growth after 1972. Since computers have many of the same characteristics as electric motors (space-saving, energy-saving, materials-saving), a continuing puzzle is the failure of computers to boost productivity growth as electric motors

34. The idea that protection can raise productivity is related to an idea that emerges from the McKinsey (1992) cross-country study, that West Germany boosts productivity in retailing by regulations that directly limit shop opening hours and indirectly stifle the development of shopping centers (thus creating crowded busy stores in contrast to the U. S. malls that are empty for many of their weekly opening hours).

35. Figure 2 is based on the "standard" capital series. With variable retirement the equipment/structures ratio rises slowly from 0.200 in 1929 to 0.248 in 1945, whereas with fixed retirement the ratio is 0.200 in 1929 and 0.199 in 1945.

apparently did.[36]

VII. CONCLUSION

It is interesting that there is no mention of the big wave in recent commentaries on productivity by such prominent authors as Abramowitz (1986, 1991), Baumol-Blackman-Wolff (1989), Maddison (1982, 1987, 1989), and Nelson-Wright (1992). Most of the focus in the recent literature has been on the worldwide productivity slowdown, on convergence among leading industrial nations, and on catch-up of these nations to the U. S. level of productivity. There has been remarkably little attention to the fact that in the century before 1973 U. S. productivity did not grow at a uniform rate, or at a peak rate during 1948-73, but rather displayed a sharp acceleration at some point after 1913. Yet this fact which makes up the early part of the big wave was evident as soon as Kendrick's (1961) results were computed, and Solomon Fabricant emphasizes it in his introduction to Kendrick's book (see the quote at the beginning of this paper). This paper has shown that the standard data on output, labor input, and capital input imply "one big wave" in multi-factor productivity (MFP) growth, with MFP growth exhibiting a symmetric wave that peaks in 1928-50 and slows gradually moving backwards to 1870-91 and forward to 1972-96. Much of this paper has discussed adjustments to MFP growth for changes in the composition of labor and capital input and adjustments to the quantity of capital input to take account of variable retirement, GOPO capital,

36. A development related to "heavy" materials and to the "big wave" is that the geographical concentration of U. S. manufacturing rose to a peak in 1940 and then fell (Kim, 1992). The economy may have received a one-time boost in MFP from the dispersion of manufacturing to more efficient locations in the 1940-70 period, made possible by "lighter" materials, motor transport, and the diffusion of air conditioning.

and highway capital. These adjustments change the symmetry, flatten out the wave, and move it backwards; MFP growth is very slow during 1870-91, relatively steady at roughly one percent per year from 1891 to 1972, and then almost completely disappears in 1972-96. The peak interval for MFP growth is now 1950-64 rather than 1928-50, although the margin is narrow and the 1928-50 period remains in second place despite the extensive data revisions that have the effect of boosting input growth and reducing MFP growth more in the 1928-50 interval than in any other period.

We have argued that previous attention to the post-1972 productivity slowdown is misguided. The question should be recast: why was productivity growth so much faster between 1891 and 1972 than either before or after, and fastest of all between 1928 and 1964? Our preferred hypotheses combine several explanations, most notably the concurrence of a multitude of important inventions occurring simultaneously prior to and at the beginning of the rapid growth period. Two other leading explanations with the correct timing rely on a theoretical connection between open economies and slow growth in incomes, real wages, and productivity. The closing of American labor markets to immigration between the 1920s and 1960s, thus boosting wages and stimulating capital-labor substitution, contributed to the big wave. So in like manner did the combination of high tariffs, depression, and war, in closing off American goods markets from the influence of imports, thus postponing the convergence of incomes with America's trading partners and temporarily boosting wage growth for American workers.

This paper is undeniably pessimistic in its implications. If the big wave resulted from great inventions whose effects have now been fully diffused through the economy, together with a temporary shift towards closed labor and goods markets, the outlook for a revival of MFP growth is not promising. The optimists declare the arrival of a "new economy" in which the benefits of the hi-tech revolution and globalization will bring about a revival of rapid growth, but in my view the remorseless progression of diminishing returns has left the greatest benefits of the computer age in the past, not awaiting us in the future.

REFERENCES

ABRAMOWITZ, MOSES (1986). "Catching Up, Forging Ahead, and Falling Behind," *Journal of Economic History*, vol. 46 (June), pp. 385-406.

__________ (1991). "The Postwar Productivity Spurt and Slowdown: Factors of Potential and Realisation," in G. Bell, ed., *Technology and Productivity: The Challenge for Economic Policy* (Paris: OECD), pp. 19-37.

ASCHAUER, DAVID A. (1989). "Is Public Expenditure Productive?" *Journal of Monetary Economics*, vol. 23 (March), pp. 177-200.

BAILY, MARTIN NEIL AND GORDON, ROBERT J. (1988). "The Productivity Slowdown, Measurement Issues, and the Explosion of Computer Power," *Brookings Papers on Economic Activity*, vol. 19 (no. 2), pp. 347-420.

__________ AND SCHULTZE, CHARLES L. (1990). "The Productivity of Capital in a Period of Slower Growth," *Brookings Papers on Economic Activity: Microeconomics 1990*, vol. 21, no. 3, pp. 369-420.

BALKE, NATHAN S., AND GORDON, ROBERT J. (1989). "The Estimation of Prewar GNP: Methodology and New Results," *Journal of Political Economy*, vol. 97 (February), pp. 38-92.

BAUMOL, WILLIAM J., BLACKMAN, SUE ANNE BATEY, AND WOLFF, EDWARD N. (1989). *Productivity and American Leadership: the Long View* (Cambridge MA: MIT Press).

BERNDT, ERNST R. AND TRIPLETT, JACK (1990). *Fifty Years of Economic Measurement: the Jubilee of the Conference on Research in Income and Wealth (*Chicago: University of Chicago Press for NBER).

BLANCHARD, OLIVIER J., AND QUAH, DANNY (1989). "The Dynamic Effects of Aggregate Demand and Supply Disturbances," *American Economic Review*, vol. 79 (September), pp. 655-73.

BORJAS, GEORGE J. (1994). "Long-run Convergence of Ethnic Skill Differentials: The Children and Grandchildren of the Great Migration," *Industrial Labor Relations Review*, vol. 7 (no. 2), pp. 553-73.

BRESNAHAN, TIMOTHY F., AND GORDON, ROBERT J., eds. (1997) *The Economics of New Goods*

(Chicago: University of Chicago Press for NBER).

DAVID, PAUL A. (1990). "The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox," *American Economic Review Papers and Proceedings*, vol. 80 (May), 355-61.

__________ AND WRIGHT, GAVIN (1999). "Early Twentieth Century Productivity Growth Dynamics: An Inquiry into the Economic History of `Our Ignorance'." Working paper, All Souls College, Oxford, April.

DE LONG, J. BRADFORD, AND SUMMERS, LAWRENCE H. (1991). "Equipment Investment and Economic Growth," *Quarterly Journal of Economics*, vol. 106 (May), pp. 445-502.

DENISON, EDWARD F. (1962). *The Sources of Economic Growth in the United States and the Alternatives Before Us* (New York: Committee for Economic Development), Supplementary Paper no. 13.

__________ (1979). *Accounting for Slower Economic Gorwth: The United States in the 1970s* (Washington: Brookings).

__________ (1985). *Trends in American Economic Growth, 1929-82* (Washington: Brookings).

DUMÉNIL, GÉRARD, AND LEVY, DOMINIQUE (1990). "Continuity and Ruptures in the Process of Technological Change," working paper, CEPREMAP, August.

FELDSTEIN, MARTIN S. AND ROTHSCHILD, MICHAEL (1974). "Towards an Economic Theory of Replacement Investment," *Econometrica*, vol. 42 (May), pp. 393-423.

__________ AND FOOT, DAVID K. (1971). "The Other Half of Gross Investment: Replacement and Modernization Expenditures," *Review of Economics and Statistics*, vol. 53 (February), pp. 49-58.

FORD, ROBERT, AND PORET, PIERRE (1991). "Infrastructure and Private-Sector Productivity," *OECD Economic Studies*, no. 17 (Autumn), pp. 63-89.

FRAUMENI, BARBARA M. (1999). "Productive Highway Capital Stock Measures," paper written under subcontract to Battelle Memorial Institute, Federal Highway Administration, Department of Transportation, January.

GOLDIN, CLAUDIA (1998). "America's Graduation from High School: The Evolution and Spread of Secondary Schooling in the Twentieth Century," *Journal of Economic History*, vol. 58 (June), pp. 345-74.

__________ AND KATZ, LAWRENCE F. (1999). "The Returns to Skill in the United States across the Twentieth Century," NBER working paper 7126, May.

__________ AND MARGO, ROBERT A. (1992). "The Great Compression: The Wage Structure in the United States at Mid-Century," *Quarterly Journal of Economics*, vol. 107 (February), pp. 1-34.

GORDON, ROBERT J. (1967). "Problems in the Measurement of Real Investment in the U.S. Private Economy." Ph. D. Dissertation, M.I.T.

__________ (1969). "$45 Billion of U.S. Private Investment Has Been Mislaid," *American Economic Review*, vol. 59 (June), pp. 221-38.

__________ (1990). *The Measurement of Durable Goods Prices* (Chicago: University of Chicago Press for NBER).

__________ (1997). "Is There a Tradeoff between Unemployment and Productivity Growth?" in D. Snower and G. de la Dehesa, eds., *Unemployment Policy: Government Options for the Labour Market* (Cambridge UK: Cambridge University Press), pp. 433-63.

__________ (1998). "Monetary Policy in the Age of Information Technology: Computers and the Solow Paradox," Paper presented to Bank of Japan conference, *Monetary Policy in a World of Knowledge-based Growth, Quality Change, and Uncertain Measurement*, June 19.

__________ (1999a). "U. S. Economic Growth Since 1870: One Big Wave?" *American Economic Review Papers and Proceedings*, vol. 89 (May), pp. 123-8.

__________ (1999b). "Has the `New Economy' Rendered the Productivity Slowdown Obsolete?" Unpublished working paper, Northwestern University, June.

GRILICHES, ZVI (2000). *Research and Development, Education, and Productivity: A Personal Retrospective (*Cambridge MA: Harvard University Press), forthcoming.

HATTON, TIMOTHY J. AND WILLIAMSON, JEFFREY G. (1992). "International Migration and World Development: A Historical Perspective," NBER Historical Paper no. 41, September.

JOHNSON, GEORGE, AND STAFFORD, FRANK (1992). "Models of Real Wages and International Competition," unnumbered University of Michigan working paper, July.

JORGENSON, DALE W. (1966). "The Embodiment Hypothesis," *Journal of Political Economy*, vol. 74 (February), pp. 1-17.

__________ (1990). "Productivity and Economic Growth," in Berndt-Triplett (1990), pp. 19-118.

__________, AND GRILICHES, ZVI (1967). "The Explanation of Productivity Change," *Review of Economic Studies*, vol. 34 (July), pp. 249-83.

KENDRICK, JOHN W. (1961). *Productivity Trends in the United States* (Princeton: Princeton University Press for NBER).

KIM, SUKKOO (1992). "Expansion of Markets and the Geographic Distribution of Economic Activities: The Trends in U. S. Regional Manufacturing Structure, 1860-1987," unnumbered UCLA working paper, October 14.

KLEINKNECHT, ALFRED (1987). *Innovation Patterns in Crisis and Prosperity: Schumpeter's Long Cycle Reconsidered* (London: Macmillan).

KUZNETS, SIMON (1961). *Capital in the American Economy: Its Formation and Financing* (Princeton: Princeton University Press for NBER).

MADDISON, ANGUS (1982). *Phases of Capitalist Development* (New York: Oxford University Press).

__________ (1987). "Growth and Slowdown in Advanced Capitalist Economies: Techniques of Quantitative Assessment," *Journal of Economic Literature*, vol. 25 (June), pp. 649-98.

__________ (1989). *The World Economy in the 20th Century* (Paris: OECD).

MCKINSEY GLOBAL INSTITUTE (1992). *Service Sector Productivity* (Washington: McKinsey & Company).

NELSON, RICHARD R., AND WRIGHT, GAVIN (1992). "The Rise and Fall of American Technological Leadership: The Postwar Era in Historical Perspective," *Journal of Economic Literature*, vol. 30 (December), pp. 1931-64.

NORDHAUS, WILLIAM D. (1982). "Economic Policy in the Face of Declining Productivity Growth," *European Economic Review*, vol. 18 (May/June), pp. 131-58.

__________ (1997). "Do Real-Output and Real-Wage Measures Capture Reality? The History of Lighting Suggests Not," in Bresnahan-Gordon (1997), 29-66.

ROMER, PAUL M. (1987). "Crazy Explanations for the Productivity Slowdown," *NBER Macroeconomics Annual 1987*, pp. 163-201.

__________ (1990). "Capital, Labor, and Productivity," *Brookings Papers on Economic Activity: Microeconomics 1990*, vol. 21, no. 3, pp. 337-67.

WILLIAMSON, JEFFREY G. (1992). "The Evolution of Global Labor Markets in the First and Second World Since 1830: Background Evidence and Hypotheses," NBER Historical paper no. 36, February.

WRIGHT, GAVIN (1990). "The Origins of American Industrial Success: 1879-1940," *American Economic Review,* vol. 80 (September), pp. 651-68.

Data Appendix

This appendix lists the sources of output and "standard" labor and capital input. The adjustments for changes in labor and capital composition and for variable retirement are described in the text and the notes to the tables. Sources of GOPO and highway capital are listed here.

BEA tables are cited by the number used in the Survey of Current Business, August 1998, and the most recent data are ratio-linked to earlier BEA sources for the same concept that sometimes use different table numbers.

Nonfarm Nonhousing Business Output

1870-1929: Kendrick (1961), Table A-III p. 298 (total output) less Table A-III p. 298, (government) less Table A-III, P298 (farm) less Table A-XV p. 320 (housing).

1929-96: BEA, Table 1.8.

Nonfarm Nonhousing Business Labor Hours

1870-1889: Kendrick (1961), Table A-XXII p.332 (total hours) less Table A-X p.312 (farm). Since the Kendrick data are based on decade averages, in order to get cyclical variation, Kendrick's numbers are fitted by ordinary least squared regression onto Balke-Gordon (1989) output.

1889-1948: Kendrick (1961), Table A-XXIII P.338

1948-96: BEA, Table 6.9C for nonfarm private domestic hours minus hours in real estate from Table 6.8C multiplied by hours per employee in the Finance, insurance, and real estate sector obtained as the ratio of Table 6.9C to Table 6.8C.

Nonfarm Nonhousing Business Capital

1870-1929 Equipment: Kendrick (1961) Table A-XVI p.323 (Equipment) minus Table III, p. 367 (Farm Equipment).

1929-1996 Equipment: BEA Fixed Reproducible Tangible Wealth CD-ROM, Table Tw2a, nonresidential equipment minus farm equipment.

1870-1929 Structures: Kendrick (1961) Table A-XVI P.323 (Nonresidential structures) minus Table III, p. 367 (farm structures). These are both interpolated from decade averages. Because of the unusual behavior of the Kendrick structures figures for 1890-1900, data from Raymond

Goldsmith were substituted instead.

1929-1996 Structures: BEA Fixed Reproducible Tangible Wealth CD-ROM, Table Tw2a, nonresidential structures minus farm structures.

GOPO (Government-owned, privately operated) Capital

1870-1925: It was assumed that most government owned privately operated capital in the early 1920's is merchant vessels built by U.S. shipyards in World War I, and so GOPO is set equal to zero prior to 1918.

1925-1988: BEA wealth data tape.

Highway Capital

1925-1996: Fraumeni (1999).

TABLE 1

Output, Inputs, and MFP for Non-farm Non-housing Business GDP, Annual Growth Rates over Selected Intervals, 1870-1996

Years	Output	Labor	Capital	MFP
1870-1891	4.41	3.56	4.48	0.39
1891-1913	4.43	2.92	3.85	1.14
1913-1928	3.11	1.42	2.21	1.42
1928-1950	2.75	0.91	0.74	1.90
1950-1964	3.50	1.41	2.89	1.47
1964-1972	3.63	1.82	4.08	0.89
1972-1979	2.99	2.38	3.46	0.16
1979-1988	2.55	1.09	3.35	0.59
1988-1996	2.74	1.74	2.26	0.79

Long-term Trend

Years	Output	Labor	Capital	MFP
1870-1913	4.42	3.24	4.16	0.77
1913-1972	3.14	1.28	2.07	1.60
1972-1996	2.75	1.71	2.98	0.62

Sources: See Data Appendix.

TABLE 2

Annual Percentage Growth Rates of Output, Inputs, and MFP, With and Without Composition Adjustments, for Non-farm Business GDP, 1950-1996

	1950-64	1964-72	1972-79	1979-88	1988-96
Output (Y)	4.35	4.23	3.60	3.14	1.98
Labor					
Hours (H)	0.99	1.64	2.18	1.85	1.16
Composition	0.40	-0.03	0.00	0.54	0.52
Quality-Adjusted (L)	1.38	1.61	2.18	2.39	1.67
Capital					
Stock (K)	2.91	3.82	3.23	3.31	1.74
Composition	0.85	1.29	1.23	1.45	0.59
Quality-Adjusted (J)	3.76	5.11	4.46	4.76	2.33
MFP					
Based on H and K	2.69	1.83	1.08	0.84	0.70
Based on L and J	2.23	1.54	0.75	0.04	0.11
Effect of Quality Adj.	0.46	0.28	0.32	0.80	0.59
Addenda:					
Y/H	3.36	2.59	1.42	1.29	0.83
Y/L	2.97	2.61	1.42	0.75	0.31
Y/K	1.44	0.41	0.37	-0.17	0.25
Y/J	0.59	-0.88	-0.85	-1.63	-0.35

Sources: Y, L, J, Adjusted MFP from *Multifactor Productivity Trends, 1995 and 1996*, BLS, Release USDL 98-187, May 6, 1998.

H, K, and composition effects provided in unpublished e-mails from Michael Harper of the BLS. MFP based on H and K was calculated by aggregating H and K using the same implicit weights as are used by the BLS to aggregate L and J.

TABLE 3

Elements of Denison's Quality Corrections to Labor Input, Annual Percentage Growth Rates, Total Economy, 1913-65

	1913-28	1928-50	1950-64	1964-72	1972-79
1. Employment	1.35	1.01	0.64	1.87	2.70
2. Potential hours per employee	-0.38	-0.75	-0.36	-0.63	-0.61
3. Hours of labor input (1+2)	0.97	0.36	0.28	1.24	2.10
4. Labor input (3+5)	1.36	0.78	0.46	1.43	2.23
5. Quality adjustment for hours (4-3)	0.39	0.42	0.18	0.19	0.14
6. Quality adjustment for education	0.57	0.62	0.60	0.67	0.75
7. Quality adjustment for age, gender	0.11	0.02	-0.06	-0.45	-0.47
8. Total quality adjustment (5+6+7)	**1.07**	**1.06**	**0.72**	**0.40**	**0.42**
9. Alternative education adjustment	0.49	0.48	0.54	0.71	0.84
10. Alt. total quality adjustment (7+9)	**0.60**	**0.50**	**0.48**	**0.25**	**0.37**
Elements of Education Adjustment	1910-30	1930-50	1950-64	1964-72	1972-76
11. Effect of increased years of education	0.30	0.38	0.43	0.56	0.67
12. Effect of Increased days per year of education	0.27	0.23	0.17	0.11	0.08
13. Total education adjustment	0.57	0.62	0.60	0.67	0.75

Sources: See next page.

Sources for Table 3

Sources for 1913-28 by line number:

1,2,4	Denison (1962), Table 5, p. 37.
6,7	Denison (1962), Table 11, p. 85
9	Line 11 divided by 0.6.
11,12	Denison (1962), Table 9, p. 72.

Sources for 1928-79 by line number (note that 1929 data in sources below are extrapolated backwards from 1929 to 1928 using sources for 1913-28 listed above):

1	Denison (1985), Table 3-1, p. 85, col. (1).
2	Denison (1985), Table 3-2, p. 86, col. (2)
5	Denison (1985), Table 3-1, p. 85, col. (9) divided by potential hours from the source of line 2.
9	Line 11 divided by 0.8.
11	Denison (1979), Table F-5, p. 169, col. (1).
13	Denison (1979), Table F-5, p. 169, col. (3).

TABLE 4

Elementary School Enrollment as a Share of Population Aged 5-14, and Illiterate Share of Total Population, Selected Years, 1870-1950

	1870	1890	1910	1930
1. Enrollment in Kindergarten and Grades 1-8 (thousands)	7481	12520	16898	21278
2. Population aged 5-14 (thousands)	8287	12465	16393	21855
3. Percent of Population Enrolled	90.3	100.4	103.1	97.4
4. Illiterate as Percent of Population aged 10 and over	11.5	7.7	5.0	3.0

Source: *Historical Statistics of the United States from Colonial Times to the Present,* Bureau of the Census, 1960. Line 1: series H226; line 2 series A72 plus A73; line 3 equals line 1 as a percent of line 2; line 4: series H408.

Note: a. 1871 rather than 1870.

TABLE 5

**Adjustments to Capital Input,
Annual Growth Rates over Selected Intervals, 1870-1996**

Years	Re-weight Equip. 3:1 (1)	Back-cast BLS Comp. Adj. (2)	Effect of Variable Retirement: Equip-ment (3)	Effect of Variable Retirement: Struc-tures (4)	Effect of Variable Retirement: Total (5)	Add GOPO (6)	Add High-ways (7)
1870-1891	0.03	0.06	-.--	-.--	-.--	-.--	-.--
1891-1913	0.04	0.07	-.--	-.--	-.--	-.--	-.--
1913-1928	0.12	0.21	-.--	-.--	-.--	-.--	-.--
1928-1950	0.38	0.68	0.85	0.61	0.66	0.13	0.17
1950-1964	0.42	0.85	-1.11	-0.66	-0.76	-0.06	0.37
1964-1972	0.74	1.29	-0.69	-0.60	-0.64	-0.09	-0.01
1972-1979	0.77	1.23	-0.48	-0.49	-0.49	-0.03	-0.32
1979-1988	0.20	1.45	0.00	0.11	0.06	-0.02	-0.27
1988-1996	0.41	0.59	0.48	0.19	0.40	0.00	-0.13
Long-term Trends							
Years							
1870-1913	0.03	0.07	-.--	-.--	-.--	-.--	-.--
1913-1972	0.37	0.68	-0.05	-0.01	-0.03	0.02	0.20
1972-1996	0.43	1.10	-0.02	-0.10	-0.07	-0.02	-0.24

Sources: See next page

Sources for Table 5

Sources by Column

(1) Equipment and structures data in 1992 dollars from same sources as Figures 1 and 2. Data shown in this column are the growth rate of the equipment and structures aggregate when each dollar of equipment capital is weighted 3.0 times one dollar of structures, minus the growth rate when equipment and structures are weighted dollar for dollar.

(2) 1948-96, unpublished BLS series obtained from Michael Harper. 1870-1948, extrapolated backwards by dividing the growth rate of column (1) by 0.56, which is the average ratio of column (1) to column (2) during 1950-79.

(3)-(5) See text and data appendix.

(6)-(7) See data appendix.

Notes: Data listed for 1913-72 in columns (3)-(7) refer to 1925-72.

TABLE 6

Summary of Input Adjustments, Selected Intervals, 1870-1996

Years	Standard Labor Input (1)	Comp-Adj. Labor Input (2)	Effect of Labor Adj. (3)	Standard Capital Input (4)	Comp-Adj. Capital Input (5)	Comp & Quant-Adj. Capital Input (6)	Effect of Capital Adj. (7)
1870-1891	3.56	4.05	0.49	4.48	4.53	4.53	0.05
1891-1913	2.92	3.42	0.50	3.85	3.92	3.92	0.07
1913-1928	1.42	2.01	0.59	2.20	2.41	2.52	0.32
1928-1950	0.91	1.41	0.50	0.66	1.34	2.28	1.62
1950-1964	1.41	1.81	0.40	2.94	3.79	3.52	0.58
1964-1972	1.82	1.86	0.04	4.15	5.44	5.02	0.87
1972-1979	2.38	2.40	0.02	3.46	4.69	4.10	0.64
1979-1988	1.51	1.99	0.48	3.27	4.56	4.31	0.96
1988-1996	1.35	1.93	0.58	2.23	2.90	3.19	0.96
Long-term Trends							
Years							
1870-1913	3.24	3.73	0.49	4.16	4.22	4.22	0.06
1913-1972	1.28	1.72	0.44	2.06	2.75	3.01	0.95
1972-1996	1.71	2.09	0.38	2.98	4.04	3.87	0.99

Sources by column:

(1)-(2) Table 2 and Table 3, line 10, plus text discussion for 1870-1913.

(3) Column (2) minus column (1).

(4) Same sources as Table 1.

(5)-(6) Table 5.

(7) Column (6) minus column (4).

TABLE 7

MFP for Non-farm Non-housing Business GDP, Annual Growth Rates for Selected Intervals, 1870-1996

Years	Standard Inputs (1)	Standard Capital, Labor Comp. Adjustment (2)	Labor and Capital Composition Adjustments (3)	L & K Comp. Adjustments and Capital Quantity Adj. (4)	Effect of all Adjustments (4)-(1)
1870-1891	0.54	0.22	0.20	0.20	-0.34
1891-1913	1.20	0.87	0.85	0.85	-0.35
1913-1928	1.43	1.03	0.96	0.93	-0.50
1928-1950	1.92	1.58	1.36	1.05	-0.87
1950-1964	1.59	1.32	1.04	1.13	-0.46
1964-1972	1.05	1.02	0.59	0.73	-0.32
1972-1979	0.25	0.24	-0.17	0.02	-0.23
1979-1988	0.73	0.41	-0.02	0.07	-0.66
1988-1996	0.82	0.43	0.21	0.12	-0.70
Long-term Trend					
Years					
1870-1913	0.88	0.55	0.53	0.53	-0.35
1913-1972	1.60	1.30	1.08	0.99	-0.61
1972-1996	0.62	0.37	0.01	0.07	-0.55

Sources: MFP calculated from standard and adjusted input series as listed in Table 6.

	PI^1	IP^2	*Scientific instruments*	*Difficult cases*
1850–59	0	1	0	0
1860–69	1	2	0	1
1870–79	1	5	0	0
1880–89	3	4	0	0
1890–99	0	2	0	0
1900–09	1	5	0	1
1910–19	0	4	0	1
1920–29	6	2	0	0
1930–39	14	4	2	6
1940–49	9	5	4	1
1950–59	2	8	3	4
1960–69	3	4	9	2

[1] *PI* = Product innovations (radically new products).
[2] *IP* = Improvement and process innovations.

Table 8

Types of Innovations in Ten-Year Periods

Source: Kleinknecht (1987), p. 66.