CAPITAL FORMATION AND TECHNOLOGICAL CHANGE IN UNITED STATES MANUFACTURING

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The present study represents an attempt to apportion increases in output per man-hour between increases in capital employed per man-hour and a somewhat nebulous constellation of forces referred to as "technological change." It is hoped that a quantitative estimate of the relative importance of these two factors in contributing to an increase in the average productivity of labor in the past will help policy-makers determine what proportion of our investment resources should be devoted to improving the technology, rather than to expanding existing types of capital equipment and structures.

My procedure is to examine the annual increases in output per man-hour of labor in the manufacturing sector of the United States economy between 1919 and 1955. I shall try to determine what proportion of these annual increases can be attributed to increases in capital input per man-hour, attributing the residual to technological change. The classification of causal forces is thus exhaustive, for technological change serves as a catch-all category. The implications of this will be discussed below.

As a point of departure, I shall employ the model developed by Robert Solow,1 which represents technological change as a shift in the aggregate production function. In its most general form, the production function can be written (using Solow's notation):

\[ Q = F(K, L; t) \]  

(1) where \( Q = \) output, \( K = \) capital input, \( L = \) labor input, and \( t = \) time. If, however, time can be factored out of equation (1), then the level of technology can be written as a multiplicative factor, so that we can write (Solow, op. cit., 312)

\[ Q = A(t) f(K, L). \]  

(2)

The function can be written in this form only if technological change is neutral, i.e., such as to leave the marginal rate of substitution between capital and labor unaltered at a given factor ratio. Now, our task is to devise a measure of technological change, i.e., of the shift in the production function over time, which requires the fewest assumptions regarding the actual form of the function. Solow has shown (op. cit., 312–13) that by assuming labor and capital to be paid according to their marginal products,2 we can write

\[ \frac{A}{A'} = \frac{q}{q'} \frac{k}{k'} \]  

(3)

where \( q = Q/L \) (a dot denoting a time derivative), \( w_K = \) the ratio of net profits to net income, \( k = \frac{K}{L}; \) and \( A/A' = \) the percentage rate of technical change. An index of technology for each year can be derived from the expression

\[ F(t+1) = F(t) \left[ 1 + \frac{\Delta F(t)}{F(t)} \right] \]  

(4)

setting \( F(0) = 1. \) The index so derived should indicate the extent to which the production function has shifted since the preceding year.

Where Solow's analysis was concerned with the nonfarm private sector of the economy, he suggested (op. cit., 312n) that a more appropriate study would deal with a narrowly defined production function, one in which inputs and outputs would be specifically enumerated. While this has not been attempted here, a step has been made in this direction in considering only the manufacturing sector. While it is obvious that the inputs and product outputs of the aggregate production function of this sector do not entirely comply with Solow's recommendations, it is advantageous, we believe, to limit the study to a sector producing physical goods.

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2 In fact, the assumption of competitive factor pricing together with exhaustive classification of inputs as capital or labor is equivalent to assuming a first-degree homogeneous production function (see Solow, op. cit., 313).
only, and that increased homogeneity of output is thereby achieved.

The output series (see Chart 1) refers to real output of the manufacturing sector of the United States economy, from 1919 to 1955. While a theoretically more appealing measure of output might be value added by manufacturing, which would be net of depreciation and would eliminate double-counting in aggregation, the available data relating to this magnitude are of dubious value, largely due to the difficulties involved in the measurement of depreciation, which depends to a much too great extent on the conventions pursued by accountants and on prevailing tax laws. It is assumed, in using gross output rather than some measure akin to value added, that the latter changes proportionately to the former, both secularly and cyclically; to the extent that this assumption is not borne out by the data, there will be an unknown bias in the results.

Labor input is measured in man-hours worked in the manufacturing sector. No attempt is made to allow for different grades of labor, for changes in the intensity with which the labor is applied, for changes in the composition of the labor force, nor for the increased importance of skills and education in more recent years. We have taken labor in terms of man-hours of some constant, or average, quality. This surely results in an understatement of the increase in man-hours worked, because it is beyond doubt that today's worker is better equipped intellectually, and possibly physically (due to better diets), than his temporal predecessor. It is debatable, though, whether this increase properly should be included as labor input or whether it is a form of stored-up capital; just as today's worker is better equipped with physical capital, so is he better supplied with mental capital as a result of the dual process of capital formation and technical progress.

Capital input refers to structures, equipment, and inventory actually in use rather than merely in existence. While we can, as a rule, get a reasonably good approximation to actual man-hours worked for years in which there is considerable unemployment as well as in full employment years, corresponding figures for the capital stock are not available. To what extent the figures for capital in existence represent idle structures and equipment rather than employed inputs, comparable to the labor figures, is a matter of speculation.

From the standpoint of the production function, our interest centers not on the ratio of capital in existence to labor, but on the ratio of capital in use to labor. The latter corresponds more closely to the notion of factor proportions in economic theory, while the former, insofar as it has any meaningful interpretation at all, denotes a sort of historical accident. To convert the raw capital data to what we are after, some measure of idle capacity must be devised. Although some attention has been devoted to the concept of capacity and its utilization in the post World War II years, no attempt was made, for earlier periods, to gauge the extent to which capital (in the manufacturing sector) was actually employed, so that no data are available relating to this issue. Nevertheless, an attempt

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* Joint Economic Committee, Productivity, Prices, and Incomes, 148.
* Joint Economic Committee, op. cit., 148.

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*The raw data for the years from 1929 to 1955 are from Donald G. Wooden and Robert C. Wasson, "Manufacturing Investment Since 1929 in Relation to Employment, Output, and Income," Survey of Current Business, XXVI (November 1956). For the years prior to 1929, few data relating to the capital stock in manufacturing were available, so a series was pieced together from a number of sources. The series for the entire period, giving the ratio of capital to man-hours worked, gives evidence of a strong upward trend, but is nevertheless marked by sharp cyclical instability. While the secular rise in the capital-labor ratio so measured probably represents a "real" phenomenon, in the sense that it signifies a changing composition of inputs in the aggregate production function, the cyclical variation does not necessarily signify such a change. There is good reason to believe that the cyclical variation represents for the most part idle capacity, which is included in the measurement of capital.
must be made to adjust the available data to remove the asymmetry caused by our labor figures referring to \textit{employed} labor, and our capital data relating to \textit{existing} capital.

One way would be to express both labor and capital inputs not in terms of actually employed factors, but in terms of existing resources. In years when both labor and capital are fully employed, the ratio obtained by this procedure would precisely correspond to that of employed capital to employed labor. When either factor is underemployed, however, the figures would deviate from those which are relevant to this study. In fact, use of this procedure is equivalent to making the assumption that labor and capital will suffer underemployment to the same extent, i.e., that the percentage of the labor force employed is equal to the percentage of the capital stock in use. This assumption is in fact made by Solow; his procedure is to multiply the capital stock, for each year, by the proportion of the labor force employed in that year. This, of course, leads to the same results as though he had merely used the ratio of existing capital to existing labor. While admitting that this adjustment is not ideal, Solow expresses the belief that the results which are based on it are probably better than had no adjustment for idle capacity been made (op. cit., 314). He seems to consider, that is, that the assumption that capital and labor are laid off in constant proportions during a recession is valid as a first approximation.

One must remember, however, that Solow’s figures for the capital stock in existence refer not to the economy as a whole, but to the nonfarm private sector. And there is some question whether one can speak of the percentage of the labor force employed, when referring to a sector of the economy. If the employment figures relate to the economy as a whole, then one must assume that the ratio of employed workers to total workers in the particular sector under consideration is identical with this ratio for the economy. Specifically, Solow must assume that the percentage of the nonfarm private labor force (whatever that means) that is employed is the same as the percentage of the over-all labor force that is employed; and it hardly seems likely that cyclical changes in employment will fall evenly on all sectors. Hence, there is some question whether one is justified in applying unemployment figures for the economy as a whole to a particular sector.

If, instead, a measure of unemployment for the sector in question is attempted, a conceptual difficulty is encountered. To refer to a nonfarm private labor force is in effect to assume absence of inter-sector labor mobility, an assumption which is contradicted by empirical evidence on cyclical variations in employment.

Let us grant, however, that this problem can be overcome, and that one is able to obtain a measure of the fraction of the total nonfarm private labor force which is employed, for each year. To postulate that this ratio corresponds to that of employed capacity to total capacity will lead to an \textit{over}-correction for idle capacity. This is most evident in a depression, when net disinvestment is occurring, so that the capital stock is diminishing in size. During this period, however, the “labor force” (in the nonfarm private sector) is increasing, both due to a secular influence and because during a depression more members of the household are often compelled to seek jobs. In the early years of the depression, then, a given number of employed workers constitutes a smaller percentage of labor force employment than during the preceding boom, when the labor force was smaller. This tends to overstate the amount of idle capacity. Due to net disinvestment, the capital stock itself is decreased during the recession, tending to further overstate the amount of idle capacity. The net result is that, for some early depression years, the ratio of employed capital to man-hours worked, according to Solow’s paper, is actually lower than in 1929, rather than higher, as one would expect. Most economists would assert that there is a tendency to substitute capital for labor during a depression. At most, one might assume, as Solow undoubtedly intended, that there are constant factor proportions in the short run, so that capital and labor will be laid off proportionately. But in this case the proper adjustment for idle capacity is to multiply the ratio of the number employed in the year in question to the labor force during the last full employment year, by the capital stock existing before net disinvestment occurred. This in effect will hold the capital-labor ratio constant throughout the period of under-
employment. Ideally, one would like to permit the capital-labor ratio to increase in the case of a prolonged period of underemployment, as in the 1930's; i.e., in the initial stages of the depression, the constant proportions assumption might serve as a first approximation to actual conditions, but after a year or two, it appears likely that some substitution of capital for labor will occur. This is to be expected because of the inflexibility of wage rates downward, as well as because of the limit set to the rate of net disinvestment. Possibly, after a still longer period of time, when capital in use is again equal to capital in existence, the capital-labor ratio might begin again to decline. We might expect this result in the late 'thirties (as well as during the war years).

The procedure employed in this paper to convert capital in existence to capital in use involves viewing the ratio of capital in use to labor in use as the product of two ratios: the capital-output ratio, and the output-labor ratio. (Of course, the relationship holds, by identity.) Changes in the capital-output ratio can be divided into two classes: those which have as their origin long-run forces in the economy, such as to lead to a secular change in the average productivity of capital (the reciprocal of the capital-output ratio), and those which consist of cyclical fluctuations in this ratio. It is our belief that while the latter may exist, they are of small enough magnitude to be safely ignored. By assuming that cyclical changes in the ratio of employed capital to output are non-existent, we are in effect maintaining that any deviation from the trend in the observed ratio of capital to output is spurious. Thus, a trend line was fitted (see Chart 2) by the method of least squares to the capital-output ratio figures, using full-employment years only. It was postulated that deviations from this trend represented, in the large, fluctuations in employment rather than real changes in the factor proportions in manufacturing. This seems reasonable, for the types of factors which determine the ratio of capital to output in the production function are forces which do not vary much from year to year, and hence can be considered negligible compared to the forces which bring about apparent changes in this ratio.

Having thus computed a trend for the capital-output ratio, we multiplied the observed changes in the output-labor ratio, which we accepted as being representative of the "true" changes, by the corresponding trend values of the capital-output ratio. The result was a cyclically adjusted series for the capital-labor ratio, as appears in Chart 3. The decision to use trend values of the capital-output ratio rather than fit a trend line directly to the capital-labor ratio observations was made on empirical grounds. The capital-output trend fitted the data better than did a capital-labor trend. The data suggested that deviations from the former trend were largely a result of the capital figures' reflecting idle capacity. The observations which were omitted were years with substantial unemployment of labor and war years; the former were substantially above the trend line, while the latter fell below the line. The observations which were actually employed represented a compromise in the sense that while some less-than-normal years were included, we felt that fewer observations would have made the least-squares line less meaningful. It should be pointed out that use of this method has not entirely solved the problem, for the curve dips in 1932-33, which runs counter to our earlier theoretical remarks concerning behavior of the capital-labor ratio in a depression.

The last series, property's share of net income originating in manufacturing, was obtained from two distinct series, one relating to labor income, the other to total net income originating in the

*No attempt was made to separate entrepreneurial income into wage and profit components for the years 1939-45. This source of labor income is believed to be relatively insignificant in the manufacturing sector.
sector. The ratio of labor income to total income, for each year, was subtracted from unity to obtain capital’s share. It is interesting to note that in two years, 1932 and 1933, labor income exceeded total net income, indicating an apparent net loss for capital. There is some doubt, however, whether capital’s share was in fact negative in these years; an alternative explanation would focus on the difference between “actual” depreciation of fixed capital and apparent depreciation, as represented in business records. (The income data have been adjusted for capital gains and losses.) It is wholly conceivable that, while accounting records indicated a loss to propertied interests, in fact such groups made a positive net gain based on a more “realistic” calculation of depreciation. If our hypothesis is correct, the series of capital’s share can be altered to convey more meaningfully the information we want, if depreciation is adjusted to reflect changes in income above and below the expected normal level. The result will be to increase net income in the depression years, hence increasing capital’s share.

We have not undertaken this adjustment, but have preferred to think of capital’s share, not in terms of continually changing values, but in terms of a mean value expressing capital’s contribution to output for the period as a whole. We are interested not in capital’s share per se, but only insofar as it serves as an approximation to capital’s contribution to output. Because the marginal productivity doctrine expresses only a tendency rather than an instantaneous adjustment, then even were profits negative, a negative marginal product of capital is not implied. The marginal product can be zero, if capital is underemployed, but because we are working with a continuous production function, this result is not to be expected. To avoid this difficulty, we have chosen to represent capital’s contribution to output for the entire period, i.e., its marginal product divided by its average product, by the unweighted arithmetic mean of the annual ratios of profits to net income. Equation (2) can now be rewritten

$$\frac{\dot{A}}{A} = \frac{q}{\dot{q}} - \frac{\dot{k}}{k}.$$  

(This is of course equivalent to the assumption that (2) is approximated by a Cobb-Douglas function. We are not however estimating the coefficients of the function.)

From our series of output per man-hour, capital input per man-hour, and the mean value of capital’s share, we calculated $\Delta A/A$ letting $t$ range from 19 to 55, and setting $A(19) = 1$, we derived the entire $A(t)$ series, shown in Chart 4. From the chart the technology index in 1955 is seen to be 2.9. This can be interpreted to mean that the production function has shifted by a factor of 2.9, so that at the prevailing capital-labor ratio, 2.9 times the output per man-hour can be produced in 1955 as in 1919.

Turning back to the output per man-hour figures in Chart 1, we note that the 1955 figure is 3.2 times the value for 1919. Letting the ratio of output per man-hour in 1955 to that in 1919 equal $m$, and the ratio of the index of technology in 1955 to that in 1919 equal $s$, then the ratio $s/m$ should indicate what proportion of the increase in output per man-hour is attributable to technical advances. The value of $s/m$ turns out to be .9, so we may say that roughly ninety per cent of the increase in output per man-hour is due to technical change.

Inspection of the technology index expressed as a time series reveals that the path of technical change, though containing some irregularities, nevertheless is strongly dominated by a steady upward trend. The trend, which suggests either a linear relationship or an exponential, is interrupted five times, during two of which there is a distinguishable downturn. The first occurs between 1931 and 1932, the other between 1941 and 1946, the two having in common the fact that they represent exceedingly “abnormal”
periods. The minor irregularities, i.e., temporary changes in the first derivative of the function, occur in 1922–23, 1935–37, and 1950–51, each denoting a recovery period. It is entirely possible that during a recovery our index of capital tends to overstate the actual capital input, so that the index of technology is understated, hence leading to its apparent leveling off. The large dip in the curve in the 1930's may represent the fact that gross investment in this period has been tremendously curtailed, so that there is no way to put into effect whatever inventions were developed. Also, during the depression, there may have been little incentive to innovate; while the interruption during the war probably reflects the fact that during this emergency period there was little scope for replacing obsolescent equipment. Both results are what we should expect.

It was found that both linear and exponential functions gave excellent fits to the data, the former yielding an $r^2$ of .97, the latter a value of .96. There is thus little empirical basis on which to choose between the two, though expressing technological change as an exponential function of time may have more intuitive appeal. Estimating the coefficients of (6) in $A(t) = \beta_0 + \beta_1t$ we found $\beta_0 = .1577$ and $\beta_1 = .0254$.

A comparison of the results of this paper with those obtained by Solow brings out several interesting points. First, both papers attribute 90 per cent of the increase in output per man-hour to technological change.\(^7\) Solow's $F(t)$ series was considerably less regular than ours, containing more jagged edges. This is very likely due to his method of adjusting capital figures. Also, the acceleration of technical change in the 1930's, according to his paper, may well be attributable to the same factor. Both Solow's paper and the present one exhibit a rate of technical advance, which though not in any sense uniform, is nevertheless persistent; and the papers concur in granting to changes in the level of technology a decisively major role in bringing about increases in productivity.

That such a large proportion of the increase

\(^7\) In fact, Solow's initial figure was 87.5 per cent, but this is later altered upon correcting computational errors. See W. P. Hogan, "Technical Progress and Production Functions," this Review, xL (November 1958).
time, in relation to output), the rate of net investment depends on the rates of deterioration and of obsolescence. The former is largely a technological consideration, while the latter is economically determined. Obsolescence is greater the larger the rate of technological change; consequently a larger proportion of gross investment will be expended in replacement of existing equipment when there is a rapid rate of innovation. There is thus a link between innovation and capital formation such that the latter is defined partly in terms of the former; so that while we have found technological change of great importance in increasing productivity, further research would be needed to predict, for example, the effect on per-capita output of alternative rates of capital accumulation and of technical change.

The foregoing qualifications do not alter the fact that, conceptually at least, a distinction can be made between innovation and capital formation, and that this study has reinforced the findings of Robert Solow and Solomon Fabricant, in finding technical change far more important than capital formation. In view of these findings, policy-makers may wish to concern themselves more with the variables which govern the rate at which innovations are injected into the economic system than with the variables which determine the rate at which additions are made to the capital stock. Such issues as expenditure by business on research and the policies of firms regarding the replacement of obsolescent equipment will perhaps be deemed more important than the rate of net investment. (We believe that one justification for having undertaken this study lies in this very guidance.)

Aside from the policy question, the present inquiry is, we hope, of some theoretical interest. That technical improvements are of such relatively great importance should be no small cause of concern, and possibly embarrassment, to economists, who have traditionally treated technology as exogenous in the theory of production. Current procedure is to include capital, labor, and land, or sub-classification thereof, as inputs, subsuming in the functional form the technological relationship between these inputs and the product outputs. Changes in the technology are represented by shifts of the curve, i.e., certain parameters are changed in magnitude. Some writers have protested against the traditional theory of production because (1) this theory appears better suited to a world where labor and land are the only inputs, but becomes unclear upon the introduction of the third factor of production, capital; and (2) strictly speaking, the classical model of production is a static model based on the assumption of a “given state of technological knowledge,” which while perhaps useful in the Ricardian era, is of limited applicability today due to the exaggerated influence of technical progress on aggregate output in our own economy. It is, indeed, a source of concern, when the factors which are explicitly considered in the model account for only ten per cent of the increase in output per man-hour, the remainder being attributed to an exogenous force, one which is little understood, and about which we are able to offer little explanation.

There is little justification for considering the rate of invention as exogenous, for expenditure on research will certainly affect this variable, and such expenditure is influenced in turn by other economic magnitudes. There is still less justification for considering the rate of innovation as exogenous, for given the rate of invention, the rate at which new ideas are adopted is a function of such variables as the level of aggregate economic activity, the profit rate, the age composition of the capital stock, etc. Economists would do well to consider these variables as determining, at least in part, the rate at which technical changes occur.

The present paper offers evidence to support the view that technological change is of overriding importance in bringing about increased labor productivity over time and that there is a need for economists to shift emphasis from the theory of capital to the theory of technical progress, as an explanation of the growth in aggregate output.

*In “Resources and Output Trends in the U.S. Since 1870,” American Economic Review, xxi (May 1956), Fabricant has estimated the relative contribution of technological change as approximately 30 per cent, for the period 1871 to 1951.