Volume Title: Fifty Years of Economic Measurement: The Jubilee of the Conference on Research in Income and Wealth

Volume Author/Editor: Ernst R. Berndt and Jack E. Triplett, editors

Volume Publisher: University of Chicago Press

Volume ISBN: 0-226-04384-3

Volume URL: http://www.nber.org/books/bern91-1

Conference Date: May 12-14, 1988

Publication Date: January 1991

Chapter Title: The Measurement of Capital

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Chapter URL: http://www.nber.org/chapters/c5974

Chapter pages in book: (p. 119 - 158)

4 The Measurement of Capital

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> The measurement of capital is one of the nastiest jobs that economists have set to statisticians.
>
> (Hicks 1981b, 204)

The theory of capital is one of the most difficult and contentious areas of economic theory. From Karl Marx to the Cambridge controversies, there has been an ongoing disagreement among economists as to what capital is and how it should be measured.[1] Economists have variously defined capital as congealed labor, as deferred consumption, as the "degree of round-a-boutness," as a stock of durable commodities, or as a flow of factor services. There is also disagreement about whether capital can be aggregated into a single measure, and, even within the relatively hospitable confines of neoclassical theory, exact aggregation is known to be problematic.

This presents the practical economist with something of a dilemma since many interesting economic problems require a measure of capital. How, for example, are we to understand the process of economic growth if we cannot agree on how to measure one of the potentially most important factors influencing that process? What can we say about such important issues as the productivity slowdown of the 1970s and why growth rates differ across countries? These issues are too important to ignore, and estimates of capital, income, and wealth, however imperfect, must somehow be developed in order to get on with the larger tasks at hand.

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The author would like to thank Dale Jorgenson, Frank Wykoff, Ingmar Prucha, and Robert M. Schwab for their valuable comments on earlier drafts of this chapter. Judy Xanthopoulos provided invaluable research assistance.

The Conference on Research in Income and Wealth and, more generally, the National Bureau of Economic Research have been at the forefront of the development process. Many of the 50-odd volumes of the Studies in Income and Wealth series are devoted, in whole or in part, to issues of capital measurement. These studies, by such pioneers as Kuznets, Goldsmith, Stigler, and Kendrick, have laid the conceptual foundation for many of the measurement procedures used today; they provide statistical series that are still in use. It is therefore fitting that the commemoration of the fiftieth anniversary of the conference should include an essay on the current state of the art of capital measurement.

I undertake this task with the recognition that the subject is too large to be easily encompassed by a single essay. I have therefore chosen to limit my focus largely to depreciable assets used in the business sector, although the discussion will sometimes stray across this boundary and many of the results discussed will be applicable to other sectors and other types of capital. I will also allocate the bulk of my space to a sketch of the *theory* of capital measurement. This choice reflects, in part, the historical objective of the conference in bringing together measurement theory and practice. However, it also reflects the too often ignored need for theoretical consistency in the construction of data as, for example, when capital stocks are estimated using one assumption about depreciation and estimates of capital income are based on another assumption.

The chapter is organized into two major parts. The first outlines the theory of capital measurement and is divided into six sections. The first three sections cover measurement and valuation of a single homogeneous type of capital, while the following section extends the analysis to the case of many capital goods. The final two sections deal with the issues of quality change and capacity utilization. The second part of the paper examines some practical issues in the measurement of capital. The scope and nature of existing estimates and procedures are reviewed, and then critiqued in light of the theory of the preceding sections.

4.1 Applied Capital Theory

Two aspects of capital (including human capital) differentiate it from a primary input like labor: capital is a produced means of production, and capital is durable.[2] The first aspect is the primary source of the Cambridge controversy in pure theory, but the latter causes much of the actual difficulty in measuring capital. Durability means that a capital good is productive for two or more time periods, and this, in turn, implies that a distinction must be made between the value of using or renting capital in any year and the value of owning the capital asset.

This distinction would not necessarily lead to a measurement problem if the capital services used in any given year were paid for in that year, that is, if all capital were rented. In this case, transactions in the rental market would fix the price and quantity of capital in each time period, much as data on the price and quantity of labor services are derived from labor-market transactions. But, unfortunately, much capital is utilized by its owner and the transfer of capital services between owner and user results in an implicit rent typically not observed by the statistician. Market data are thus inadequate for the task of directly estimating the price and quantity of capital services, and this has led to the development of indirect procedures for inferring the quantity of capital, like the perpetual inventory method, or to the acceptance of flawed measures, like book value. In this section, I begin by reviewing the strengths and weaknesses of these indirect methods, starting with the easiest case of a single (relatively) homogeneous type of capital and proceeding to more difficult cases later on.

4.1.1 The Single Homogeneous Good Case

We start by assuming that the statistician can observe the quantity of new capital added to the stock in each year, I_t, but not the amount of capital stock itself, K_t (we will ignore, for the moment, the distinction between stocks and flows). The problem is to infer the latter from the former, recognizing that part or all of past additions to the stock may have been retired from service and that the services yielded by older capital may be less productive. The problem, in essence, is to develop a reasonable procedure for adding up the individual I's into an estimate of K.

The perpetual inventory method is one attempt at solving this problem. In the perpetual inventory method, investment from all surviving vintages is weighted by a number, ϕ_{t-v}, between zero and one to allow for the possibility that older capital is less productive than its newer counterparts, and the weighted investment series is then added up to form a total capital measure. The result may be expressed by the following equation:

$$(1) \qquad K_t = \phi_0 I_t + \phi_1 I_{t-1} + \ldots + \phi_T I_{t-T} ,$$

where $\phi_0 = 1$, and where $v = t - T$ is the date of the oldest surviving vintage.[3] Since one unit of vintage v capital is treated as the equivalent of only ϕ_{t-v} units of new capital, the stock K_t has the natural interpretation as the number of units of new investment needed to equal the productive capacity of past investment ($I_t, I_{t-1}, I_{t-2}, \ldots, I_{t-T}$). Or, in other words, equation (1) defines the capital stock in *efficiency* units.[4]

It is evident from equation (1) that estimates of the efficiency weights ϕ_{t-v} are needed to complete the measurement of K given data on the I's. However, it is not evident how the ϕ's are determined or how they can be estimated. One possibility is to assume that the ϕ's are inherent in the nature of capital. For example, a block of dry ice (or a bar of soap) may shrink at a rate proportional to surface area, so that older blocks are proportionately smaller than new blocks. In this case, old and new capital can be thought of as differing by a constant ϕ and the aggregate K can be seen as a physically homogeneous entity. Much the same can be said of light bulbs, since older vintages shine as brightly as new ones (until they fail), and a homogeneous K can be formed by assigning ϕ a value of one for all surviving vintages and adding up past investment.

The efficiency sequence can be determined, in both examples, from the nature of the good itself—dry ice is homogeneous, and thus old and new units are prefect substitutes up to some constant ϕ. If the same were true of all capital, then the measurement problem would be reduced to determining the relative technological "size" of new and used capital. Unfortunately, most capital does not accommodate this kind of measurement because older machines are typically neither physically smaller nor dimmer than their newer counterparts. Nevertheless, such machines may be less efficient because of increased downtime, higher maintenance requirements, or reduced speed or accuracy, or they may embody less advanced technology than new machines.

The possiblity that older vintages of capital may be less productive suggests that the ϕ sequence might more usefully be defined in terms of the production process itself. The ϕ's could be thought of as relative marginal products, and the resulting K may be interpreted as the ability of the surviving vintages $(I_t, \ldots, I_{t-T})$ to produce output. This approach does not rule out the "dry ice" case of inherent productivity differences, but does allow for the possibility that relative efficiency is a matter of economic choice and that different technologies may imply different ϕ's for the same type of capital. Or, in other words, the capital aggregation depends on the nature of the technology and on market behavior.

This link between aggregate capital and the production function was developed by Leontief (1947a, 1947b), Solow (1960), and Fisher (1965). The basic issue involves the conditions under which different vintages of capital and technology can be collapsed into an aggregate production function defined with respect to an aggregate measure of capital. It is assumed that each vintage of capital can be combined with labor via its own production function to produce output

$$(2) \qquad Q_{t,v} = f^{v}(L_{t,v}, I_v) \quad v = t, t-1, t-2, \ldots, t-\mathrm{T},$$

where $Q_{t,v}$ is the output produced by capital of vintage v and $L_{t,v}$ is the homogeneous labor applied to that capital. The production functions are allowed to differ in order to incorporate the possibility of technical change, that is, old machines are installed with the technology prevailing in year v. Output from all vintages is assumed to be homogeneous and aggregate output is thus the sum of the $\mathrm{Q}_{t,v}$, that is,

$$(3) \qquad Q_t = \sum_{v} Q_{t,v} = \sum_{v} f^v(L_{t,v}, I_v).$$

The aggregation problem is to write (4) as

$$(4) \qquad Q_t^* = F[L_t, K(I_t, \ldots, I_{t-T})],$$

where $L_t = \sum_{v} L_{t,v}$, Q_t^* is the maximum output that can be produced assuming labor is optimally allocated among vintages, and $K(\cdot)$ is independent of L. Necessary and sufficient conditions for this capital aggregation are given by the Leontief theorem, which states that the marginal rate of substitution between any pair of inputs within the aggregate must be independent of the inputs outside the capital aggregate:

$$(5) \qquad \frac{\partial}{\partial L_t}\left[\frac{\partial Q^*/\partial I_v}{\partial Q^*/\partial I_\xi}\right] = 0 \quad \text{for all } v, \xi = t, \ldots, t-T,$$

or

$$(6) \qquad \frac{\partial}{\partial L_t}\left[\frac{\partial f^v/\partial I_v}{\partial f^\xi/\partial I_\xi}\right] = 0 \quad \text{when } f_L^v = f_L^\xi; \quad v, \xi = t, \ldots, t-T.$$

Fisher (1965) shows that, under constant returns to scale, this condition requires that differences between vintages must be expressible as

$$(7) \qquad f^v(L_{t,v}, I_v) = f(L_{t,v}, b_{t-v} I_v).$$

That is, the technology must be such that the difference between the productivity of old and new capital is a fixed constant depending only on vintage.[5] Or, as Hall (1971) puts it: "In vintage production functions with constant returns, the basic theorem of capital aggregation establishes that a capital aggregate exists if and only if the marginal product of capital of age τ at time t has the fixed ratio . . . to the marginal product of new capital at time t" (242). In our notation, this amounts to

$$(8) \qquad \frac{\partial Q^*/\partial I_v}{\partial Q^*/\partial I_t} = \phi_{t-v}, \quad v = t, t-1, \ldots .$$

Thus, formal aggregation theory leads us back to the perpetual inventory method of capital aggregation. Old capital enters the production process as if it were equivalent to a smaller amount of new capital—as in the case of dry ice.

There is little reason to believe that real-world technologies exhibit the separability required by the Leontief conditions. Moreover, even if aggregation over vintages were possible, there is no guarantee that the aggregated production function (4) would be a valid representation of the technology of an entire industry or industrial sector. Further conditions are required for aggregation over establishments within an industry, for example, the Gorman conditions—and these are extremely restrictive.[6]

Capital aggregation must therefore be regarded as approximate, or as applying in exact form only under exceptional circumstances. Applied economists can either accept this unfortunate situation or try to work directly with a disaggregated form of their model. But as Fisher (1965) notes, "Estimation of the parameters of the production function using the various types of capital [i.e., vintages] is at best a nonlinear estimation problem of considerable magnitude, and may, in fact, be insoluble since it requires the *explicit* solution of the labor allocation problem in terms of parameters to be estimated and the quantities of the various capital goods" (263; emphasis added).

4.1.2 Asset Efficiency

The measurement of capital stocks using the perpetual inventory method requires an estimate of the efficiency sequence $(\phi_0, \phi_1, \ldots, \phi_T)$. Unfortunately, this sequence is rarely observed directly, and indirect methods of inferring relative asset efficiency are necessary. One possibility is to exploit the assumed relationship between ϕ and relative marginal products developed in (8). This possibility is pursued in the following section. Another approach is to estimate the relative efficiency indirectly by assuming that the ϕ's follow some pattern that depends on an observable useful life T.

Several efficiency patterns have been discussed in the literature on estimating ϕ. Of these patterns, the one-hoss shay pattern commands the greatest intuitive appeal. Casual experience with commonly used assets suggests that most assets have pretty much the same level of efficiency regardless of their age—a one-year-old chair does the same job as a 20-year-old chair, and so on.[7] Thus, it is frequently assumed that ϕ takes the following form:

$$(9)\quad \phi_0 = \phi_1 = \ldots = \phi_{T-1} = 1, \quad \phi_{T+\tau} = 0 \quad \tau = 0, 1, 2, \ldots.$$

In the one-hoss shay form, assets retain full efficiency until they completely fall apart (hence the term "one-hoss shay," although "light bulb" efficiency decay would be equally apt). In this form, the efficiency sequence is completely characterized by the useful life T, and the measurement problem reduces to the problem of estimating T.

The straight-line efficiency pattern is the second commonly used form. Under straight line, the efficiency function takes the form

$$(10)\quad \begin{aligned} &\phi_0 = 1, \phi_1 = 1 - \frac{1}{T}, \phi_2 = 1 - \frac{2}{T} \ldots, \\ &\phi_{T-1} = 1 - \frac{T-1}{T}, \quad \phi_{T+\tau} = 0 \qquad \tau = 0, 1, 2, \ldots. \end{aligned}$$

In the straight-line form, efficiency decays in equal increments every year, that is,

(11) $$\phi_{\tau-1} - \phi_{\tau} = \frac{1}{T} \quad \tau = 1, \ldots, T-1.$$

As with the one-hoss shay form, T completely determines the efficiency pattern. The popularity of the straight-line pattern reflects the widely used convention, borrowed from *depreciation* accounting, that assets should be amortized in equal increments over a useful life.

Geometric decay is the third widely used pattern. In this form, productive capacity decays at a constant rate δ, that is,

(12) $$(\phi_{\tau-1} - \phi_{\tau})/\phi_{\tau-1} = \delta,$$

implying

(13) $$\phi_0 = 1, \phi_1 = (1-\delta), \phi_2 = (1-\delta)^2, \ldots, \phi_{\tau} = (1-\delta)^{\tau}, \ldots.$$

The geometric form is widely used in theoretical expositions of capital theory because of its simplicity. But, while it enjoys empirical support from studies of used capital prices, it is nevertheless regarded by some (e.g., Harper 1982) as empirically implausible because of the rapid loss of efficiency in the early years of asset life (e.g., 34% of an asset's productivity is lost over four years with a 10% rate of depreciation). Moreover, assets are (implausibly) never retired, so that the efficiency sequence is no longer a function of the useful life T. However, δ is frequently derived from published estimates of T using the double declining balance formula, $\delta = 2/T$, obtained from tax accounting, although other declining balance formulae are also used.[8]

We have thus far taken the date of retirement T to be the same for all assets in a given cohort (all assets put in place in a given year).[9] However, there is no reason for this to be true, and the theory is readily extended to allow for different retirement dates. A given cohort can be broken into components, or subcohorts, according to date of retirement and a separate T assigned to each. Each subcohort can then be characterized by its own efficiency sequence $\phi^{(i)}$, which depends among other things on the subcohort's useful life T_i. The contribution to total capital at time t made by a cohort of vintage v is the sum over the subcohorts of that vintage

(14) $$\sum_i \phi_{t-v}^{(i)} I_v^{(i)}.$$

The stock of capital at time t is then equal to

(15) $$K_t = \sum_i \phi_0^{(i)} I_t^{(i)} + \ldots + \sum_i \phi_{t-v}^{(i)} I_v^{(i)} + \ldots.$$

Letting $\omega_v^{(i)} = I_v^{(i)}/I_v$ be the weight of the ith subcohort in vintage v investment, this can be written as

(16) $$K_t = \left(\sum_i \phi_0^{(i)} \omega_t^{(i)}\right) I_t + \ldots + \left(\sum_i \phi_{t-v}^{(i)} \omega_v^{(i)}\right) I_v + \ldots.$$

When the subcohort weights ω are stationary over time, that is, independent of ν, (16) reduces to (1). In this case, the efficiency weight ϕ in (1) can be interpreted as the average efficiency of the investment in the cohort, and it thus captures both in-place loss of efficiency and efficiency loss due to retirement.

The average efficiency function of a cohort can be quite different from the individual efficiency functions $\phi^{(i)}$. Every $\phi^{(i)}$ can have the one-hoss shay form, while $\omega^{(i)}$ can be such that the average efficiency decline is geometric. This point has important consequences for the measurement of ϕ: as noted, the intuition that suggests that assets decay according to the one-hoss shay pattern is based on the observation of the individual $\phi^{(i)}$. But equation (16) implies that the extension of this intuition to an entire cohort of assets may involve a fallacy of composition in which each asset in the cohort follows one pattern but the cohort as a whole follows a different pattern.

Two final points should be noted before leaving the subject of efficiency functions. First, the early literature on capital measurement distinguished between net and gross capital stock. The net stock is defined as our (1) or (16) (we will largely ignore the distinction throughout the rest of this part of the paper). The gross stock is defined by

$$(17) \qquad K_t^G = I_t + I_{t-1} + \ldots + I_{t-\tau},$$

in the special case when all assets are assumed to be retired at the same point in time, or by the more general form

$$(18) \qquad K_t^G = \Omega_0 I_t + \Omega_1 I_{t-1} + \ldots + \Omega_T I_{t-T},$$

when retirements are distributed over time and Ω_τ is the (stationary) proportion of assets surviving to time τ.

Estimates of gross capital stock are commonly published along with estimates of the net stock (e.g., U.S. Department of Commerce 1987), and gross stocks are used in some analyses of productivity change.[10] However, it is clear from the separability condition of (18) that $\phi_{t-\nu}$ is defined with respect to relative marginal products, so it is the "net" measure of capital that is consistent with the production function $Q_t = F(L,K)$. That is,the net stock K_t, along with labor L_t, produces gross output Q_t, and the gross stock of capital is consistent with the production function only when the efficiency sequence is one-hoss shay, (9). But, in this case, net and gross stocks are the same, and the argument in favor of the gross capital stock is really an argument that the net stock *must* be one-hoss shay regardless of empirical evidence about the ϕ's.

Finally, it is important to emphasize a point made by Feldstein and Rothschild (1974): there are limitations to the use of any perpetual inventory method based on the procedures for estimating ϕ discussed in this section. For example, we have assumed that firms are not free to retire old capital as economic conditions dictate, maintenance and repair activities do not influence the ϕ's, and a higher rate of utilization does not cause asset efficiency to decline more rapidly. Each assumption is rather dubious, and a more complete model would recognize the endogeneity of (ϕ_0, ϕ_1, ϕ_2, . . .) via these effects (albeit at the cost of vastly complicating the analysis).

4.1.3 Asset Valuation and Depreciation

The preceding sections have dealt with the problem of measuring the quantity of capital. We now turn to the corresponding problem of measuring the wealth associated with the physical quantity of capital K_t. While the value of an asset is clearly related to that asset's productivity, the exact nature of the relationship is far from obvious and is the source of much confusion in the literature on capital measurement.

In competitive equilibrium, the cost of producing an asset is equal to the value of owning the asset, which, in turn, is equal to the present value of the expected rents (user costs) generated over the life of the asset. For a newly produced asset, this relationship takes the form

$$(19) \qquad P^I_{t,0} = \sum_{\tau=0}^{\infty} \frac{P^K_{t+\tau,\tau}}{(1+r)^{\tau+1}},$$

where $P^I_{t,0}$ is the equilibrium purchase price of a new asset at time t, the term $P^K_{t+\tau,\tau}$ is the expected annual gross income generated by the asset when it is τ years old (in year $t + \tau$), and r is the nominal rate of interest at which the income flows are discounted (this is assumed constant for simplicity).[11]

The situation for vintage assets is analogous, except that the supply of vintage assets is inelastic over the range of prices in which vintage assets remain in service.[12] Thus, the equilibrium purchase price is

$$(20) \qquad P^I_{t,s} = \sum_{\tau=0}^{\infty} \frac{P^K_{t+\tau,s+\tau}}{(1+r)^{\tau+1}}, \quad s = 1, 2, 3, \ldots,$$

where $s = t - v$ denotes asset age. This expression is a generalization of (19) and indicates that the value of an asset of any vintage is equal to the remaining value of the gross income, or rent, associated with the asset.

While equation (20) says nothing about asset efficiency, there is an indirect relationship arising from cost minimization. When rental markets exist for capital of all vintages, cost minimization implies that capital of each vintage will be rented up to the point that the value of its marginal product is equal to the rental price. Thus, the marginal rate of substitution between vintage v capital and new capital is equal to the corresponding ratio of the rental prices:

$$(21) \qquad \frac{P^K_{t,s}}{P^K_{t,0}} = \frac{\partial Q/\partial I_v}{\partial Q/\partial I_t} = \phi_s, \quad s = 1, 2, \ldots,$$

where the second equality follows from (8). Equation (21) states that the relative efficiency parameter, ϕ_s, can be interpreted as a ratio of relative rental values as well as the ratio of relative productive efficiencies. Thus, there is the following symmetry between prices and quantities: $I_{v,s} = \phi_s I_{v,0}$ and $P^K_{t,s} = \phi_s P^K_{t,0}$.

This symmetry implies that the rental price of vintage v capital is ϕ_s times the rental price of new capital. The asset price, $P^I_{t,s}$, in (21) can therefore be written in terms of the relative efficiency sequence and the rental price of new assets:

$$P^I_{t,s} = \sum_{\tau=0}^{\infty} \frac{\phi_{s+\tau} P^K_{t+\tau,0}}{(1+r)^{\tau+1}} \quad s = 1, 2, \ldots . \tag{22}$$

This expression links asset valuation to asset efficiency. It has been derived in the case in which rental markets exist, but is also valid for the case in which capital is utilized by its owner. Indeed, (22) can be "solved" to obtain an expression of the implicit rent in terms of the other variables of (22).

$$P^K_{t,s} = [r - \rho_{t,s} + (1+\rho_{t,s})\delta_{t,s}]P^I_{t,s}, \quad s = 0, 1, 2, \ldots , \tag{23}$$

where

$$\rho_{t,s} = \frac{P^I_{t+1,s+1}}{P^I_{t,s+1}} - 1, \tag{24}$$

is the expected "inflation" in the vintage asset price occurring between years t and $t + 1$, and

$$\delta_{t,s} = -\left[\frac{P^I_{t,s+1}}{P^I_{t,s}} - 1\right], \tag{25}$$

is the rate of decline in the asset price with age s (or, more accurately, the decline in price as vintage v capital becomes like vintage $v - 1$ capital). Equation (23) thus has a straightforward interpretation: when assets are owner utilized, the equilibrium value of the implicit rental must cover the real opportunity cost of an investment of value $P^I_{t,s}$ as well as the loss in asset value as the asset ages. In practice, elaborations of this formula, based on Jorgenson (1963) and Hall and Jorgenson (1967), are used to impute a value of the rental price and thus the value of the marginal product of capital.

The term δ deserves attention in its own right, since it can be shown to be the rate of economic depreciation. Hicks (1946) defines income as the maximum amount that can be spent during a period while maintaining capital values intact; economic depreciation is then defined as the sum of money, in constant dollars, that needs to be set aside in order to maintain that capital value in real terms. In our notation, the Hicksian definition of depreciation is equivalent to $P^I_{t,s} - P^I_{t,s+1}$. This in turn implies that depreciation is equal to $\delta_{t,s}P^I_{t,s}$ by (25), which leads to the conclusion that the variable δ is the Hicksian rate of economic depreciation. When $\rho \neq 0$, a revaluation adjustment is necessary but essentially the same interpretation carries over.

Following Jorgenson (1973), equation (25) can also be used to link economic depreciation to changes in asset efficiency. Rearranging terms in (25) yields

$$(26)\qquad \delta_{t,s} P^{I}_{t,s} = P^{I}_{t,s} - P^{I}_{t,s+1} = \sum_{\tau=0}^{\infty} \frac{(\phi_{s+\tau} - \phi_{s+\tau+1})\, P^{K}_{t+\tau,0}}{(1+r)^{\tau+1}},$$

for an asset of age s. This expression states that Hicksian economic depreciation is the present value of the rental income loss due to the efficiency decay $\phi_{s+\tau} - \phi_{s+\tau+1}$ occurring in each year in the future ($\tau = 0, 1, 2, \ldots$). In other words, depreciation occurs because the efficiency pattern is shifted one year for every year the asset ages. It is the shift in the *entire* efficiency pattern that leads to a decline in asset value.

Equation (26) shows that economic depreciation (a price effect) and efficiency decay (a quantity effect) are not independent concepts. One cannot select an efficiency pattern independently of the depreciation pattern and maintain the assumption of competitive equilibrium at the same time. And, one cannot arbitrarily select a depreciation pattern independently from the observed path of vintage asset prices P^{I}_{s} (suggesting a strategy for measuring depreciation and efficiency). Thus, for example, the practice of using a straight-line efficiency pattern in the perpetual inventory equation in general commits the user to non-straight-line pattern of economic depreciation.[13]

This framework is useful for revealing what economic depreciation is, but it is also useful for revealing what it is *not*. Depreciation is not the replacement cost of the efficiency units used up in any year, that is, $\Sigma(\phi_{s} - \phi_{s+1})P^{I}_{t,0}$, because $P^{I}_{t,s}$ is not generally equal to $\phi_{s} P^{I}_{t,0}$ unless decay is geometric. This can be seen intuitively by considering a one-hoss shay asset with a 10-year useful life. The efficiency lost between years 8 and 9 is zero, by definition, so the cost of replacing the loss units is also zero. However, the decline in the price of the asset is certainly not zero, since the asset is almost at the point of retirement. As a result, Hicksian depreciation occurs because the efficiency pattern has shifted, despite the retention of asset efficiency.

A parallel confusion arises over the valuation of the capital stock. Recall that K defined in (1) can be thought of as the number of efficiency units embodied in the existing stock—that is, the amount of *new* capital that must be purchased in order to yield the same productive capacity as the existing vintages of capital. It is thus natural to think of the value of the stock as the cost of purchasing these equivalent efficiency units: $P^{I}_{t,0}K_{t}$. However, this is not the case. The value of the stock is the asset value of the separate pieces of the stock, that is, the amount that would be obtained from selling each piece of capital at its market price:

$$(27)\qquad V^{K}_{t} = \sum_{v} P^{I}_{t,s} I_{v}\,.$$

This is the wealth associated with the stock K_{t}. It is not the same as $P^{I}_{t,0}K_{t}$, except when depreciation follows the geometric pattern (again, because in general $P^I_{t,s} \neq \phi_s P^I_{t,0}$). Intuitively, if the stock is one-hoss shay, the value (as measured by $P^I_{t,0}K_t$) of a stock composed entirely of one-year-old assets is the same as the value of the identical number of nine-year-old assets. However, if this type of asset lasts only 10 years, the willingness to pay for the two stocks (as measured by [27]) can be vastly different.

One final valuation issue is of interest. The historical cost of acquiring capital is typically reported on the balance sheets of firms. This measure of capital stock is referred to as the "book value" of the capital stock and is equivalent to

$$V_t^B = \sum_{v=t-A}^{t} \phi_s^A P^I_{v,0} I_v \,, \tag{28}$$

where A is the accounting period over which the capital costs are amortized, and the sequence ϕ_s^A is the unamortized balance of the investment made s years ago when new assets cost P^I_v,0. This book value differs from market value for several reasons: first, the accounting life A is not necessarily the same as the useful life T;[14] second, the depreciation method ϕ^A is typically based on the straight-line form and, thus, in general differs from the true pattern of economic depreciation; finally, and most important, inflation may cause the price of new assets to rise, so that $P^I_{v,0} \neq P^I_{t,0}$.

This analysis suggests that the book value of capital stock is generally not equal to the true value of the stock K_t. But, neither is the corresponding perpetual inventory estimate because the true values of the ϕ sequence are so hard to measure. While the perpetual inventory method avoids the historical cost valuation problem, book value estimates may nevertheless play an important role in assessing the reasonableness of the perpetual inventory method. Furthermore, perpetual inventory estimation is often impossible because of inadequate data on past investments (this is typically the case with data for individual companies), and book values then become the principal source of information about capital stocks.[15]

4.1.4 Heterogeneous Capital

A practical theory of capital measurement must be able to handle the multitude of capital goods that are present in the real world. Unfortunately, the extension of capital theory to the case of many goods involves at least as many difficulties and restrictive conditions as the single-good case. However, as before, practical theory proceeds under the assumption that even a restrictive theory offers a better guide to measurement than no theory at all.

Following the one good case, it is assumed that the technology is homothetically separable into a function of the N distinct types of capital flows used in production (I will continue to ignore the distinction between stocks and flows and assume that for each asset the one is proportional to the other):

$$Q_t = F[L_t, K(K_t^1, \ldots, K_t^N)], \tag{29}$$

where each K^i is itself an aggregate over individual investment vintages (I assume, here, that the conditions for vintage aggregation discussed in sec. 4.1.1 are satisfied for each type of capital). A necessary condition is that the marginal rate of substitution *between* each type of capital be independent of the amount of labor used:

$$(30) \qquad \frac{\partial}{\partial L_t}\left[\frac{\partial Q/\partial K_t^i}{\partial Q/\partial K_t^j}\right] = 0, \quad i, j = 1, \ldots, N.$$

Under this restriction, the aggregator function $K(\cdot)$ determines the nature of the capital aggregate, and the measurement of aggregate capital thus becomes a matter of discovering the form of $K(\cdot)$. This can be done by direct estimation of $F(\cdot)$ and $K(\cdot)$, which obviates the need for constructing the capital aggregate, or by Divisia indexing procedures.

The Divisia index is constructed by weighting the growth rate of each type of capital by its share in total capital income, $S_t^i = P_t^{K^i} K_t^i \,/\, \Sigma\, P_t^{K^i} K_t^i$, and summing the result:[16]

$$(31) \qquad \frac{\dot{K}_t}{K_t} = \Sigma\, S_t^i \frac{\dot{K}_t^i}{K_t^i}.$$

This can be shown to be related to the logarithmic differential of the production function $F(\cdot)$ when rental prices are proportional to marginal products. As shown in Hulten (1973), the existence of a linearly homogeneous aggregator function $K(\cdot)$ allows this expression to be integrated to obtain the "level" of the aggregate capital in each year (with one time period arbitrarily normalized at one.)[17]

The Divisia index is formulated in continuous time and is therefore not generally applicable to economic data. In practice, a discrete approximation to (31) is used in which the continuous growth rates are replaced by the difference in natural logarithms, $\ln K_t^i - \ln K_{t-1}^i$, and the continuous shares by the arithmetic average $(\frac{1}{2})(S_t^i + S_{t-1}^i)$. The result is the discrete time Törnqvist-translog index of capital.[18] When rental prices are proportional to marginal products (e.g., under cost minimization) and when the production function has the homogeneous translog form, the Törnqvist-translot index of capital is exact (Diewert 1976).

This approach provides an internally consistent, but restrictive, procedure for aggregating capital. A problem arises, however, when the number of asset types N is very large. The Törnqvist-translog approach requires that a capital stock and a rental price be calculated for each type of capital, which in turn requires an investment series, asset prices, and efficiency sequences for each type of asset. This is a difficult requirement when the number of assets gets even moderately large, and it is impossible for the thousands (if not millions) of varieties of capital actually used in production.

The enormous variety of capital assets virtually insures that some types of capital will be treated as homogeneous even though they are not. Categories like "commercial buildings" and "machine tools" come to be regarded (out of necessity) as homogeneous for the purpose of measurement, despite the fact that they include quite diverse types of capital. In such cases, the quantity of the pseudohomogeneous good is found by adding up current dollar values of each component good and deflating the result to the price level prevailing in some base year. Data on current investment expenditures are relatively easy to obtain, but finding a plausible price index for the deflation process is another matter.

The price index problem is greatly simplified if individual asset prices move together (i.e., are proportional). In this case, the price *levels* differ only by a constant, so that units of quantity can, in principle, be redefined to make asset prices identical. This is the case in which the Hicks aggregation theorem applies and a capital stock can be calculated provided that the aggregate efficiency sequence is the same for each component of the aggregate.

The theory of hedonic prices provides another solution to the problem of excessive variety. In this framework, individual capital goods are viewed as bundles of characteristics rather than as discrete physical entities. For example, different types of personal computers may be classified with respect to speed, memory size, graphics capability, and so on. The "inputs" to the production function (1) are then the amount of each characteristic rather than the amount of each physical good. The hedonic approach is particularly useful when there are many varieties of capital embodying a few characteristics—that is, when there are many bands and/or options that can be reduced to far fewer characteristic dimensions.

Under certain conditions, hedonic techniques can be used to estimate the "prices" associated with different characteristics. These prices can be used to deflate the total dollar expenditure on a group of pseudohomogeneous capital goods or to deflate the components individually. But, while this is an appealing approach, it is greatly limited by the fact that capital goods are purchased as physical units and the prices of component characteristics are not directly observable. Furthermore, the shadow prices of the individual characteristic tend to be complicated functions of all other characteristics and not just parameters as with physical goods, so estimation is often difficult.

In the final analysis, the great diversity and variety of the capital stock virtually insures that simple adding-up procedures will occur at some level of disaggregation. Simple, and usually ad hoc, deflation procedures will inevitably be used for some portion of investment, and the use of more sophisticated translog and hedonic techniques may reduce aggregation bias but will not eliminate it. But, as Griliches (1971) has noted in his survey of hedonic methods, "half a loaf is better than none."

4.1.5 Embodied Technical Change

An important variant on the heterogeneity problem deserves attention in its own right: different vintages of capital may differ in quality because they embody different levels of technological efficiency. The practice of aggregating investment of different vintages as per the perpetual inventory method of equation (1) should take into account the improvement in technology since it is a measure of capital stock in efficiency units. The stock of computers, for example, should reflect the increases in computing power per machine of new assets entering the stock as well as the loss in power through decay and retirement of existing machines.

The Fisher aggregation result discussed in section 4.1.1 suggests a procedure for incorporating embodied technical change into the perpetual inventory calculation. The vintage production functions $f^v(L_{t,v}, I_v)$, defined in 4.1.2, may differ because of differences in technology built into capital I_v when it is new. According to equation (7), the Fisher aggregation condition requires that any difference in embodied technology be representable by a fixed coefficient, which, in turn, means that aggregation can take place when embodied technical change—that is, better capital—is equivalent to having more capital.

Analytically, the Fisher condition can be represented by a relative efficiency index ϕ that drifts upward over time as the technology embodied in new machines improves. A 10% improvement in technology will, for example, result in $\phi_{(t+1),0} = 1.1\ \phi_{t,0}$, implying that a new unit of investment would then count as 10% more capital than a unit of new capital in the preceding year. Assuming, for simplicity of exposition, that efficiency decays at a geometric rate δ, which is the same for all vintages, and letting b_v denote the pure index of embodied technical progress, so that $\phi_{t,v} = b_v(1-\delta)^{t-v}$, the perpetual inventory equation can be written

$$(32)\qquad K_t = b_t I_t + (1-\delta)b_{t-1}I_{t-1} + \dots + (1-\delta)^s b_v I_v + \dots,$$

which is effectively the same as (1) except for the b_v. Estimation of the b_v would then produce the desired measure of capital, given δ.

The adjustment for embodied technical change can be obtained by multiplying the number of units of new investment in year t by the appropriate index b_v. However, this solution supposes that an estimate of b_v is available and, in general, that there is nothing in the translation of "better" into "more" that guarantees that the index of "more" is observable. Hall (1968, 1971) has shown that there is a fundamental indeterminacy in separating the effects of efficiency decay, embodied technical change, and disembodied technical change. The efficiency of an asset of vintage v at time t is the product of all three effects: if efficiency declines at a constant rate, δ; new investment embodies technical improvements at a constant rate, γ; and overall disembodied technical change is occurring at a constant rate, λ; the efficiency index is given (in continuous time) by

$$(33)\qquad \phi_{t,v} = e^{-\delta s}e^{\gamma v}e^{\lambda t}.$$

Since $s = t - v$, this can also be written as

$$(33')\qquad \phi_{t,v} = e^{(\lambda + \gamma)t}e^{-(\gamma+\delta)s} = e^{\alpha t}e^{\beta s}.$$

Any number of combinations of $(\delta, \gamma, \lambda)$ can yield a given (α, β), and there is thus an identification problem.

This problem also occurs on the price side in identifying the separate effects of depreciation (the change in vintage asset price with respect to age, $t-v$), obsolescence (the change with respect to vintage, v), and inflation (the change with respect to time, t). Assuming constant rates of growth, the price of a vintage v asset at time t can be shown to equal

$$P^I_{t,s} = e^{(\rho+\gamma)t}e^{-(\gamma+\delta)s}. \tag{34}$$

This implies that the trend in efficiency decay and obsolescence cannot be identified using data on used asset prices.

Hall suggests the following procedure to solve his identification problem: "As we have seen, if our framework is restricted to consideration of the *efficiency* of capital in use, the trend is ambiguous, and it would be senseless to try to estimate it. An alternative to this view is to suppose that embodied technical change, far from being a mystery, can be explained in terms of changes in the observed *characteristics* of capital goods. By characteristics, we mean size, weight, power, and other information of an engineering nature" (1971, 258; emphasis added). This approach brings us back to hedonics as a solution to the quality problem, but this time in response to quality change over time rather than asset diversity at any point in time. It is worth noting, here, that Hall's suggestion has been implemented for the computer component of equipment investment in the U.S. National Income and Product Accounts, and Gordon (1989) has extended this to 17 types of producers' durable equipment.[19]

The hedonic approach captures differences in quality that are revealed in price differentials. In competitive equilibrium, prices will tend to be driven into equality with marginal costs, implying that only those quality differences that are associated with cost differentials will be picked up by hedonic methods. This, in turn, implies that hedonic techniques will capture only part of the embodied change in the index ϕ. The use of hedonic prices to deflate investment expenditures is a complete solution to the embodiment problem only under restrictive assumptions.

4.1.6 Capital Stocks versus Capital Flows

Capital stock estimates are widely used in econometric and growth accounting analyses of production. However, the production function $Q = F(K, L)$ is conventionally interpreted as a relationship between the *flow* of output and the *flow* of input services. We have thus far ignored the distinction between capital stocks and flows and must now consider the problem of converting estimates of the latter into a flow equivalent.

The minimalist solution to this problem is to assume that capital flows are proportional to stocks, so that the one is a perfect surrogate for the other. In this case, capital utilization—defined as the ratio of the flow to the stock—is assumed to remain constant over time and, in particular, over the business cycle. However, while convenient, proportionality is clearly a dubious assumption, since published estimates of utilization tend to vary over the cycle.

An alternative approach is to multiply the estimated capital stock by an estimate of capital utilization. But, while this solves the problem of introducing variation in stock estimates over the business cycle, it merely converts the problem from one of measuring capital services (given the capital stock) to one of estimating utilization. If the flow of capital services cannot be measured, then estimation of the ratio of services to stock is also problematic. Ambiguity about the exact nature of capital services is at the center of the problem. What, exactly, is a capital "service"? Is a chair in "service" only when it is occupied? Or, does the availability of the chair for potential occupancy count for something too? If so, are potential services equivalent to actual services? And, how do we assess the decorative value of the chair if it adds to the office ambience? In the same vein, is an office building utilized only during business hours, or is it utilized all the time to keep out thieves and inclement weather?

In both cases, the services (whatever they are) cannot readily be observed because they are not easily defined. The measurement of such services, or of capital utilization, is thus problematic. An alternative approach is to dispense with the notion of capital service altogether and to analyze production from the standpoint of capital stocks alone. This is the approach taken in the recent literature on temporary equilibrium, in which the production function is interpreted as a relationship between the flow of output and a flow of variable labor input applied to a quasi-fixed stock of capital. Because the stock is taken as fixed in the short run, short-run fluctuations in demand can only be accommodated by changes in the amount of labor used in production. The capacity of the capital stock is defined with respect to the cost-minimizing level of output for the given amount of capital, and the optimal level of capacity occurs when actual output is at the cost-minimizing level. Capacity utilization, in this sense, is increased when more labor is applied to the fixed amount of capital.[20]

There are two concepts of rental price in the temporary equilibrium framework. The ex ante rental price is defined as the implicit (or possibly explicit) rent that is expected to be paid in each future period. The ex ante equilibrium condition is given by the analog of (19)

$$P^I_{t,0} = \sum_{\tau=0}^{\infty} \frac{P^K_{t+\tau,\tau}}{(1+r)^{\tau+1}}, \tag{35}$$

where the rental price, $P^K_{t+\tau,\tau}$ is now the expected cost in year $t+\tau$ given that demand is at its expected level, and r is now the rate of interest expected to prevail in future periods. The actual, or ex post, rental price, $Z^K_{t+\tau,\tau}$, is the gross quasi-rent realized from the capital stock when labor is adjusted to meet fluctuations in demand. It is the residual income accruing to the quasi-fixed stock (revenue less payments to all variable inputs):

$$(36) \qquad Z^K_{t+\tau,\tau} = (P^Q_{t+\tau}Q_{t+\tau,\tau} - P^L_{t+\tau}L_{t+\tau,\tau})/K_{t+\tau,\tau}.$$

If the expected value of $P^K_{t+\tau,\tau}$ is assumed to equal $Z^K_{t+\tau,\tau}$ then $Z^K_{t+\tau,\tau}$ can be substituted in (35). Furthermore, Berndt and Fuss (1986) show that it is the ex post $Z^K_{t+\tau,\tau}$ that equals the value of the realized marginal product of capital in each period. This implies that the ex post price is the appropriate concept for applications in which prices are used to estimate realized marginal products (e.g., in growth accounting analyses).[21]

Another approach to the capital service problem has developed along the lines of the Walras-Hicks-Malinvaud recursive method of production.[22] In this framework, the firm is viewed as using labor and capital stock to produce output *and* capital that is one year older. The firm is viewed as buying its stock at the beginning of the production period, using it to produce output, and then selling what is left of it at the end of the period. The objective of the firm is to maximize the difference between the cost of acquiring the capital plus the cost of labor on the one hand, and the revenue from selling output plus the proceeds from the sale of the used capital on the other. For the case in which capital is purchased when new:

$$(37) \qquad \pi^*_t = \frac{P^Q_t Q_t - P^I_{t+1,1}\phi_1 I_t}{(1+r)} - P^L_t L_t - P^I_{t,0} I_t.$$

The extension to capital of all vintages is straightforward. This expression is maximized subject to the constraint on technology, which now takes the implicit form $F(Q_t, \phi_1 I_t, I_t, L_t, t) = 0$. It is not obvious that this is the same problem as the maximization of profits, defined as the difference between revenue $P^Q Q$ and cost $P^L L + P^K I$, subject to $Q_t = F(I_t, L_t, t)$, but rearrangement of the terms in (37) and use of (23) reveals that the two are in fact equivalent. This implies that the optimal production plan can be viewed as emerging from a structure in which period-by-period capital costs are based on the implicit rent a firm must charge itself or on the implicit sale of capital by the firm to itself.

The conceptual equivalence of the two approaches does tend to conceal an interesting interpretation that can be given to the recursive framework. The technology $F(Q_t, \phi_v I_s, I_s, L_t, t) = 0$ can be defined with respect to the *stock* of the capital good and the issue of service flow left implicit. And, in this spirit, the amount of capital used up in production, $\phi_v - \phi_{v+1}$, can be made a choice variable of the firm, that is, the amount of depreciation is chosen as part of the overall production plan. The recursive model thus provides a natural framework for endogenizing the ϕ sequence, although it is not clear whether or not a measure of aggregate capital exists in this case, given the theoretical requirements of the Fisher conditions discussed at the outset.

The temporary equilibrium and recursive models of production fit more neatly into the category of "new developments" than into "accepted practice."

This may change in coming years, but it seems safe to say that these models have yet to have an impact on current national income and accounting practice, which relies on the more conventional measurement framework outlined above.

4.2 Practical Problems in the Measurement of Capital

The bits and pieces of theory presented in the preceding sections provide a practical framework for measuring capital stocks. The principal options are to look for a direct estimate of the capital stock, K_t, or to adjust book values for inflation, mergers, and accounting procedures, or to use the perpetual inventory method. This last option requires an estimate of the value of investment spending, $P^I I$, a quality-adjusted investment deflator, P^I, an efficiency sequence ϕ, and possibly a retirement distribution. Any of these procedures can be implemented at any level of industrial or asset detail for which the necessary data exists.

The discussion of section 4.1 reviews the conceptual difficulties with the various procedures. Statisticians involved in the actual estimation of capital stocks are, however, aware that the conceptual problems are only part of the problem. Dozens, if not hundreds, of "small" practical problems also cause headaches: Should estimates be assembled on a company or establishment basis? By industry of use or industry of ownership? Using data on investment expenditures or investment shipments? According to which industry and asset classification?

The various practical issues that must be addressed are too numerous and detailed to be dealt with in a relatively brief survey article. We will focus, instead, on three of the central problem areas of the perpetual inventory method: the estimation of investment in current dollars by industry and asset, the development of suitable investment-good deflators, and the estimation of efficiency sequences and retirement distributions. The following sections deal with these topics in turn, and a final assessment is offered in the conclusion.

4.2.1 Investment Data

Data on the current dollar value of U.S. investment are available from a variety of sources. The principal ones include: the U.S. National Income and Product Accounts (NIPA), the Bureau of Economic Analysis's (BEA) plant and equipment survey (P&E), and the investment data underlying the BEA capital stock studies (CSS). These data and others (like those from the input-output studies) are based on different classification systems and different degrees of coverage and must be interpreted accordingly. The NIPA equipment data, for example, are based on deliveries of investment goods, while the P&E and CSS data are largely based on investment expenditures. The P&E data, however, are collected on a company basis while the CSS data refer to establishments.

The choice between alternative investment series depends primarily on how the series will be used and not on inherent differences in data quality. Studies of the financial structure of firms or industries, for example, require company-based investment data since the decisions of interest are generally made at the company level of organization. Studies of productivity change, on the other hand, require establishment-level data since technology and production decisions are generally implemented at the establishment level within the company.[23] Similarly, studies of the distribution of wealth may require data on the *ownership* of capital, while studies of production require data on the *utilization* of capital. Leased capital should be attributed to the owner in the first type of study, but attributed to the user in the second.

There is thus no uniquely correct source of investment data. Furthermore, the choice among competing investment series depends on the desired level of asset and industry detail. There is a relative abundance of data for the economy as a whole, but the choice is far more limited at lower levels of aggregation. The BEA capital stock studies (Gorman et al. 1985; U.S. Department of Commerce 1987) provide the most extensive "official" investment data set for the United States: estimates of fixed nonresidential private investment (in current and constant dollars) are provided at the two-digit SIC industry level of detail; estimates are also provided for residential capital (by legal form of organization), durable goods owned by consumers (by type of good), fixed nonresidential government capital (by type of government and type of equipment and structure), and fixed nonresidential capital (by legal form of organization). The study also presents separate estimates of nonresidential capital for 22 types of producers' durable equipment and 14 types of nonresidential structures, and a cross-classification by two-digit industry and type of capital is available.

This impressive degree of detail requires data from many sources. Table A of the 1987 BEA study lists no fewer than 21 such sources. And, this covers only new nonresidential fixed investment. This multiplicity of sources is required in order to achieve the desired industry detail and to obtain sufficiently long investment series. The length of the investment series is an issue because, under the perpetual inventory method, the capital stocks at any point in time are the weighted sum of past investments. The investment series used in the perpetual inventory method must therefore span the years for which the efficiency weights are positive, or at least span the time period in which the weights are large enough to affect significantly the capital stock.

This problem can be illustrated by the case of geometric depreciation. With a constant rate of depreciation δ, the perpetual inventory equation (1) can be written as

$$(38) \quad K_t = I_t + (1-\delta)I_{t-1} + \ldots + (1-\delta)^{t-\nu}I_\nu + (1-\delta)^{t-\nu+1}K_{\nu-1}.$$

That is, the capital stock at time t is the efficiency-weighted sum of investment back to year ν, plus the remaining efficiency of the capital stock of time $\nu - 1$. By making the investment series sufficiently long, that is, making ν sufficiently large, $(1-\delta)^{t-\nu+1}$ can be made arbitrarily small and the size of $K_{\nu-1}$ can then be ignored (i.e., assumed to be zero). Otherwise, a value for $K_{\nu-1}$—a "benchmark"—must be estimated.

The investment series presented in the BEA study are quite long. Investment data for various types of nonresidential structures are carried back to the period 1832–89, while the various producers' durable equipment series commence in the interval from 1877 to 1917. At a depreciation rate of 4% for structures, an investment made in 1832 had only 1% of its efficiency left by 1948. If equipment depreciates at a rate of 15% per year, only .5% of an investment made in 1900 remains in 1948. The BEA series are thus sufficiency long that the initial level of the capital stock can be set equal to zero, which is fortunate because there are no reliable benchmarks on which to base alternative estimates.

The need to combine data from different sources does, however, introduce additional errors into the estimates. Each different series must be adjusted to the classification of the data base as a whole (generally an establishment/industry-of-ownership/1972-two-digit-SIC basis). These adjustments, or "bridges," are a potential source of error because, for example, the bridges are frequently problematic.[24]

Still, it seems reasonable to conclude that this part of the capital measurement problem is in reasonably good shape, particularly in view of the difficulty of the problem of capital measurement and strides that have been made by the BEA in recent years. However, the same cannot be said of investment in other types of productive capital. There is no integrated wealth account that puts land, inventories, R&D investment, and investment in other intangibles on an equal footing with the BEA tangible fixed wealth estimates. Data on inventories can be obtained from the BEA (although the move to the full cost absorption method of accounting is a major problem), and estimates of R&D spending can be obtained from other sources, but there is no unified data base for productive capital as a whole, much less one that is linked to the financial claims against the income generated by productive assets.[25]

The availability of investment data at the firm level of detail is also a major problem. Firm-level data seldom produces sufficiently long times series on investment that the benchmark $K_{\nu-1}$ in (38) can be ignored. The perpetual inventory method is thus not feasible, and as previously noted, analysts are typically forced to adjust book value data in order to obtain estimates of capital stock.

4.2.2 Investment-Good Deflators

The perpetual inventory method requires an investment series expressed in constant dollars (or in physical units, but this is not normally a feasible option). Since data on capital formation typically originate from market transactions of investment goods, a price deflator is needed to convert market data in nominal dollars to a real (inflation adjusted) dollar basis. As we have seen in section 4.1, the process of deflation can introduce additional, and potentially serious, errors into the data.

Two potential sources of error have already been identified: the application of a single deflator to goods that are in fact heterogeneous and the adjustment for quality change. To this list can be added a host of practical problems in sample design. The range of issues is sufficiently large, and detailed, that it deserves (and has received) attention in its own right. A brief summary of the deflation procedures used in the BEA capital stock studies is given in the 1987 BEA publication cited above, and I will thus limit the discussion here to the two areas in which price deflation is widely thought to be a major problem: computers and nonresidential structures.

Investment in computers presents a particularly serious problem because of the phenomenal growth of computing power. According to our efficiency interpretation of the perpetual inventory capital stock, such advances in computing power must be counted as an increase in the quantity of capital rather than its price, and the deflator for computing equipment must therefore be adjusted for quality change. The study by Cole et al. (1986) provides a major step in this direction by estimating three types of hedonic price indexes for four categories of computing equipment (processors, disk drives, printers, and displays). They report a dramatic decrease in quality-adjusted price: for processors, the three hedonic methods yielded an average annual price change of −18.2% for the years 1972–84. With the 1982 index equal to 100, this implies a price decline from 888 in 1972 to 80 in 1984. The other categories of computing equipment showed similar price declines: −14% per year for disk drives, −13.2% for printers, and −7% for displays.

The hedonic methods yield much larger price declines than the more conventional "matched model" approach. The latter produced average annual percentage price declines of −8.5, −6.9, −3.5, and −1.3. The conventional approach thus portrays a very different, and probably inaccurate, picture of real investment in computing equipment. The hedonic approach seems preferable and has been adopted by the BEA (Cartwright 1986), which had previously assumed no change at all, and by Gordon (1989), who presents hedonic price estimates for a broad range of producers' durable equipment. The hedonic approach is, however, not free of theoretical and empirical problems (e.g., Denison 1989). For example, the three hedonic methods reported by Cole et al. (1986) yield rather different results in the case of processors (a range of −17.6% to −19.2% per year), disk drives (−12.6% to −16.9%), and printers (−10.4% to 15.5%). These are sizable differences considering that they represent compound rates of growth, and Cole et al. conclude: "Although there may be widespread agreement that the present procedure for deflating expenditures on computing equipment is inadequate, a completely satisfactory alternative is not readily devised" (1986, 49).

Nonresidential structures are another case in which price deflation is a major problem. Pieper (in this volume) provides a detailed analysis of this problem, and I will only note here that there are two major issues: the use of cost indexes rather than price indexes as deflators and the use of proxy indexes (an index derived from a different sector). The main conceptual difference between cost and prices indexes is the rate of productivity change in the construction industry. If construction wages and materials, and so on, grow at a rate of 5% a year, and the efficiency with which labor and materials are used grows at 2%, competition will cause prices to increase at only 3% a year. The use of a cost index as a deflator for construction is therefore justified only when productivity change is zero or a noncompetitive market structure causes productivity gains to be captured by the producers. Neither situation is particularly appealing as an a priori assumption about the construction industry. Furthermore, the use of proxy deflators is only justified when the proxy and target industries have identical price trends. This is also a problematic assumption about the construction industry, and it seems reasonable to conclude that major biases may be present in the deflation process.

4.2.3 Efficiency and Retirement Patterns and the Estimation of Capital Stocks

Deflated investment expenditures measure the amount of capital added to the existing stock. Since most fixed capital is produced and sold in markets, there is a data "trail" that can in principle be followed. The same cannot be said about deletions from the stock. The reduction in capital can occur through in-place declines in efficiency and through retirement. Neither presents a broad trail of market data that can be used to determine the magnitude of the deletions. As a result, imputational methods like those described in section 4.1.2 of this paper are necessary, and this aspect of the capital measurement problem is widely thought to be the most unsatisfactory.

The BEA capital stock studies follow a procedure based on the perpetual inventory equation (16). Implementation of this approach requires three ingredients: a mean useful life, a retirement distribution centered on that life, and an efficiency pattern $\phi^{(i)}$. In the BEA methodology, a useful life is estimated for the various types of structures and equipment included in the capital stock studies. These useful lives are derived from a variety of sources, including the 1942 edition of *Bulletin "F,"* (U.S. Department of the Treasury), data from regulatory agencies, and the (largely) unpublished studies conducted by the Office of Industrial Economics during the 1970s. Retirements are assumed to occur according to the Winfrey distributions developed in the 1930s: a modified Winfrey *S*-3 curve is used for nonresidential capital and residential structures and an *L*-2 curve is used for consumer durables. The nonresidential *S*-3 distribution is a truncated bell shaped curve in which retirement starts at 45% of mean life ($T_{\min}$) and stops at 155% ($T_{\max}$). The Winfrey distribution is used to determine the fraction of any year's investment I_t retired at the end of $T_{\min}$ years, $T_{\min} + 1$ years, $T_{\min} + 2$ years, . . . , $T_{\max}$ years. I_t is then allocated to subcohorts $I_t^{(i)}$ accordingly, and the $\phi^{(i)}$ for each subcohort is calculated under the assumption of one-hoss shay deterioration (eq. [9]). Given estimates of $\phi^{(i)}$ and $I_t^{(i)}$, an equation similar to (18) is used to estimate the capital stock.[26]

The Bureau of Labor Statistics has also developed estimates of capital stock for use in their multifactor productivity program. The BLS procedures for fixed nonresidential capital are similar to those of the BEA, with the major difference being the use of the Hulten-Wykoff (1981a, 1981b) depreciation studies to obtain data-based estimates of the efficiency function $\phi^{(i)}$. The Hulten-Wykoff studies present estimates of economic depreciation (including obsolescence) derived from vintage asset prices. In view of equation (34), the rate of depreciation (plus obsolescence) is equivalent to the rate of change of the vintage price $P^I_{t,s}$ with respect to s; thus, a panel sample of vintage prices for a range of t and s can be used to estimate the pattern of economic depreciation.[27] Hulten and Wykoff use this type of data for various categories of nonresidential structures, construction equipment, machine tools, and autos to test whether depreciation followed either of the three patterns described in section 4.1.2—one-hoss shay, straight line, or geometric. None of these forms was accepted by the data, but the estimated pattern was closest to the geometric form. A "best geometric approximation" was computed for each of the asset types in the study, and this was used to derive estimates of the rate of depreciation for the full range of the BEA fixed nonresidential capital assets.[28]

The studies of Fraumeni and Jorgenson (1986), Jorgenson, Gollop, and Fraumeni (1987), Boskin, Robinson, and Huber (1989), and Boskin, Robinson, and Roberts (1989) use the Hulten-Wykoff estimates of δ more or less directly.These studies accept the best geometric approximation and use the self-dual property of geometric depreciation to calculate capital stocks K_t and user costs $P^K_{t,0}$ using the same δ. This procedure assumes that the obsolescence component of s should be treated as a write-down of the physical stock. The BLS study (U.S. Department of Labor 1983), on the other hand, steers a middle course between these studies and the BEA capital stock studies. The BLS study assumes that the efficiency function has the beta, or hyperbolic, form (see n. 8):

$$(39) \qquad \phi_\tau = \frac{T-\tau}{T-\beta\tau}, \quad \tau = 0, 1, \ldots, T \quad \text{and} \quad -\infty < \tau \leq 1.$$

BLS constrained β to lie in the interval [0, 1], thereby constraining the efficiency function to lie between the straight-line and one-hoss shay forms. Using estimates of T obtained from the BEA, BLS found the value of β that provided the closest fit to the Hulten-Wykoff price depreciation patterns. It was determined that a beta value of 0.75 resulted in the best fit for structures and 0.50 for equipment.

A definitive appraisal of alternative methods is impossible without an independent benchmark.[29] However, any appraisal of these procedures would have to note that the Winfrey retirement studies are now a half-century old, and that it is unlikely that the three Winfrey distributions used by the BEA capture the diversity of retirement patterns present in the full range of residential and nonresidential capital. Furthermore, part of the useful life data is also dated—some of these lives are derived from the 1942 *Bulletin "F"*—and, while the OIE data are much more recent, they are largely inaccessible and therefore hard to evaluate. It should be noted, however, that both the OIE data and the *Bulletin "F"* data were assembled in order to administer the income tax code and were not developed explicitly for the purpose of measuring capital. Furthermore, the service lives used by the BEA and others are fixed for the entire period covered by the study; they do not vary over the business cycle as plants open and close nor do they change in response to obsolescence. This is potentially one of the most serious problems with the perpetual inventory method.[30]

Data on useful asset life and on retirement patterns are extremely scant, and there are few alternatives to current procedures (which do, by and large, make sensible use of the available information). Improvement in these areas must await future data development. On the other hand, the question of the appropriate efficiency pattern is the subject of active, and unresolved, debate. One view holds that the market price of used assets is a valuable source of information about the relative productivity of old and new assets and that the perpetual inventory method should incorporate this information. Opponents of this view argue that the use of vintage asset prices suffer from the"lemons" problem, in which only inferior, and hence nonrepresentative, assets enter resale markets. Thus, it is argued, the market price of used assets falls more rapidly than the true, or shadow, price of the nonlemon assets, which are rarely sold. According to this view, the rapid decline in the price of lemons explains why vintage price studies almost invariably find a near-geometric depreciation pattern. Therefore, since this pattern is intuitively implausible and supported only by biased data, the critics conclude that it should be rejected.

Proponents of the vintage price approach respond by arguing that the markets for used machine tools, construction equipment, and nonresidential buildings are typically dominated by specialists whose business is to know the quality of used assets. The asymmetrical information condition of the lemons model is thus not present (Hulten and Wykoff 1981b). And, while there are certainly problems with market data on vintage prices, most price data are flawed in some way or another.[31] The basic issue is whether or not market information should be ignored or discarded while one-hoss shay or constrained beta efficiency functions are adopted on the basis of largely subjective notions about asset deterioration.[32]

This issue will hopefully be resolved by further research on the characteristics of used asset markets, by using market data on capital rents, or perhaps by the econometric studies of endogenous depreciation described above in section 4.1. For now, it is one of the central problems of practical capital theory.

4.2.4 Conclusion

The measurement of economic variables almost always involves significant problems, but Sir John Hicks is certainly correct in his appraisal of the special difficulties encountered in the area of capital measurement. The theoretical problems are indeed "nasty," and the practical problems are even nastier. Despite the very substantial effort and ingenuity of economists and statisticians at the BEA, the BLS, the Census Bureau, and other agencies, much remains to be accomplished. And, in my judgment, real progress must await the development of new data sources.

Fortunately, such development is under way at the U.S. Treasury's Office of Depreciation Analysis and at Statistics Canada (see Koumanakos 1989). Both agencies are undertaking surveys of the retirement and depreciation practices of individual firms, and of the market prices of used assets. These studies hold the promise of clarifying the nature of used asset markets and will, it is hoped, generate information on the useful lives of a variety of industrial assets. But, even these valuable studies will leave us without a benchmark value for the capital stock. There is a critical need for such a benchmark in order to test the validity of alternative procedures and, more important, in order to "anchor" the perpetual inventory estimates of capital in nonbenchmark years. It therefore seems appropriate to end this survey with a renewed call for a national capital benchmark.

Notes

1. The literature on the theory of capital is enormous. In addition to standard references on the history of economic thought, summaries of the relevant issues may be found in Harcourt (1972), Diewert (1980), Burmeister (1980), and Hicks (1981a).

2. Whether or not a good is durable obviously depends on the length of the accounting period. A machine that lasts five years would not be considered a durable good if the accounting period is taken to be 10 years, and a bouquet of flowers would be durable relative to an accounting period of a few hours. Since capital is a produced means of production, it is useful to think of it as an intertemporal intermediate good that is distinguished from a normal intermediate good by an arbitrarily defined accounting period (see Hulten 1979).

3. I will generally adhere to the convention that t denotes the current year (or prime period) and v denotes some year in the past. The variable $t-v$ is the age of the capital put in place in year v (e.g., 1950) at year t (e.g., 1990), and T is the age of the oldest surviving asset. We will sometimes use the variable $s = t-v$ to denote asset age.

4. Aggregation in the case of nonconstant returns is also studied by Fisher (1965), but general results are hard to obtain. We will restrict our discussion to the "easy" case of constant returns and note that this is yet another restrictive condition under which aggregation is unambiguously possible.

5. It might also be noted that the Leontief theorem implies a restriction on the substitution possibilities between pairs of inputs. Berndt and Christensen (1973) show that (5) implies that the Allen elasticity of substitution between capital of vintage v and

labor must equal the Allen elasticity of substitution between vintage ξ capital and labor. In other words, inputs within the aggregate must be equally good substitutes for inputs outside the aggregate.

6. See Diewert (1980) for an extensive discussion of the problems associated with the various types of aggregation, along with references to the relevant literature.

7. According to Jack Faucett Associates (1970) "This viewpoint can be defended on purely technological grounds: that with reasonable care and maintenance this is what capital goods do and there is nothing that can be done about it" (39).

8. The beta-decay, or hyperbolic, function developed by Jack Faucett Associates (1970), and used by Harper (1982) and the BLS (U.S. Department of Labor 1983), is also worthy of mention since it generalizes the three patterns discussed in the text. The beta-decay function is defined with respect to useful life T, the age of the asset τ, and a parameter β that determines the shape of the function:

$$\phi_\tau = \frac{T-\tau}{T-\beta\tau}, \quad \tau = 0, 1, \ldots, T \quad \text{and} \quad -\infty < \beta \leq 1.$$

When $\beta = 1$ the function has the one-hoss shay form, and then $\beta = 0$ it has the straight-line form. Negative values of β can simulate geometric depreciation. The beta-decay approach thus adds flexibility to the derivation of an efficiency pattern from estimates of useful life, but the problem of determining the appropriate form (i.e., value of β) is still present. As noted in section 4.2.2, the "dual" of this problem has been addressed by using the Box-Cox flexible functional form applied to used asset prices (Hulten and Wykoff 1981a, 1981b).

9. A problem arises, however, in actually identifying this as retirement. Assets may be retained in stand-by pools after they have been removed from service in order to provide extra capacity when needed. Thus, ϕ may in some sense go to zero before the time T, when the asset is actually removed from the capital stock. To account for such circumstances, a more sophisticated model of the capital stock than the one offered in this review is necessary.

10. The BLS (U.S. Department of Labor 1983) provides a comparison of the assumptions about gross and net capital stock used in the studies of Denison (1979), Kendrick and Grossman (1980), and Jorgenson (1980).

11. The nature of expectations is obviously an important determinant of the present value of future income. A variety of assumptions have been employed in the literature on the investment price–rental price correspondence, most commonly static expectations and perfect foresight (see Harper, Berndt, and Wood 1989 for an elaboration of this point). It is also important to emphasize that capital is treated here as variable, and the adjustment costs are assumed to be zero.

12. The supply of vintage assets will depend, in part, on the retirement decision. An asset will presumably be removed from service if the remaining present value of the income from an asset falls below its scrap value.

13. Recall, here, the eq. (12) for geometric decay. This equation implies that $\delta(1-\delta)^{\tau+s}$ can be substituted for $\phi_{s+\tau} - \phi_{s+\tau+1}$ in (26). This, in turn, yields an expression for (25) in which economic depreciation is constant at the rate δ. In other words, when efficiency decay occurs at a constant rate, the investment good price decays at the *same* constant rate. Furthermore, Jorgenson (1973) notes that the geometric decay is ceteris paribus the only one in which both efficiency and investment prices decline according to the same pattern (see, however, Feldstein and Rothschild 1974 for qualifications of this result). Straight-line efficiency decay, for example, is not consistent with straight-line economic depreciation.

This property of geometric decay results in a simplified form of the rental eq. (23), and simplifies the perpetual inventory equation as well, since (1) can be written

$K_t = I_t + (1-\delta)K_{t-1}$. The same δ used in this computation can be used in the calculation of the rental price.

14. The accounting life A may be biased upward relative to the useful life T because managers may wish to understate depreciation costs in order to make current profits appear higher (the opposite is true for tax accounting, in which the incentive is to overstate depreciation cost). The short-run increase in accounting profit will, of course, be matched by an offsetting decrease sometime in the future, but the pressure on management to succeed now may make this consideration irrelevant. And, if the capital stock continues to grow, the decrease can be postponed, perhaps perpetually.

15. See Atkinson and Mairesse (1978) and Pakes and Griliches (1984) for a discussion of the methods that can be used to extract information from book value data.

16. Dots over variables denote a derivative with respect to time. The variable $\dot{K}_t/K_t$ is thus the rate of growth of K_t.

17. Equation (31) defines a growth rate and must be converted into a level index by line integration. Given the homotheticity of the aggregates, the separability condition (30) is both necessary and sufficient for path independent line integration and thus the existence of the level index.

18. The translog production function is due to Christensen, Jorgenson, and Lau (1973). However, the discrete approximation actually predates this paper (Törnqvist 1936; Theil 1960). Applications of this approximation to capital aggregation are developed in Christensen and Jorgenson (1969, 1970) and Jorgenson, Gollop, and Fraumeni (1987).

19. For a general discussion of the issues involved in linking price hedonics and technical change, with specific application to computers, see Triplett (1987, 1989). As an example of hedonic price deflation, consider the case in which the cost of a certain kind of personal computer is $2,000 in both 1987 and 1988, but the computer has doubled in computing power over this period. Then, the effective or equivalent cost of the 1988 computer is $1,000. If the $1,000 figure is used to deflate the cost of purchasing the computer in 1988 rather than the $2,000 figure, the improvement in quality ($b_{1988} = 2$) is built into the estimate of real investment, $b_{1988}I_{1988}$.

There has been an ongoing controversy over whether hedonic deflation is *ever* appropriate (see Triplett (1983) for a discussion of this debate). Denison (1989) argues against hedonic quality adjust on the grounds that advances in knowledge ought to be kept separate for increases in capital input, and quality adjustments have the effect of embedding technical advances in the measure of capital. However, Hulten (1989) shows how price-based estimates of quality change, such as those presented in Gordon (1990), can be "detached" from the quality-adjusted capital stock and exhibited as a separate contributor to output growth. Furthermore, it is shown that any attempt to ignore embodied technical change when it is present will suppress into the total factor productivity residual this "detachable" term that can be separately measured.

20. A related approach stresses the use of shift labor and the "work week" of capital as the framework for analyzing utilization (Betancourt and Clague 1981; and Foss 1981,1984).

21. The growth accounting papers by Jorgenson and Griliches (1967) and Christensen and Jorgenson (1969) develop the ex post user cost as a practical means of estimating the rate of return to capital and, thereby, of constructing a capital aggregate for use in the Divisia aggregation eq. (31). Berndt and Fuss (1986) were apparently the first to realize that this procedure results in a theoretically consistent correction for capital utilization (see also Hulten 1986).

22. This framework is described in Diewert (1977), and implemented in the endogenous depreciation models of Epstein and Denny (1980), Bischoff and Kokkelenberg (1987), and Kim (1988).

23. This is, indeed, the rationale for the company-establishment distinction. Com-

panies are legal entities of industrial organization while establishments are economic units which produce similar products. A company is frequently a collection of establishments as, e.g., a company which produces autos and washing machines.

24. The use of multiple data sources raises other questions of consistency. There are intrinsic differences in the way different series are constructed, and there is no a priori reason to expect that they give the same result. Seskin and Sullivan (1985), for example, compare the P&E investment data with the NIPA data at the aggregate level of detail (after expressing the P&E data on a NIPA basis) and find that the two series have somewhat different growth trends. The difference is not large, except in the early years of the comparison, but the difference does serve as a warning that combining data from differences sources may introduce internal inconsistencies into the data set.

25. For the extension of the accounting framework to include a longer list of capital goods and an integrated income and wealth account, see Christensen and Jorgenson (1973a, 1973b), Kendrick (1976), and Eisner (1985).

26. It is widely believed that BEA assumes straight-line depreciation in calculating capital stocks. The confusion arises over the distinction between depreciation and asset efficiency—i.e., between prices and quantities—noted in sec. 4.1 of this paper. BEA does indeed use the straight-line assumption in estimating wealth (its "net stocks"), but uses the one-hoss shay assumption in estimating the corresponding quantity of capital (its "gross stocks"). The two estimates are consistent, in the sense of sec. 4.1 under a zero rate of discount. For a more detailed discussion of the conceptual underpinnings of the BEA estimates, see Young and Musgrave (1980). A more detailed description and listing of the actual lives and retirement distributions is given in Gorman et al. (1985, 42–45) and in U.S. Department of Commerce (1987, xxi–xxiv).

27. Panel data on used assets prices must be adjusted for the retirement pattern of assets (the ω in [16]). Otherwise, vintage price data will reflect on the value of surviving assets and will therefore not reflect the average experience of the whole vintage. Hulten and Wykoff adjust for this problem by deflating observed vintage prices by an estimate of the probability of survival.

28. The procedure adopted by Hulten and Wykoff was based on the declining balance formula $\delta = X/T$, where δ is the rate of economic depreciation, T the useful life, and X a parameter defining the degree of the declining balance (e.g., $X = 2$ defines the double declining balance form). Estimates of T were available from BEA by asset category, but δ was available only for those assets studied by Hulten and Wykoff and others. Given estimates of δ and T for this more limited list, an estimate to X was obtained: 1.65 for equipment and .91 for structures. These values of X were then assumed to hold for all assets, and a value of δ was obtained for each T.

29. BEA has compared its estimates of historical-cost gross capital stock with IRS and census book values. Gorman (1987) reports that, in 1977, the BEA estimates for the corporate sector were 95% of the corresponding IRS estimate. These ratios showed substantial variation across major industry, ranging from 73% percent for mining to 121% for services. The comparison of the BEA estimates with census establishment data produced a ratio of 101%, with a variation of 93%–132% across major industries. These comparisons suggest a reasonable fit in the aggregate, but a less good fit at the industry level of aggregation (although this is partly due to a lack of data for insuring full compatibility). Furthermore, it should be noted that the comparisons are made using *gross* book value and not the net value that I have argued is the appropriate capital concept.

30. It is worth nothing, in this regard, that the recent study by Hulten, Robertson, and Wykoff (1989) found that depreciation rates derived from vintage asset prices showed a remarkable degree of stability over the period of the energy crisis. The rapid rise in energy prices in 1974, and again in 1979, could be expected to reduce the value of older energy-inefficient capital. The results of this study suggest that this did not

happen in any systematic way for the two classes of assets studied: machine tools and construction equipment. This finding is consistent with the earlier result by Hulten and Wykoff (1981a) that the depreciation pattern of structures was relatively stable over the period 1955–71. These findings suggest that depreciation rates are relatively constant over the business cycle and during periods of potential obsolescence, but they do not address the question of whether retirement patterns, and thus useful lives, vary over the cycle.

31. According to eq. 21, the relative efficiency of an s-year-old asset is equal, in equilibrium, to the rental price of an s-year-old asset relative to the rental price of a new asset. Thus, the efficiency pattern could also be estimated from data on market rental prices (see Taubman and Rasche 1969). However, this approach is also subject to the criticism that rental markets are thin, that rental prices differ by length of lease, and that tax considerations like "sales-lease-back" arrangements are important determinants of the rent (see the literature review in Hulten and Wykoff [1981b]).

32. Recall, here, the fallacy of composition that can arise when each component of an investment cohort is one-hoss shay but the retirement process is such that the whole cohort decays according to a geometric pattern. The vintage asset prices used in the Hulten-Wykoff studies were adjusted for the probability of retirement and thus correct for the cohort retirement effect.

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Comment

Ernst R. Berndt

As a young economist just out of graduate school, I once had the privilege of listening to an exchange among three very wise men (given the age distribution of participants at this Conference on Research in Income and Wealth jubilee, you can understand why I refrain from calling them old, wise men)—Dale Jorgenson, Zvi Griliches, and Larry Lau. Based on his recently completed research that utilized sophisticated econometric estimation techniques, flexible functional forms, and the theoretical rigor provided by the notions of functional separability and consistent aggregation, Dale Jorgenson provocatively summarized his findings by saying something to the effect that "I do not believe value added exists." Looking toward Dale's bookshelf containing works by John Kendrick, Jack Faucett, Ed Denison, and others, Zvi Griliches scratched his beard and responded, "Of course value added exists. There's a whole set of value added measures on that bookshelf." And Larry Lau smiled. For me, this was heady stuff—measuring something that does not exist.

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Today, on the occasion of the fiftieth anniversary of the Conference on Research in Income and Wealth, (CRIW), I have a sense of déjà vu from that meeting in the old Harvard economics building at 1737 Cambridge Street, for I am obliged to present and discuss Chuck Hulten's paper on the measurement of capital input—How does one measure something that may not "exist"?

Now a wise man as well, Hulten begins his paper by acknowledging the tension between theory and practice when it comes to capital measurement, even opening with a celebrated quote from Sir John Hicks, "The measurement of capital is one of the nastiest jobs that economists have set to statisticians." In terms of theoretical criteria, there certainly is good reason to believe that the theoretical conditions required for a consistent aggregate measure of capital input to exist are not in fact satisfied. Dale Jorgenson's point—that value added does not exist—very likely carries over to capital input in the same way. But Zvi Griliches is also right. Come hell or high water, many of us will be using and/or producing measures of aggregate capital input, even if it does not "exist."

Appropriately, Hulten's paper reflects this ambiguity and tension—he seeks to inform us about how in practice we might best measure capital input, recognizing that compromises must be made and that approximation must be employed. Let me stress that this is not being intellectually dishonest—it is not an Easterner attempting to grapple with a mystical notion imported from California, nor for that matter is it Donald Regan groping with Nancy Reagan's astrology; in fact, how one measures capital is a very serious practical problem. Over the years, Hulten has thought about this issue from several vantages: as an academic theorist, as an econometrician measuring depreciation profiles, and as an employee of the government statistical establishment. It is fitting that he author this paper.

Before summarizing this paper, I believe it is useful to think of the purposes for which measures of capital input are employed. While there may be numerous others, three come to mind immediately. First, capital input measures have often been used to help explain and predict *investment* in producers' durable equipment and nonresidential structures. A rather simple and time-honored framework, for example, is that of the form

$$I_t = \lambda(K_t^* - K_t),$$

where current period net investment is a proportion λ (perhaps, λ_t) of the "gap" between "desired" or long-run equilibrium capital stock K_t^* and the actual beginning of time period capital stock K_t. Measures of capital stock, and of the estimated capital stock gap, are used to help explain net investment.

Second, capital input measures have been used by some to measure *productive capacity,* or potential output, say, y_t^*. In one well-known procedure, for example, the optimal capital-output ratio is $g = K_t/y_t^*$; given estimates of K_t and g (or, perhaps, g_t), potential or capacity output y_t^* is computed as $y_t^* = K_t/g$, and then actual output y_t is compared to capacity output y_t^* to obtain a measure of capacity utilization. In short, capital stock measures are often used to measure potential or capacity output, as well as capacity utilization.

Third, capital is but one of many inputs, and measures of capital input are required if one wants to measure *multifactor productivity growth* (MFP). Specifically, a common procedure for calculating MFP growth is

$$MFP_{growth} = \dot{y}/y - \dot{x}/x,$$

where $\dot{y}/y$ is growth in output and $\dot{x}/x$ is growth in aggregate input, which in turn is typically a share-weighted sum of growth in each of the X_i inputs, including capital, that is,

$$\dot{x}/x = \Sigma_i \, s_i \, (\dot{x}_i/x_i),$$

where s_i is the cost share and $\dot{x}_i/x_i$ is the rate of growth of the *i*th input. One point I will want to stress in my remarks here is that I believe the best way to measure and, especially, to weight capital input depends in large part on which of these three applications one has in mind. More on this later.

The first part of Hulten's paper provides an overview of applied capital theory and contains six sections. Hulten begins by noting that what makes capital measurement different is not just that capital is durable (for so, too, is labor input), but most transactions between the owner of capital and the user of capital input are implicit, and thus there is a paucity of data concerning explicit market prices and quantities for capital inputs. These measures must therefore instead be inferred.

In section 4.1.1, Hulten shows that even when capital goods are homogeneous in nature, they must be distinguished by vintage, and it must further be recognized that the differing vintages of surviving capital have varying marginal products. This leads to an aggregate capital stock over vintages, measured in efficiency units, computed as in the *perpetual inventory* relation,

$$K_t = \phi_0 I_t + \phi_1 I_{t-1} + \ldots + \phi_T I_{t-T},$$

where the efficiency weights are in the range $0 \leq \phi_t \leq 1$ and I_{t-T} is the oldest surviving vintage of capital, originally acquired as a new investment in time period $t - T$. This first section then concludes with a brief review of the separability assumptions required for the existence of an aggregate of homogenous capital over vintages.

In section 4.1.2, Hulten considers the ϕ_t weights in greater detail, weights that are necessary for computing K_t using the perpetual inventory method. Here he distinguishes three forms of decay: the "one-hoss shay" efficiency profile of, say, a light bulb, where

$$\phi_0 = \phi_1 = \ldots = \phi_{T-1} = 1, \phi_{t+\tau} = 0, \quad \tau = 0, 1, 2, \ldots,$$

from straight-line decay, where

$$\phi_0 = 1,\ \phi_1 = 1-(1/T),\ \phi_2 = 1-(2/T),\ \ldots,\quad \phi_{T-1} = 1 - (T-1)/T,$$

and

$$\phi_{T+\tau} = 0, \quad \tau = 0, 1, 2, \ldots,$$

and geometric or constant exponential decay, where

$$\phi_0 = 1,\ \phi_1 = (1-\delta),\ \phi_2 = (1-\delta)^2,\ \ldots,\ \phi_t = (1-\delta)^t,$$

where δ is the constant rate of physical deterioration.

Because it is so convenient analytically, the geometric form of decay is very widely used, but, as Hulten notes, geometric decay implies a very rapid loss of efficiency in the early years of the life of an asset, a decay so rapid that many think it implausible.

One remark worth making here is that although Hulten acknowledges that the asset life T may not be fixed, in practice T is measured by the mere passage of time and not by the cumulative hours the asset has been utilized over its life; unless one assumes constant utilization rates over time, T and cumulative utilization can differ. For example, following the fuel price shocks of 1973–74 and 1979–80, American car owners reduced considerably the total miles driven per year, from over 10,000 to a bit more than 9,000, that is, annual utilization rates fell. Since on average cars were still being scrapped after about 100,000 cumulative miles, the average lifetime T at which cars were scrapped *increased* as a result of the energy price shocks, even though total cumulative utilization at time of scrapping was essentially unaffected. I state this not only to highlight the fact that T may change and may be endogenous but, more important, to emphasize the distinction between lifetime measured as the passage of time versus lifetime measured as cumulative utilization. Incidentally, for several assets such as farm tractors and aircraft, data on cumulative utilization are available.

One very useful result that Hulten highlights is that because of varying vintage composition over time, the average efficiency function of an entire cohort can be quite different from the individual efficiency functions; while each asset in a stock cohort might, for example, follow the one-hoss shay form, the cohort as a whole can follow a rather different age-efficiency pattern. Some further analytical and simulation work on this topic seems warranted.

The other very useful discussion in this section is the one on net and gross capital stocks. This distinction is often confused in the literature, and Hulten's clear discussion is most welcome. It is worth noting, however, that the Ω weights of Hulten's equation (18) currently used by the BEA in forming their measure of gross capital are based on the Winfrey mortality distribution, originally published by Robert Winfrey at the Iowa Engineering Experiment Station in 1935. Although the July 1985 issue of the *Survey of Current Business* notes that these 1935 weights have been slightly revised, the Winfrey mortality distribution is critical to the practical construction of gross capital stocks. If one wants to assess this gross capital stock construction procedure, I believe one must confront the issue of how accurate are these mortality distribution tables today. Recall that the Winfrey distribution is even older than the Conference on Research in Income and Wealth.

The third section of Hulten's paper relates the value of an asset (the present value of its net quasi rents) to the age-efficiency profile, the ϕ_t's. This is a very important topic, and could involve a massive manuscript all by itself. Briefly, Hulten relates the value of an asset as it ages to its age-efficiency profile. The value implies a price—the asset price—whereas the latter, the age-efficiency profile, involves quantity flows. Although he and others have repeatedly pointed it out elsewhere, Hulten again stresses the frequently misunderstood point that only in the case of geometric decay does the age-price or the age-depreciation profile have the same shape as the age-efficiency profile. In particular, if deterioration is one-hoss shay, the age-price depreciation profile has a different shape; if deterioration is straight-line, then the age-price profile is not a straight line but instead is curvilinear.

There are many things that could be said here. Let me simply make three observations. The first is that Hulten himself has contributed significantly to deterioration-depreciation-efficiency profile measurement by using econometric techniques and estimating the shape of age-price profiles for various durable assets, based on used price data. I would like to see more of that research and, especially, see more of it embodied in our capital stock estimates.

Second, by stressing the fact that the value of an asset depends on the present value of its *expected* quasi rents, Hulten has brought us to the investment application of capital stock—one of the three applications I noted earlier. In this context, Hulten derives the one-period rental price of capital as, ignoring taxes for the moment, $P_K = (r + \delta)q_K - f(\dot{q}_K/q_K)$, where $f(\cdot)$ is the expected change in the asset price (expected capital gains). To me, this suggests that when measuring capital and capital rental prices for purposes of analyzing the investment decision, one must use ex ante expectations—both for interest or discount rates, and for capital gains. In particular, contrary to much literature, it does not make sense to use an ex post rate of return when doing ex ante investment analyses, unless one believes that all expectations are perfectly realized ex post.

Third, I do not think our applied community fully realizes just how precarious are the foundations to how one constructs a formula for the rental price of capital and, in particular, how one incorporates expectations. Though by far the most widely used, the seminal Hall-Jorgenson formula is but one of several different formulae that can be constructed, consistent with economic theory. On this matter, I recommend for useful reading the 1980 paper by W. Erwin Diewert, "Aggregation Problems in the Measurement of Capital," in the NBER volume edited by Dan Usher, and a 1989 empirical study by Mike Harper, David Wood, and me.

Let me next move on to section 4.1.4 of Hulten's paper, where he introduces heterogeneous capital, and then discusses aggregation. The aggregation that Hulten appears to consider here is that of aggregating heterogeneous capital stocks rather than heterogeneous capital service flows. Recall that in the late 1960s, Griliches, Denison, and Jorgenson were involved in a well-known debate that involved a number of measurement issues. One point stressed by Griliches and Jorgenson is that one should aggregate over flows, not stocks. Why? Since nonresidential structures, for example, are longer lived on average than producers' durable equipment, the amount of service flow derived per year from a $1 stock of equipment is larger than that from a $1 stock of structures. Since equipment investment has been growing more rapidly than that for structures, the aggregate of service flows has also been growing more rapidly than the aggregate equipment-structures stock. This change in the average "quality" of capital (as Griliches and Jorgenson called it) is important, both conceptually and empirically.

In the last section of the applied theory portion of this paper, Hulten considers several capital stock–capital service flow issues. To my taste, Hulten is a bit too willing to move from capacity to capital utilization. Going back to Cassell's work in 1937, one can define capacity utilization as the ratio of actual output to some capacity output (in Cassell's case, the output at which the short- and long-run average total cost curves are tangent). By contrast, capital utilization has been defined as the ratio of desired capital (given output quantity and input prices) to actual capital. As has been pointed out by, among others, Berndt and Fuss (1989), these two measures of utilization coincide only if there is but one fixed input (capital) and if production is characterized by constant returns to scale.

One point made by Hulten in this section is worth stressing, however. Specifically, if one wants to use a measure of capital to calculate actual multifactor productivity (MFP) growth (one of the three applications I mentioned earlier), then theory tells us quite clearly that we should weight the various traditionally measured capital inputs by their *realized* marginal products, not their *expected* marginal products. This means that in choosing capital service price weights, one should employ shadow values or ex post rates of return, and not the ex ante returns that are appropriate in the investment context. This illustrates the point I made earlier, that to some extent the appropriate measure of capital price and quantity depends on the particular application one has in mind.

Having considered these applied theory issues, in the second major portion of this paper Hulten briefly deals with practical problems in the measurement of capital. A number of important issues are addressed, including the importance of the so-called lemons problem. This is a very well-written discussion and will surely be of use to students using data on investment, investment good deflators, and capital stock constructs. Several issues not discussed here, however, include the following: How does one treat maintenance expenditures? Should they be expensed as primarily labor input or amortized as investment? If the latter, how should their age-efficiency pattern be formulated, over what lifetime? This could be particularly important in the construction of public sector capital stocks, such as those for highways and airports. Second, in terms of capital rental prices, which types of marginal or average tax rates should one employ? Does the choice depend on the application?

In summary, Hulten has written a very useful and readable paper on applied theory and practical issues in the measurement of capital. It is particularly appropriate for this conference, and it surely deserves a prominent place on the reading lists of our graduate courses in applied economics.

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