ISSUES IN THE MEASUREMENT OF ECONOMIC DEPRECIATION

INTRODUCTORY REMARKS

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I. INTRODUCTION

Most capital goods are used up in the process of producing output. Machine tools wear out, trucks break down, electronic equipment becomes obsolete. When an asset reaches a point at which it is no longer economical to repair and maintain, it is withdrawn from service. As the physical deterioration and retirement of assets cause the productive capacity to decline to zero, a parallel loss in asset financial value occurs. This depreciation of value is a cost that must be subtracted from gross revenue in order to determine the income accruing to the asset. It is also the amount that must be added to the balance sheet in order to keep wealth intact.

These are relatively straightforward distinctions that are routinely used in various fields of economics: in studies of economic growth, particularly in the new growth theory with its focus on the role of capital formation; in environmental economics, with its concerns about sustainable growth; in production theory with the study of capital formation; in industrial organization with issues involving the rate of return to capital; and in public finance, with its interest in the taxation of income from capital. It is therefore perplexing that these important distinctions have been the source of much confusion and error. It is common, for example, to see "deterioration" called "depreciation," though the former is a quantity concept and the latter refers to financial value. Other confusions have led to the inference that there are two logically separate concepts of capital, one appropriate for wealth accounting and the other for the study of productivity and growth.

Part of the problem lies with the historic confusion and controversy within capital theory itself. The controversy is manifest in academic debates over the role of capital in economic growth (viz. the "Cambridge Controversies" in capital theory). A major source of difficulty arises from the fact that, by definition, a capital good yields its services over the course of several years and the fact that capital goods are generally owner utilized. This leads to a fundamental difference vis a vis non-capital inputs like labor and materials that complicates the measurement problem enormously and necessitates the use of imputational methods and approximations to get at the underlying economic prices and quantities. Unlike labor, which is purely an input, capital goods are both inputs and outputs of the production process, and this fact adds yet another dimension to the analysis.

In the spring of 1992 the current state of research on capital, wealth, and depreciation was the subject of a one-day Conference on Research in Income and Wealth symposium, held in Washington D.C. at the Board of Governors of the Federal Reserve under the auspices of the National Bureau of Economic Research. This symposium ranged over many of the issues in

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the measurement of economic depreciation, and presented both an appraisal of past research and an important set of new results. The five following papers of this issue of *Economic Inquiry* are devoted to the proceedings of the workshop in the hope that further research interest will be stimulated in this crucial and under-researched branch of economics.

II. ISSUES IN DEPRECIATION ANALYSIS

Given the history of confusion surrounding the concept of economic depreciation, it would seem useful to precede the conference papers with a few introductory remarks about the problem of depreciation. We will start with the simple example of a small manufacturing company that owns three machines: one that was purchased at the beginning of the current year (1996) at a cost of $100,000, one purchased five years ago at a cost of $80,000, and one purchased twenty years ago for $40,000. The three machines are intended to perform the same set of tasks and are essentially the same, except for wear and tear due to age and to design improvements that have occurred over time. The average useful life of this type of machine as calculated for accounting purposes is fifteen years, and the firm uses the straight-line method of accounting depreciation. The net book value of the firm (historical cost, less accumulated straight-line depreciation) is thus $146,667, and annual accounting depreciation is $12,000. Finally, the operating revenue after expenses is $20,000.

These data are typical of the information available for analyzing macro- and microeconomic issues that involve capital variables (issues of growth, production, investment, wealth, etc.). The basic question is whether or not such data are sufficient for the demands made on them. The answer is, unfortunately, that they are not. Knowledge of the historical pattern of investment is not sufficient to determine the amount of productive capacity in a firm, industry, or economy. This becomes apparent when the example above is reworked in analytical form.

The collection of capital goods available for production in year t may be represented by $[I_t, I_{t-1}, \dots, I_{t-T}]$—in the case of our small firm, this collection has three elements corresponding to a new capital good, and one five-year-old and one twenty-year-old capital good. The historical cost (and gross book value) of the collection is equal to

$$(1) \qquad BV^K_t = P^I_{t,0} I_t + P^I_{t-1,0} I_{t-1} + \dots + P^I_{t-T,0} I_{t-T}$$

where $P^I_{t,0}$ denote the purchase price of a new capital good in year t. For our example, $P^I_{1996,0} = \$100{,}000$, $P^I_{1991,0} = \$80{,}000$, $P^I_{1976,0} = \$40{,}000$, and thus BV^K_{1996}, the gross book value, is equal to $220,000. The historical price of new machines $P^I_{t,0}$ is observable, but it tells little about the value (or shadow price) of a machine that has been in operation for a number of years, $P^I_{t,s}$. This second price, reflecting the remaining present value of the income accruing to the machine, is the amount that a rational investor would be willing to pay to acquire the machine in a second-hand market. The total value of the collection $[I_t, I_{t-1}, \dots, I_{t-T}]$ is thus equal to

$$(2) \quad V^K_t = P^I_{t,0} I_t + P^I_{t,1} I_{t-1} + \dots + P^I_{t,T} I_{t-T}.$$

This is clearly different than the gross book value measure, BV^K. It is also different, in practice, from net book value, V^K, ($146,667), constructed by accountants using straight-line depreciation. Although this is intended to approximate V^K, such measures are problematic because mechanical book value measures bear no necessary relationship to the remaining asset financial value after adjusting for true economic depreciation—unless of course the latter should happen to coincide with a straight-line depreciation pattern.

It is also different from the value of the services rendered by the collection of capital goods, as well as from the in-use productive capacity of the collection. The former is equal to the product of the annual shadow price that each good in the collection could be rented for, $P^{K}_{t,s}$, and the available quantities I_{t-s}, summed over the active vintages.

$$\pi^{K}_{t} = P^{K}_{t,0}\, I_{t-1} + P^{K}_{t,1}\, I_{t-2} + \dots + P^{K}_{t,T-1}\, I_{t-T}. \tag{3}$$

This term π^{K}_{t} is the total gross rental value of the capital goods in the collection, or, in accounting terminology, property income. It corresponds in our numerical example to the $20,000 generated by the firm with three assets. Note that it is the sum of past investments valued using vintage *rental* prices, while the value of capital stock is the sum value at vintage *asset* prices.

The price P^K is a straightforward concept when capital goods are rented in formal markets. This occurs with residential apartments and houses, space in office buildings and retail stores, automobiles, hand tools and construction equipment, etc. In these cases, there is an explicit market price corresponding to P^K. However, most types of fixed capital are owner-utilized, and the rent is therefore implicit—e.g., the implicit rent that homeowners "pay" themselves for using the house they own. This gives rise to the terminology "quasi-rent" and "user cost" when referring to the gross annual return to owner-utilized capital.

The quasi-rent and user cost of capital are notionally equivalent to the rental price, since the latter is the opportunity cost that owners must forgo when deciding to use their own capital goods. There are, however, some important qualifications that tend to make the user cost concept elusive, and sometimes deceptive. First, most owner-utilized capital is fixed in the short run, and the return to this quasi-fixed capital is an ex post residual, the amount left over from revenue after all current expenses are paid. Hence the term "quasi rent." The rental price, on the other hand, is the ex ante cost of acquiring the right to use the capital good for a stipulated period of time. Under perfect foresight with full utilization the two concepts will tend to converge. With uncertainty, they may not.

There is also a second problem: the ex ante expected degree to which capital is utilized may differ from ex post utilization, even if fluctuations in demand are correctly anticipated. And, older capital may be less intensely utilized than newer units. These situations lead to the possibility that the implied services obtained from a given capital good may vary with intensity of use. This is recognized in the older user-cost literature as the dual to a stock-flow distinction and, in this context, the rental price P^K is viewed as the annual price of capital services, while P^I is the stock price of capital. A more recent view does away with this stock-flow distinction, noting that the flow of services is not inherent in the stock of capital itself, but depends on the amount of variable inputs applied to the quasi-fixed stock (Berndt and Fuss [1986] and Hulten [1986]). This leads to an ex ante rental versus ex post quasi-rent of the concept of the capital stock. In this model capital utilization is defined as a function of the wedge between the two rents.

These distinctions take us far beyond the purpose of this simple introduction, but anyone approaching this field should be aware of these issues. From here on, we will ignore them by assuming that demand is constant and that capital is utilized at a constant rate. We will also assume perfect foresight.

The productive capacity of the collection $[I_t, I_{t-1}, \ldots, I_{t-T}]$ is yet another variant on the symmetries implied by equations (1), (2) and (3). The "quantity" of capital associated with this set of capital goods is defined as the amount of new investment that would be needed to produce exactly the same amount of output. The goods in each vintage are assumed to be equivalent to some fraction of the capital in the newest vintage, regardless of how the characteristics of the capital goods have changed over time. Given this assumption, past vintages of capital can be added up to get the total amount of "capital stock":

$$(4) \qquad K_t = \varphi_0 I_t + \varphi_1 I_{t-1} + \ldots + \varphi_T I_{t-T}.$$

The weights, φ_s, express the productive capacity of s-year-old assets as a fraction of the productive capacity of a newly produced asset. The φ's are thus indexes of a relative efficiency in which in-use efficiency of a new asset is normalized: $\varphi_0 = 1$.[1]

Studies of economic growth and productivity which are based on production functions with capital as an input need estimates of the capital stock equation (4); studies of income and wealth need estimates of equation (2) and the components of equation (3), adjusted for true depreciation. However, what is available is only equation (1), the left-hand side of equation (3), and, of course, the approximate accounting value of the left-hand side of equation (2). The data which are typically available are thus not sufficient, but what further steps are needed to bridge the gap? This question has occupied the field of income and wealth accounting for several decades and has required some creative answers. The papers in this issue discuss some of these answers and provide some new ones. As a background for this discussion, we lay out, in the following section, the basic framework of depreciation analysis.

III. THE FRAMEWORK OF DEPRECIATION ANALYSIS

The three equations set out above can, and have, been treated as separate independent entities. However, this leads to potential inconsistencies that are a problem for economic studies of production, growth, taxation, etc., and it is therefore useful to treat the equations above as part of a unified framework. There are several possible candidates for such a framework, the obvious candidate being that provided by *neoclassical* economic theory.[2]

Three relationships of the neoclassical model govern the capital accounting exercise. The first is the aggregate production function, which may be expressed as

$$(5) \qquad Q_t = A_t F(L_t, K_t)$$

$$= A_t F(L_t, [\varphi_0 I_{t-1} + \varphi_1 I_{t-2} + \ldots + \varphi_T I_{t-(T+1)}]).$$

Given this aggregate representation technology, the marginal product of any vintage s of investment can be expressed as

$$(6) \qquad P^K{}_{t,s} / P^Q{}_t = \partial Q_t / \partial I_{t-s} = \varphi_s \partial Q_t / \partial K_s.$$

We have imposed here the second key assumption: that rental prices $P^{K_{t,s}}$ are proportional to marginal products. This duality relation is essential for establishing the link between capital income and the productive capacity of capital goods, and thus between equation (3) and the aggregate capital stock (4). This expression is also significant because it demonstrates

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[1] The φ's can be given an interpretation in terms of the stock-flow distinction (i.e., they convert the stock into a flow of services equivalent), or they can be seen as stock weights that express capital goods of different ages into a common income generating equivalent.

[2] See Hulten [1990; 1995] for a discussion of the possibilities.

that the efficiency index φ_s is really nothing more than the sequence of the ratios of the marginal products of s-year-old assets to the marginal product of a new asset.[3]

The third economic relation of importance is the link between marginal products (rents) and the price of capital goods $P^I_{t,s}$. The price of a capital good in a fully arbitraged asset market is just equal to the present value of the income that the asset is expected to generate over the remainder of its useful life. The general expression for the remaining present value of an s-year-old asset is

$$(7) \qquad P^I_{t,s} = \sum_{\tau=0}^{T} P^K_{t+\tau,s+\tau} / (1+r)^{\tau+1},$$

where we have assumed for simplicity that the discount rate is constant over time. When $s = 0$, we have the expression for a new asset. This expression links the asset financial valuation equation (2) to revenue equation (3) and to stock equation (4).

This framework lays bare the fundamental economics of the capital vintage model and makes clear the crucial role of the φ-efficiencies in the process of depreciation-deterioration. The φ's are a key determinant of the rental price, and by extension, of the asset price, which can be expressed, after some algebraic manipulation, as

$$(8) \qquad P^I_{t,s} = \sum_{\tau=0}^{T} \varphi_{s+\tau} P^K_{t+\tau,0} / (1+r)^{\tau+1}.$$

The result is a formulation that expresses the remaining present value of an asset in terms of the rental price of a *new* asset. This expression provides an important insight into the link between the production (quantity) and valuation (price) sides of the capital problem. The relative marginal product of capital could be inserted into (7) in place of φ, in which case it becomes clear that the financial value of the stock of capital derives from its productivity in generating future output.

Equation (7) also provides an insight into the nature of economic externalities and depreciation. Expression (7) can be made to yield

$$(9) \qquad \delta_{t,s} P^I_{t,s} = P^I_{t,s} - P^I_{t,s+1} = \sum_{\tau=0}^{T} (\varphi_{s+\tau} - \varphi_{s+\tau+1}) P^k_{t+\tau,0} / (1+r)^{\tau+1}$$

where $\delta_{t,s}$ is the percentage difference in price of capital between two successive ages in the *same year* (i.e., $\delta_{t,s} = 1 - (P^I_{t,s+1} / P^I_{t,s})$. This expresses the erosion of capital financial value due to the process of aging. It is also the definition of economic depreciation: the amount of capital financial value that must be "put back" in order to keep the real value of the wealth intact. This is the definition of economic depreciation noted in the introduction, and it is seen to be equal to the present value of the *shift* in asset efficiency from one age to the next. In other words, when an asset is used in the production of output over the course of a year, it is the erosion of current *and future* productive capacity $\{(\varphi_{s+\tau} - \varphi_{s+\tau+1}): \ \tau = 0,1,\ldots\}$, which Jorgenson calls the mortality sequence, that causes the erosion of asset value $(P^I_{t,s} - P^I_{t,s+1})$.

IV. EFFICIENCY AND DEPRECIATION PATTERNS

There are an infinite number of possible efficiency functions, and indeed, every piece of capital probably has its own unique pattern. However, the literature has focused on three cases:

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3. As an aside, the Leontief [1947] Aggregation Theorem states that capital can be aggregated using equation (4) if, and only if, the ratio φ is a constant number. Moreover, the aggregate production function (5) exists only under this condition.

(1) The constant efficiency pattern, also known as the "one-hoss-shay" pattern, which has the form:

$$(10) \qquad \varphi_0 = \varphi_1 = \ldots = \varphi_{T-1} = 1,\ \varphi_{T+t} = 0 \qquad t = 0,1,2,\ \ldots$$

In the one-hoss-shay form, assets retain full efficiency until they completely fall apart. In this form, the efficiency sequence is completely characterized by the service life T, and the measurement problem reduces to the problem of estimating T.

(2) The straight-line pattern, in which the efficiency falls off linearly until the date of retirement:

$$(11) \qquad \varphi_0 = 1,\ \varphi_1 = 1 - (1/T),$$
$$\varphi_2 = 1 - (2/T),\ \ldots,\ \varphi_{T-1} = 1 - [(T-1)/T]$$
$$\varphi_{T-\tau} = 0 \quad \tau = 0,1,2,\ \ldots$$

In this form, efficiency decays in equal increments every year, i.e., $\varphi_{t-1} - \varphi_t = 1/T$. As with the one-hoss-shay pattern, T completely determines the efficiency pattern.

(3) Geometric decay, in which the productive capacity of an asset decays at a constant rate $\delta = (\varphi_{t-1} - \varphi_t)/\varphi_{t-1}$. This gives the efficiency sequence

$$(12) \quad \varphi_0 = 1,\ \varphi_1 = (1-\delta),\ \varphi_2 = (1-\delta)^2,\ \ldots,$$
$$\varphi_t = (1-\delta)^t,\ \ldots$$

This form is characterized by a single parameter as in the preceding cases, but the parameter is now the rate δ rather than the service life T.

These patterns describe the path of efficiency over time, and they should not be confused with the corresponding path of economic depreciation. Equation (9) makes it clear that the two paths are linked, and it is well known that the one-hoss-shay pattern of efficiency implies straight-line depreciation with a zero rate of discount, and a concave pattern with a positive discount rate. It is also clear from equation (9) that straight-line efficiency is not the same as straight-line depreciation. Indeed, only the geometric form has this self-dual property, which makes it an attractive alternative on a priori grounds.

V. ESTIMATION OF EFFICIENCY AND DEPRECIATION PATTERNS

It is clear, given the central importance of the φ-efficiencies, that any attempt to implement the empirical framework laid out in the preceding section requires an estimate of the efficiency pattern. The bad news is that, since the φ's are ratios of marginal products, they are not directly observable. The good news is that the association between the rental prices and the φ's in equation (6) means that the former can, in principle, be used to estimate the latter. In other words, if there were active rental markets for capital services as there are for labor services, the observed prices could be used to estimate the marginal products. And, the rest of the framework would follow from these estimates.

But, again, there is bad news: most capital is owner utilized, like much of the stock of single-family houses. This means that owners of capital, in effect, rent it to themselves, leaving no data track for the analyst to observe. This leads to the situation where the rental price must be estimated from the φ's, not the other way around. This is accomplished by using the Hall-Jorgenson [1967] "user cost" formulation, in which equation (8) is solved to yield:

$$(13) \quad P^K{}_{t,s} = [r - \rho_{t,s} + (1 + \rho_{t,s})\delta_{t,s}]P^I{}_{t,s}.$$

This expression has a straight-forward interpretation: the equilibrium (shadow) rental cost of an asset equals the ex post return to the money invested in the asset

r, adjusted for asset revaluation, $\rho = (P^I_{t+1,s+1} / P^I_{t,s+1}) + 1$, plus the cost of economic depreciation. In this formulation, the rate of return, r, is measured on an ex post basis and thus includes any excess returns or rents accruing to the asset (or any deficits).[4]

This still leaves the question of estimating the φ's and δ's. Fortunately, there are several possibilities besides the use of rental prices. If there is a thick resale market for a particular type of asset, the δ's can be estimated from the definition $\delta_{t,s} = 1 - (P^I_{t,s+1} / P^I_{t,s})$, and this leads to estimates of the φ's [when depreciation is geometric, $\varphi_s = (1 - \delta)^s$]. However, though more readily available than rental prices—indeed richly available for many asset types—resale price data are not available every year for every type of asset, and thus $\delta_{t,s}$ cannot be computed for the universe of depreciable capital. This leads to the necessity of approximation methods in order to build up a picture of the general experience of the entire stock of capital.

We have followed this approach in a series of studies of non-residential structures and producers' durable equipment in the U.S. (Hulten and Wykoff [1981a; 1981b]), Hulten, Robertson, and Wykoff [1989], and Wykoff [1989]. Our basic approach is based on the observation of a sample of second-hand asset resale prices which we use to discriminate between the leading depreciation patterns noted above. If economic depreciation has the straight-line form, for example, then a regression analysis which uses flexible functional forms should indicate that the asset's price declines linearly with age; if assets retain their full productive capacity up to the point of retirement, i.e., are one-hoss shays, the analysis should indicate a pattern that declines more slowly than the straight-line pattern when the discount rate is positive; if depreciation has the geometric form, then the fitted pattern should decline at a constant rate with age.

We have used this approach to study the depreciation patterns of a variety of fixed business assets in the United States (e.g., machine tools, construction equipment, autos and trucks, office equipment, office buildings, factories, warehouses, and other buildings). The straight-line and concave patterns are strongly rejected; geometric is also rejected, but the estimated patterns are extremely close to (though steeper than) the geometric form, even for structures. Although it is rejected statistically, the geometric pattern is far closer to the estimated pattern than either of the other two candidates. This leads us to accept the geometric pattern as a reasonable approximation for broad groups of assets, and to extend our results to assets for which no resale markets exist by imputing depreciation rates based on an assumption relating the rate of geometric decline to the useful lives of assets.[5] A recent paper by Barbara Fraumeni reviews the literature on economic depreciation and finds that the weight of evidence strongly supports this form of depreciation. A summary of our estimates of asset class depreciation rates, which has been condensed and updated, is provided in Table I.

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[4] The ex post rate of return is found by inserting the user cost formula (1) into the expression for capital income (3) and solving for r. This is possible because the other terms are observable, or, in the case of the average rate of economic depreciation δ, can be imputed or estimated. Berndt and Fuss [1986] show that the ex post rental price, so defined, equals the marginal product of capital.

[5] Information is available on the average service life, T, from several sources. The rate of depreciation for non-marketed assets can be estimated using a two-step procedure based on the "declining balance" formula $\delta = X/T$. Under the "double declining balance" form, $X = 2$. The value of X can be estimated using the formula $x = \delta T$ for those assets for which these estimates are available. In the Hulten-Wykoff studies, the average value of X for producers' durable equipment was found to be 1.65 (later revised to 1.86). For non-residential structures, X was found to be 0.91. Once X is fixed, δ follows for other assets whose average service life is available.

TABLE I
Rates of Economic Depreciation

Asset Class	Approximate Depreciation Rate
Producers' Durable Equipment	
Furniture & Fixtures	12%
Agricultural Machinery	12%
Industrial Machinery and Equipment	12%
Construction Tractors and Equipment	18%
Farm Tractors	18%
Service Industry Equipment	18%
Electrical Equipment	18%
Aircraft	18%
Trucks and Autos	30%
Office and Computing Equipment	30%
Non-Residential Structures	03%

Source. Based on more detailed estimates by Hulten and Wykoff [1981a], revised and updated.

VI. CRITICISMS OF THE USED ASSET PRICE APPROACH

The geometric form is a matter of great controversy (see, for example, the debate between Feldstein and Rothschild [1974] and Jorgenson [1973]). Feldstein and Rothschild point out that the φ's and δ's are variables that are subject to choices about the degree of utilization and maintenance, and other factors. They also note that depreciation can take many forms: increased down time through breakage or repair, loss in serviceability from wear and tear, wastage of materials, etc. A theory of efficiency functions should capture all of this and, in principle, allow each asset to be different. Importantly, there is no reasonable expectation that the pattern is fixed, much less fixed with a geometric pattern.

The geometric form is also regarded by many observers as intuitively implausible because of the rapid loss of efficiency in the early years of asset life (for example, 34 percent of an asset's productivity is lost over four years with a 10 percent rate of depreciation). Moreover, pure geometric decline means that assets are never completely retired and this implies that the service life is infinite. When viewed from this intuitive standpoint, the most plausible pattern may well seem to be the "one-hoss shay," in which capital appears to retain the bulk of its productive capacity throughout its useful life. It is hard to believe that the productive capacity of desks, chairs, and blackboards "evaporates" at a constant rate every year. It thus would seem that the geometric pattern is decidedly inappropriate.

Criticism has also been voiced about the viability of used-asset market price data as an indicator of in-use asset values. One argument, drawing on the Akerlof

Lemons Model, is that assets resold in second-hand markets are not representative of the underlying population of assets, because only poorer quality units are sold when used. Others express concerns about the thinness of resale markets, believing that it is sporadic in nature and is dominated by dealers who under-bid.

VII. EVALUATION OF THE EVIDENCE

Taken together, these intuitive arguments above suggest that this is a case in which the econometric evidence leads to the wrong result. However, it may also be true that the intuition, not the econometrics, is faulty. Intuition tends to be based on personal experience of individual cases, particularly personal experience of consumer automobiles. Moreover, what may be true on a case-by-case basis may not be true of an entire population of assets. If so, this has important implications for evaluating econometric results, which typically reflect the average experience of whole populations and not individual units.

For instance, it may well be true that every single asset in a group of 1000 assets depreciates as a one-hoss shay, but that the group as a whole experiences near-geometric depreciation. This fallacy of composition arises from the fact that different assets in the group are retired at different dates: some may last only a year or two, others ten to fifteen years. When the experience of the short-lived assets is averaged against the experience of the long-lived assets, and the average cohort experience is graphed, it will look nearly geometric if the 1000 assets have a retirement distribution of the sort used by the Bureau of Economic Analysis (i.e., one of the Winfrey distributions). Thus, the average asset (in the sense of an asset that embodies the experience of 1/1000 each of 1000 assets in the group) is not one hoss shay, but something that is much closer to the geometric pattern. This can easily be verified by performing this experiment using the parameters of the Bureau of Economic Analysis's capital stock program.[6]

There are, of course, applications in which the experience of one individual asset is at issue. However, most applications in growth, production analysis, environmental economics, industry studies, and tax analysis, are concerned primarily with the average experience of a heterogeneous population of capital, and not with the idiosyncratic behavior of each individual asset. In this regard, the Feldstein and Rothschild critique may well be correct about the complexity of the depreciation process for individual assets while, at the same time, the idiosyncrasies of individual experience actually average out in the population, so that one observes comparatively stable and predictable depreciation patterns over all. Such stability was found in our 1989 study with James Robertson.

Intuition about the lemons problem also may be potentially faulty. Business capital, unlike personal autos, is resold for reasons not associated with asset quality per se, but because of events such as plant closings, shifts in product demand, or decisions related to tax optimization, inventory control or liquidity requirements. Structures, similarly, may be sold for the same reasons that any piece of real estate is sold. There is thus no strong basis for believing that only "lemons" come on to the market. Moreover, it is by no means clear that asymmetrical information is a problem: the decision to buy a used asset like a building is usually made by experts in the resale market whose economic survival depends on the ability to spot defective assets. Akerlof himself explains that sellers have an economic incentive to help potential buyers overcome the asymmetric

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[6] The fallacy of composition in effect is exacerbated by the fact that heterogeneous assets are necessarily grouped together to make the estimation problem manageable. The machine tool class, for example, includes tools that last three years (grinders) with tools that last more than thirty years (metal presses).

information problem. Indeed, were this not so, the logic of the lemons argument itself would imply *no* (or very tiny) used-asset markets.

VIII. TECHNICAL CHANGE AND OBSOLESCENCE

When new vintages of capital are introduced into the market, they often contain new "state of the art" technology. If this new technology is superior, then the arrival of new, better vintages of capital will depress prices of existing old vintages of capital which do not contain the new technology. This decline in value of old vintages is *obsolescence* the decline in price resulting from the introduction of new vintages of capital. Thus, obsolescence is the effect on older vintages of capital of the introduction of new technology *embodied* in new vintages of capital. In other words, embodied technical change results in obsolescence of older vintages of capital if the new change cannot be grafted onto the older assets. Until now, we have not tried to identify the obsolescence term. We now turn to that problem.

This problem may be very important. Cole et al. [1986] found that quality change in the price of new IBM computers fell at compound rates of between 10 percent and 20 percent per year. Their results led the Bureau of Economic Analysis to adjust its investment goods' prices in the national accounts. Robert J. Gordon [1990] extended this adjustment to all producers' durable equipment and reports a significant quality adjustment for many assets.

The key issues in disentangling and identifying the obsolescence and decay components of depreciation can be illustrated by the following diagram which plots the asset price, $p^I_{t,s}$ for a collection of similar assets of various ages at a given point in time, t. This is the *age-price profile* estimated in Hulten and Wykoff [1981].

Economic depreciation is, by definition, the decline in price along the age dimension, i.e., the partial derivative of $p^I_{t,s}$ with respect to age s, represented in Figure 1 by the move along the lower age-price profile from a to b. This move is driven by two factors:

(1) As an asset ages, it may lose some of its original productive efficiency, and also each year moves it one year closer to its date of retirement from service. Both effects cause the remaining present value to decline.

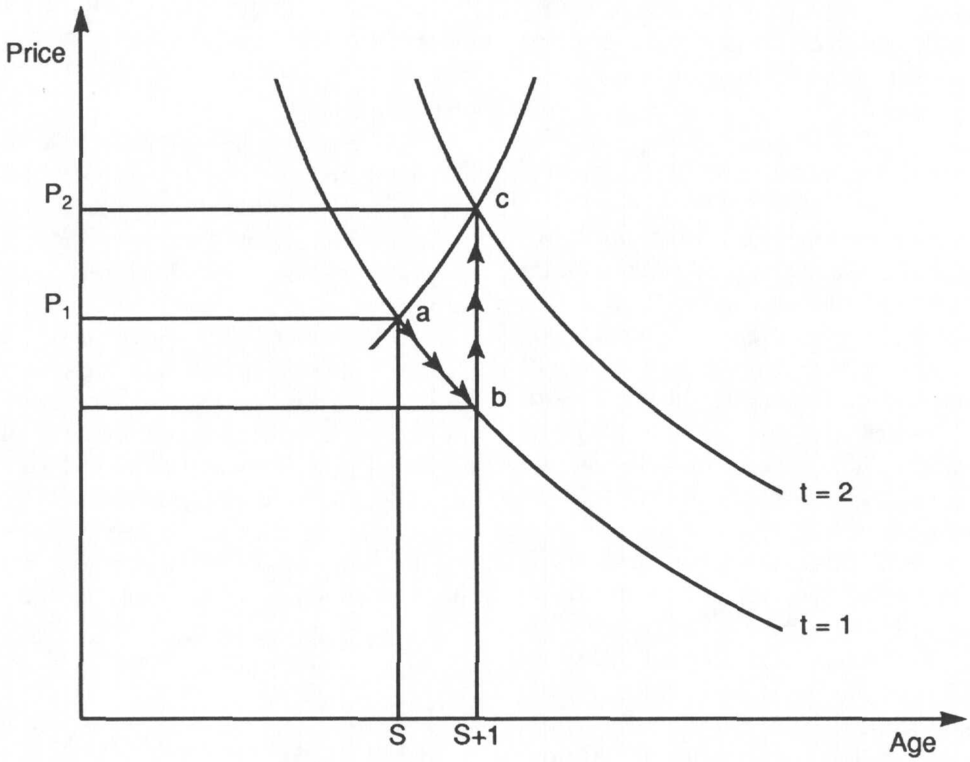
(2) As an asset ages, newer assets may appear with technologically superior designs. The arrival of the superior competitors does not reduce the productivity inherent in existing assets, but it can reduce their prices when the cost savings realized by the technically superior assets becomes (negatively) capitalized into the prices of the older, obsolescent, vintages of capital.

Figure 1 shows a shift in the age-price profile from $t = 1$ to $t = 2$. This shift also is driven by two factors:

(1) General price inflation exerts upward pressure on all prices over time and, even without inflation, supply and demand shocks can change relative prices between periods which can shift the age-price profile.

(2) The age-price profile may shift with time, and it may not, as a result of improvements in the quality of new assets.

As noted in Hulten [1995], improvements in the quality of new assets push up the price of new assets when quality improvements are achieved at a cost, i.e., research and development expenditures and more costly materials. When, however, quality improvements are costless, the transactions prices of new investment goods in competitive markets are not affected and the age-price profile does not shift with respect to time. (For example, the price of a new computer this year, adjusted for inflation, may be approximately the same as the price of new computers last year even though this year's model is technologically superior.) Since most quality changes are far from costless,



the time dimension of the age-price profile normally shifts outward.

The actual, observed total year-to-year change in the transactions price of a given asset is the outcome of all these effects, and is represented by the move from *a* to *c*. It decomposes into depreciation (the pure age effect) shown by the move from *a* to *b*, and revaluation (the pure time effect) shown by the shift from *b* to *c*.

Sorting out the various underlying effects is difficult and, when decay, obsolescence, and revaluation occur at constant geometric rates, Hall [1968] shows that the three rates cannot be identified separately from data in the two dimensional asset price array $p^{l}_{t,s}$. Hall, in [1971], goes on to demonstrate that price-hedonic estimation techniques can provide one way around this identification problem. However, again as Hulten [1995] has pointed out, a fourth factor, the cost of attaining a given rate of asset quality change, is implicit in the problem, and this factor complicates the issue by vitiating interpretation of hedonic coefficients. However, economic depreciation estimates are independent of this additional factor even though the revaluation term is not.

IX. CONTENTS REVIEW

As we noted at the outset, heated argument has marked much of the debate on capital measurement. Jack Triplett's paper deals with the famous 1970s debate between Edward Denison on the one hand and Dale Jorgenson and Zvi Griliches on the other. Triplett argues that the disagreement boiled down to a different perspective on the role of capital in the income accounting literature of Denison from the growth and productivity literature of Jorgenson and Griliches. Triplett bridges the intellectual gap between Denison and thus the Bureau of Economic Analysis to the model we have outlined above. Triplett's equation (3a) goes to the heart of the dispute that had stymied reconciliation. Triplett's equation (3a) links the Jorgenson definition of economic depreciation to the Denison concepts of exhaustion and decay. Triplett's expression $k(1,s) - k(2,s)$ in his equation (3a) is simply the Jorgenson term, $\varphi_s - \varphi_{s+1}$, the decline in efficiency which Jorgenson calls the mortality function:

$$m_s = \varphi_s - \varphi_{s+1}. \tag{14}$$

The mortality function appears in equation (9) above as a key aspect of economic depreciation. Triplett's contribution is to explain and thus reconcile a major dispute, paving the way for construction of a coherent measure of capital in the System of National Accounts.

Dale Jorgenson, a major contributor to this literature, in his up-to-date summary in this volume of the econometrics of economic depreciation links the Hall approach to the various econometric models for estimating depreciation taking into consideration both in-use depreciation and retirement. Jorgenson reviews major new data provided by the statistical agencies in the U.S. and recent attempts to estimate obsolescence as well as a summary of the empirical depreciation literature itself. Thus, combined with this introduction, Triplett's reconciliation, and Jorgenson's linkage of the theory of depreciation to empirical research we have a comprehensive and coherent research agenda into measurement of capital stocks.

Ishaq Nadiri and Ingmar Prucha significantly advance the measurement of capital by solving three problems. These are the problem of permitting endogenous depreciation, the problem of limited used-asset price data, and the problem of estimating the stocks of intangible assets, such as goodwill and research and development (R&D). When one considers measurement of depreciation of large fixed capital assets like dams, paper mills, and nuclear reactors it is obvious that a measurement solution that does not rely on used-asset prices must be found.

Nadiri and Prucha implement their framework for the total U.S. manufacturing industry. By assuming that a period-t cost function, dual to the production function, yields conventional output from the period-t input mix, and simultaneously yields the new period-t+1 values for these inputs, they render depreciation as an endogenous byproduct of cost minimization. Since their assets include expenditures on R&D, they are able to extend the analysis to measure the stock of endogenous R&D capital.

In a related contribution, Mark Doms exploits production function analysis to directly infer efficiency sequences, φ_s, for plant-level data in which capital assets are held in-place between periods. This is a two-fold contribution. Jorgenson [1973] suggested that the efficiency sequence could be thought of as an efficiency "function" whose form would depend upon the decline over age and time of marginal products of various vintages of capital, so that rather than try to measure φ_s from relative rental prices for each individual vintage $t - s$, one could estimate a pattern which would represent the path of efficiency decline throughout the life of a cohort of capital.

Doms, like Nadiri and Prucha, does not require used-asset market prices to obtain his endogenously driven efficiency function estimates. This not only enlarges the scope of measurable depreciable capital but provides a check on inferences about depreciation drawn from used-asset market prices. Doms applies his methodology to steel plant capital. Again we have an illustration of a new method for estimating Jorgenson's efficiency sequence, and thus the mortality sequence in Triplett's equation (3a).

Another major problem confronted by estimators of depreciation involves correcting used-asset prices for early asset retirement. We showed in Hulten and Wykoff [1981a] that without a correction for retirement, a censored sample would result in downward-biased estimates of the true depreciation rates. Oliner studies the consequences for vintage capital of new computerized technology that favors newer vintages of machine tools by allowing them to receive numerical instructions. This technological innovation replaces the need for a machinist, thus reducing risk, increasing quality control, and making newer vintages of capital technologically superior to the older vintages by reducing labor input costs. Oliner develops a framework for estimating obsolescence of capital while at the same time integrating a new set of retirement figures into the analysis.

One important aspect of the Oliner paper is its analysis of retirements. In theory, retirement should occur as soon as quasi-rents fall so low that the present discounted value of the remainder is less than scrap value. Until Oliner's work we had only one or two actual empirical studies of retirement. The Bureau of Economic Analysis still uses the Winfrey studies from the 1930s.

Oliner's paper is important for another reason. The role of technical change is absolutely central to growth, capital measurement and productivity. How does one measure technical change, the impact of new goods and the separable effects of obsolescence and deterioration? This is another topic that has been a subject of much debate in recent years and has led to considerable confusion. Several recent studies have started to deal with the special and important case of new technology—the new goods problem. The apparent acceleration in new goods production resulting from the technological advances of computers, electronics, telecommunications and biotechnology has wrecked havoc in measurement of quantity and price measures. The very definition of a good comes in to question. Is a VCR a mere technical advance over recording devices or is it an entirely new product without predecessors? Regardless of how one answers this question, the modeling of technical change and its impact on capital values is closely related to these problems and concerns.

X. CONCLUSION

The papers included in this special section cover many of the important issues in empirical analysis of economic depreciation. There are certainly other issues as well, for example, the issue of quality change in new assets and its link to obsolescence and depreciation, and the role played by the cost of achieving quality change (Hulten [1995b]). The link to environmental economics is another area in which further research is needed on economic depreciation and asset depletion, as is the issue of how uncertainty about future technology, prices and other events affects asset and service prices, asset retirement, and economic depreciation.

It seems to us that the analysis of economic depreciation remains a potentially fertile field for further research. The papers in this volume not only make important contributions in their own right, but also suggest new opportunities for significant contributions to this important, but rather neglected, area of economics.

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