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Obsolescence in Economic Depreciation from the Point of View of the Revaluation Term

By

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Section 1—Introduction

Economic depreciation of an asset, or cohort of assets, is the decline in the price of the asset (or the price index of the cohort of assets) resulting from an increase in age holding time constant.[2] Measures of depreciation, based either on evidence or assumption, are needed in order to measure capital stocks and income flows from economic entities that use capital. A measure of capital input is needed for empirical productivity studies. Less obviously, a measure of depreciation is needed to obtain flows of income because the flow of capital costs used in production, among other costs, must be subtracted from revenues in order to obtain income. Errors in depreciation measurement will lead to er-

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[2] This is the definition, except for the reference to cohorts, is from Hotelling (1925). See also Hicks (1942). Jorgenson (1974), Hall (1968) and (1971), Wykoff (1970), Hulten and Wykoff (1975), (1977), (1978), (1979), (1981a, b), and (1991), and Hulten (1990) apply the same concepts and employ the same terminology.
In many accounting contexts depreciation refers to a dollar set aside to allow for capital consumption allowances. This use of the term depreciation is not a price concept but the product of prices and quantities measured in dollar units. These two uses of the term, while confusing, are not necessarily inconsistent with one another, but in this paper the term "depreciation" is always used as a price concept. Multiplied by the right quantities would yield the value (price times quantity) concept, capital consumption allowances.
For tax policy purposes in the United States, according to the Bureau of Internal Revenue (now the Internal Revenue Service (IRS) (1942), (1964), (1971), (1977), depreciation is defined as "wear, tear, and obsolescence." These two definitions, the economic theory definition above and the tax policy definition, are consistent with one another.

rors in measures of costs, income, profit, factor shares, rates of return to various inputs, income tax bases, and productivity.

Quality change, by which I mean the introduction of new goods or improvement in the quality of existing goods, has drawn considerable research attention for several decades. Technological change, of which quality change is a part, appears to be a principal cause of growth as indicated by increases in total factor productivity, output per unit of total factor input.[3] An important aspect of quality change research has been estimation of the rate of change in prices of goods that has resulted from technological progress. Excluding, from total price increase, the portion that resulted from technological change leaves a measure of price change of a constant quality good or constant quality bundle of goods.

In the U.S. this research has been used to isolate cost of living increases in price measures such as the consumer price index. A common and controversial method for doing this has been to employ price hedonics, a method developed extensively in early work on hybrid corn by Zvi Griliches.[4] Price hedonics amounts to estimating the effects, at the margin, using regression methods, of characteristics of complex goods on the prices of the goods.

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[3] Angus Maddison (1987), Christensen, Cummings and Jorgenson (1981), Hulten (1990) and (2001) and Hulten, Dean and Harper (2001) present various measures of total factor productivity. Hulten (1992) points out some interpretive problems with inferring causation from growth accounting results. In the final analysis, though, technological change, if one includes improvements in human capital, would seem to account for between 1/3 and ½ of total output growth for the US business sector and similar results have been produced in Maddison (1987) and Christensen, Cummings and Jorgenson (1981) for France, Japan, Germany and the U.K.

[4] See Griliches (1956), (1957) and (1961). Griliches (1988) and (1990) contain critiques of hedonics. A huge literature is now available on the subject. An early application to used asset prices is Hall (1971). Triplett (1990) contains an excellent review of the method of hedonics. The Boskin Commission Report (1996) on bias in the consumer price index draws on results from hedonic research. Under the auspices of the Bureau of Labor Statistics, a National Academy of Sciences special committee headed by Charles Schultze produced a (2002) report that includes a critical assessment of price hedonic techniques. Hulten (2002) and Pakes (2001) are important recent assessments of price hedonics.

Then, if one can attribute an improvement in quality of the good to an increase in the "quantity" of some characteristics of the goods, then one can deduct this portion of the overall price increase to obtain a price increase of a fixed-quality good. This is the sense in which one corrects for quality change.

For instance, suppose a new computer model in period t has a fifteen-inch screen rather than the fourteen-inch screen of the previous vintage. If the marginal effect on price of an additional inch of screen is $250, then one deducts $250 from the price difference between the new computer and the earlier vintage to obtain the price increase one would incur were one to buy a machine in period t with the characteristics of the vintage t-1 machine, namely one with a 14-inch screen. If the total price increase had been $750, then if the only difference between the two vintages was one more inch of screen, then the pure price increase would be $500.

While technological change has important consequences for growth in total factor productivity and for price indexes, it also has important implications for used asset prices and therefore for depreciation, capital consumption allowances, and replacement requirements. In particular, when new vintages of assets are introduced that embody improved quality, the (shadow) price of existing assets may fall. Since economic depreciation includes obsolescence as well as wear and tear, technological innovation causes depreciation by rendering old assets relatively obsolete. The exact consequences, of obsolescence for various capital measures and other applications, are not well understood and therefore controversial.

The purpose of this paper is to explore the role of obsolescence in economic depreciation from the point of view of inter-temporal asset revaluation. In principle one can estimate the obsolescence component of depreciation from data over time on new asset prices only. These estimates of obsolescence can provide some evidence on depreciation, without direct evidence on used asset prices. This approach is especially useful for dealing with assets that enjoy sustained physical prowess but are subject to considerable technological obsolescence. It is also useful for inferring depreciation on very long-lived and very large assets that are never marketed at all once put into service.[5]

This approach also lends insight into some of the debates that have hovered over the economic depreciation literature for some time. For example, we shall see that output decay, a term coined by Feldstein and Rothschild in (1974), often thought of as a depreciation effect, has nothing to do with depreciation but reflects an inter-temporal influence. Output decay is excluded from the depreciation term by definition. This model also lays the foundation for testing several controversial issues about the use of depreciation estimates in measuring capital stocks and capital service flows. One conclusion I draw is that in the presence of technological innovation the one-horse-shay depreciation model is not rea-

[5] Computers and information technology capital are clear examples of assets for which obsolescence, as opposed to deterioration (pure aging), is a major part of the depreciation story. Some economists believe that no deterioration takes place with computers, thus the one-horse-shay model. Dams, hydroelectric plants, bridges and other infrastructure are examples of large capital outlays that rarely, if ever, are marketed once put into service. Prucha and Nadiri (1981) suggest a method employing econometric estimates of cost functions to infer depreciation from firm data. Diewert (1977, 1980) developed a discrete-time production function model in which outputs included the next period's capital stock. From this Diewert model one can infer partial economic depreciation. The Diewert model does not allow for obsolescence. Otherwise I know of no one who has developed a model for estimating economic depreciation of such large and long-lived assets.

sonable. The Griliches argument that the value of an obsolete asset is unchanged can be tested by applying this model to data on market prices and quantities.

In section two, I set the stage by reviewing the literature on and language of economic depreciation. This summary is necessary to assure that I am communicating effectively when using often obscure and confusing terms like obsolescence, deterioration, inflation, and revaluation. Section three develops the model. First, I exploit a discrete version of the user-cost-of-capital to develop our model for estimating obsolescence from observed prices and from hedonic estimates of prices. Because hedonic-estimated price measures are used to measure the obsolescence component of revaluation, a brief update and defense of price hedonics is contained in section four. Section five then shows how the hedonic price can be used to isolate obsolescence. Estimates of obsolescence can then be combined with various possible models of deterioration to obtain possible depreciation patterns. In section six, I apply the model to a small sample of data on list prices and characteristics of laptop computers over a 55-month interval. The data come from website advertisements of one vendor's new laptop computers from January 1998 to April 2002.

Section 2—Economic Depreciation

Measures of depreciation until the late 1970s were based either on assumptions, guess work or on unpublished studies and reports by accountants and Bureau of Internal Revenue (now IRS) field agents. Accountants usually assumed depreciation patterns, until 1954, were straight line. After 1954 declining balance and sum-of-years-digits patterns were introduced into the tax code on a limited basis. Application of these patterns required an additional assumption about a parameter. As a practical matter that parameter turned out to be the asset life. For example, straight line depreciation over a 5-year life results in a depreciation rate in each period of 1/5 or 20% of the original value. Straight line depreciation on an asset with a 5-year life results in the following depreciation sequence:

Straight line depreciation pattern

Assumed Asset Life 5 years

Age of the asset:	0	1	2	3	4	5
Depreciation Allowance:	--	.2	.2	.2	.2	.2
Ratio of age-s to new asset:	1	.8	.6	.4	.2	0
Price on a $1,000 asset:	1000	800	600	400	200	0

Assuming a straight line pattern of depreciation means the same dollar value is reduced from the price each year so that the implied asset price declines with age along a straight line path. Ergo straight line depreciation. If the life is assumed to be 10 years, then the asset price is assumed to lose 1/10 of its original price each year.

One can apply the asset life parameter to the patterns other than straight line; though I would argue that asset life is a poor choice of parameter in terms of a research agenda for determining the appropriate parameter value for applying depreciation patterns. In tax code parlance, double declining balance of an asset with a 10 year life meant that one could deduct $2/10^{th}$ or $1/5^{th}$ or 20% of the remaining value of the asset in each period.

According to the code tax payers could switch to 1/10 of the remainder (straight line) at the age when that exceeded the residual rate of 1/5 on the remaining balance. This rule resulted in the following pattern of loss:

Double declining balance depreciation pattern

Assumed asset life of 10 years

Age of the asset:	0	1	2	3	4	5	6	7	8	9
Depreciation allowance:	--	.200	.160	.128	.1024	.1	.1	.1	.1	.01
Ratio of age-s to new:	1	.800	.640	.512	.4096	.31	.21	.11	.01	0.0
Price on a $1,000 asset:	1000	800	640	512	409.6	310	210	110	10	0

The asset with a 10-year life is fully depreciated by age 9 as a result of the switch to the straight line pattern at that life, approximately the midpoint of life, when 1/10 exceeds the declining balance rate.[6]

Bulletin F, produced by IRS in 1942, was for many years the basis for the tax-life accountants applied to various assets. Bulletin F reported lives by asset class. Each asset was to be assigned to a Bulletin-F class. The classes were based mainly on asset characteristics, like an office building, automobile, or a machine tool. Firms depreciated their assets by placing them in the appropriate class and then applying the straight line formula to the life for that class of asset. Different procedures were then adopted by IRS agents at

[6] Some measurement specialists worry that without a switch to straight line the declining balance formula, which is a geometric pattern of depreciation, will never fully depreciate the original asset. For this reason they believe that the geometric pattern is inappropriate for practical purposes. Two points should be made about this concern. First, with large cohorts of assets, a few do remain a very long time under almost any retirement pattern so that a long flat tailing-off pattern of residual value may accurately reflect reality. Second, if we had maintained the geometric pattern for 10 years, nearly 90 percent of the original value would have been depreciated. After 20 periods, only 1.15 percent of original value remains. These residuals are small enough that the remainder could be taken once the last asset in the cohort is scrapped.

different times. Usually a firm's asset class selections were accepted by IRS. At times, IRS agents were permitted to allow taxpayers to choose a different (usually shorter) life if they could show that unusual "facts and circumstances" warranted the shorter life.

In any case, the asset lives and the patterns of depreciation permitted for tax purposes and used by accountants for book keeping were not based on published research. This meant that one had no factual basis for judging whether the book values of assets or the depreciation allowances permitted by tax law reflected actual economic depreciation rates and patterns of assets. There was quite simply no verifiable evidence on which one could evaluate the accuracy of depreciation pattern and useful-lifetime parameter assumptions.

This gap in knowledge became evident to economists when Jorgenson, Hall, and others applied depreciation rates in studies of investment behavior in the early sixties. Was the use of the declining rate pattern for depreciation more accurate than, say, a straight line pattern? Were depreciation rates based on Bulletin F lives correct or at least adequate?

In a series of papers in the late seventies and early eighties, Charles R. Hulten and I produced estimates of economic depreciation for assets and for industries in the U.S. These estimates were based on studies primarily of used asset prices for numerous individual asset classes. Based on these estimates Hulten and I inferred rates of depreciation for all asset classes in the U.S. and utilizing a capital-industry matrix we mapped these rates into industry estimates.[7] Using these rate estimates one could estimate capital stocks, capital

[7] Today some measurement economists think the Hulten-Wykoff rates are obsolete, because the importance of short-lived assets, computers, software and electronics has increased in many industries. This may well

costs and income by industry. And of course this research may have shed light on the maintained hypotheses regarding depreciation in early investment studies.

Hulten and I did not etch our empirical estimates in stone. In fact, we thought we were producing methodologies that could be employed for estimating economic depreciation. Our estimates were based on econometric analysis of used-asset prices from a wide variety of sources on a wide number and various types of assets. We applied several non-linear regression techniques and produced non-parametric figures to approximate the patterns and rates of decline of assets that were implied by used-asset prices.[8] We extrapolated our results to all asset classes in order to produce rates by asset class. Such measures were needed in order to generate flow measures such as taxable business income.[9] Our reluctance to endorse any actual empirical values reflected our belief that the methodology was new and the data relatively limited. In fact, relative to the enormous variety of capital in the U.S. economy, the number of asset types and classes for which we had adequate data to study in some detail were relatively meager. We had expected our methodology to be explored, tested, and modified by subsequent researchers.

Despite these caveats, the Hulten-Wykoff rates (as they have come to be called) have been used extensively in order to measure capital costs for a wide variety of academic and policy purposes. Most important were studies of effective tax rates and of productiv-

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be true. However, if the only reason for revision is a change in the composition of the stock by industry, then the same rates by asset class, revised by Hulten and Wykoff in (1996) can be applied to a new capital-asset by industry matrix.

[8] We modified the price data to allow for sample selection bias resulting from retirements.

[9] See (1985) The President's Tax Proposals to the Congress for Fairness, Growth, and Simplicity. Washington D.C.: U.S. Government Printing Office, May p. 144 for an example of the practical use of Hulten-Wykoff rates for measuring corporate income and using a corporate income tax.

ity growth.[10] Effective tax rates differ from statutory tax rates when economic depreciation differs from tax code depreciation. These studies were then used to assess the relative tax treatment of different industries. Productivity studies have become widespread as well.

While consumed by some, our rate estimates and our methodology were both subject to considerable criticism, much of it warranted. One concern is that used-asset prices do not reflect in-use values of used assets, because of sample selection bias. The used-asset market from which price data is obtainable, does not consist of a random sample of used assets, but is a biased selection of lemons, poor-quality assets. Based on George Akerlof's famous (1970) lemons article, the argument is that predominantly lemons (comparatively poor units) appear for resale in used markets because owners of cherries (good units) keep their assets in use.

Poorer units are more likely to be unloaded on the used market than the perfectly good units. Good units are not offered in the used market both because their owners keep using the good ones and unload the lemons, and because buyers, ignorant of individual asset quality, discount all used-asset prices not knowing which units on the market are the lemons. This means that a user would get less on the market for cherries than they are worth in use. All of this would mean that depreciation estimates based on used-asset prices bias depreciation upward and capital stocks downward.[11] Hulten and I argued that

[10] For studies of effective tax rates, using the Hulten-Wykoff rates, see Jorgenson and Sullivan (1981), Hulten and Wykoff (1982) and Gravelle (1980a) and (1980b).

[11] This line of argument seems partly to explain resistance to the Hulten-Wykoff rates by Harper (1982) and the decision by US Labor Department, Bureau of Labor Statistics, Division of Productivity Research

asymmetric information regarding asset quality was less likely in used-asset markets populated by professional buyers and that many business-used assets were sold off when projects in which firms had used the assets were completed. This meant that cherries as well as lemons were resold in used-asset markets, such as auctions.[12]

A second set of criticisms has more to do with applications of the rates than with the Hulten-Wykoff depreciation rate measures per se. Here there are two criticisms.[13] One is that inferring information about in-use asset productive efficiencies from estimates of depreciation rates may be problematic. It can be shown mathematically that a wide range of efficiency patterns may be consistent with a single estimated depreciation pattern. This implies that employing depreciation estimates to infer capital stocks may do a poor job of measuring the in-use productivity of used assets. The latter is based on the underlying decline in efficiency and not on asset prices *per se*. In (1990) Hulten shows the theoretical linkage between depreciation and the decline in asset efficiency in the user-cost framework. Within the Jorgenson model of the user-cost one can tie asset price declines to declines in in-use efficiency.

(1983) to employ the beta-decay or hyperbolic pattern, a backward S shaped pattern of depreciation. Still, BLS made an effort to reconcile their rates with the Hulten-Wykoff findings.

[12] Even Akerlof in his original lemons article (1970) points out that as a practical matter many used markets do provide sources of information for buyers. In the extreme the logic of the lemons argument is that there would be almost no used market at all because with uncertainty a used asset of any almost any value could be driven from the market by an even lower quality unit. This is an extension of Gresham's Law. It is also important to note that markets provide two mechanisms for correcting for asymmetric information: warranties provided by credible buyers and used asset price publications, like Automobile Blue Books, that guide buyers as to likely value of used assets.

[13] One procedure Hulten and I employed was the highly non-linear Box Cox power transformation. This allowed us to test within a nested framework for geometric, straight line and one-horse-shay models of depreciation. This procedure has been criticized as well. See Berndt (1991) for an analysis of the Box Cox procedure.

The second argument along the line of applications (or interpretations) of depreciation measures is especially important to us here. Zvi Griliches frequently expressed concern about reducing the value of the stock of capital by depreciating it based on obsolescence. Griliches reasoned that even if an asset becomes relatively obsolete because new technology generates a superior one, the value of the used asset should not be reduced. The older vintage asset remains as productive as it was before the new one came on line. Put another way, if obsolescence is the cause of the fall in asset price, the value of the used asset does not fall. The new asset may be worth relatively more, but the old one's in-use value is undiminished. As Griliches used to express the point, if an econometrics professor does not know the new cutting-edge ideas, his teaching is no less valuable. It simply means some one else is teaching something new. (Griliches adds the caveat that the old professor must not be teaching material that is wrong.) I suspect this argument is at the heart of a lot of debates about measuring capital stocks, especially the debates about gross and net stocks. I hope to sharpen the debate a bit.

Section 3—The User-cost and Obsolescence

Equation (1) is a discrete version of the user-cost-of-capital:

(1) $c(0, 2001) = r(2001)\ p(0, 2001) + [p(0, 2001) - p(1, 2002)]$.

Equation (1) is the user cost of a new (age-zero) vintage-2001 asset over the year 2001.[14] The in-use cost of a new asset in year 2001, in a competitive market without taxes,

[14] This version of the user-cost equation excludes taxes and does not deal with problems that arise when we think of the user cost as the *a priori* cost of using the asset. In particular, one would have to model expectations concerning p(1, 2002). An *ex post* interpretation of the user-cost or perfect foresight assumes away the problem that p(1, 2002) may differ from the outcome used price. The user-cost concept makes sense whether or not it can be estimated; i.e., used markets need not exist for the theoretical concept of an in-use cost. The user-cost formula used in Jorgenson (1963) for example appears in its more familiar form as equation (4).

c(0, 2001), equals the opportunity cost of holding the asset for the period, say for one year between 2001 and 2002, which is the product of the interest rate, r(2001), and the asset price, p(0,2001) plus the difference between the asset price when new and the (shadow) price of the asset after one year of use.

Asset prices change for many reasons and the relationship between these changes and changes in the quantity of services provided by the asset is complex. Central to the Jorgenson model is the assumption of a duality relationship between relative user-costs and relative in-use productive efficiencies. This relationship is a standard marginal condition, applied by cost-minimizing producers, in which relative factor input prices equal the marginal rate of technical substitution. Figure 1 illustrates this relationship.

If the two factor inputs are a three-year-old machine and a new machine used in current production then the optimizing producer equates the user-cost ratios to the marginal rate of technical substitution in production between the two input service flows. Jorgenson calls the sequence by age of these marginal rates of technical substitution the efficiency function.

(2) $\Phi(s) \equiv MRS(s,0)_{\Delta t=0}$ $s = 0, 1, 2, 3, 4 \ldots$

Let c(s, t) be the user cost for each asset age-s asset at time-t. The marginal condition, for all s, is then:

(3) $\Phi(s) = c(s, t)/c(0, t) \mid \Delta_{\Delta t=0}$.

The ratio of user costs equals the relative in-use efficiency. Based on this duality relationship one can infer relative efficiencies (marginal rates of substitution—relative quantities of inputs) from relative user costs (relative prices). The user-cost in equation (1) illustrates the connection between asset prices p and user-costs c.[15]

We are particularly interested here in the portion of equation (1) in square brackets, the change in asset price over the period which we denote as Δ. For purposes of exposition we make some simplifying assumptions. (These strong assumptions are dropped below as none is necessary for subsequent analysis.) If the interest rate is constant at rate r, depreciation occurs at a constant rate δ and if revaluation occurs at a constant rate ρ, and if we define $p_{s,t} \equiv p(s, t)$, then the user cost may be written in the more familiar form as:

(4) $$c(s, t) = (r + [\delta - \rho])\, p_{s,t}$$

The term on the right hand side of this expression in square brackets illustrates that the change in the asset price over the period, Δ, can be decomposed into two terms. The first term, δ, is the decline in price with age given time, *economic depreciation*. The second term, ρ, is the change in price with the passage of time given age, *revaluation*. Both terms, δ and ρ, are influenced by vintage effects, because as an asset ages it must compete with new vintages of asset and as time passes new vintages come on line.

One can further decompose the depreciation term δ into two distinct effects. The first effect on this aging asset is caused by the introduction of a new vintage of the asset. For the case of most capital assets, new vintages embody superior technology, quality improvements. (With wines this need not be the case.) We define the effect on the price of an aging asset of the presence of a new vintage as *obsolescence*. We define the effect, apart from obsolescence, of aging, as *deterioration*. Note that in my usage here both the obso-

[15] See Jorgenson (1974) and Hulten (1990) for two clear and detailed discussions of these relationships.

lescence and deterioration terms refer to price concepts; neither is a quantity concept. Of course prices of assets and quantities of assets are linked to one another assuming duality.

Equation (3) and Figure 1 illustrate how duality links price concepts to corresponding quantity concepts. Still, the price and quantity sides of duality should not be confused. Suppose for simplicity of exposition that obsolescence occurs at a constant rate θ and that deterioration occurs at constant rate γ, then, as we will show below, the following relationship holds:

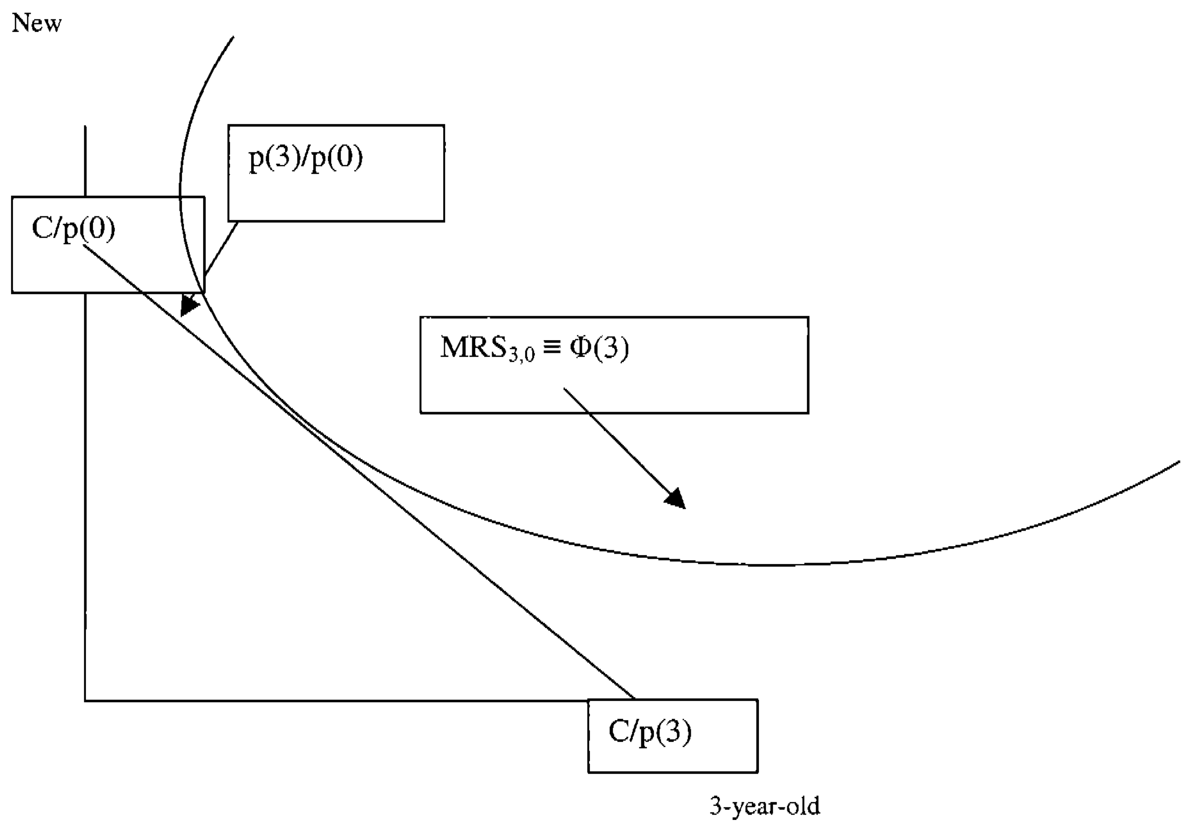
$$(5) \qquad \delta = \theta + \gamma$$

Economic depreciation δ results from two forces: obsolescence θ and deterioration γ. The precise role of obsolescence and deterioration and how they relate to quantities remains a source of debate and confusion.

The Hall Impossibility Theorem is one reason for confusion about the role of obsolescence and deterioration—in (1968) Hall shows that one cannot separately identify from price data alone price changes caused by aging (deterioration), passage of time (capital gains or losses), and changes in vintage (obsolescence). By definition the vintage of an asset is the difference between time and age. Once one specifies two of the three terms, time, age and vintage, the third is determined. A three-year-old wine in 2004 must be a vintage 2001 wine. A vintage 2001 wine is, by definition, observed at age three only in 2004. A 2001 vintage wine in 2004 must be 3 years old. The two terms chosen in equation (5) are depreciation and revaluation, but both are vitiated by containing two types of effects.

Figure 1

Price-Quantity Duality and the Efficiency Function



For clarity of exposition we use the tableau, Figure 2, assuming discrete time, to illustrate the Hall Impossibility Theorem and to clarify the connections between aging, vintage and time effects. Let each column represent a year, from 2001 to 2005. Let each row represent an age, new, one, two, three, and so on years old. In each cell is a price—the price of an asset during the designated year and of the designated age. The cell in row-4 column 2003 contains the (hypothetical) price, \$2,600, of a 4-year-old asset in 2003.

Price movements across any row, from left to right, are price changes (increases) between periods, *revaluation*.[16] Price movements down any column are price changes (decreases) with age at a point in time, *depreciation*. The actual total price change of any one asset is a movement down the diagonal—as an asset ages one period then one time period elapses as well. Recall that Δ p(0, 2001) represent the total price change, for a new 2001-vintage asset over one year of its life:

(6) $\Delta p(0, 2001) = p(0, 2001) - p(1, 2002)$

The price history of this asset corresponds to a movement down the principal diagonal from the 0-row, 2001-column to the 1-row 2002-column. In this example, we have the total price change Δ equal to \$5,000 - \$4,800 or \$200.

The total price change Δ down the diagonal can be decomposed into a vertical movement down the 2001 column and a horizontal movement across the 1-row, or into the movement across the 0-row and down the 2002 column. The total historical price change Δ is a

[16] This terminology is common in the user-cost literature and the depreciation literature. See Jorgenson (1974), Feldstein and Rothschild (1974), and Hulten, Robertson, and Wykoff (1989). Triplett (1996) uses some different terminology.

Figure 2 Tableau: asset prices by age and date

Age ↓	Year →				
	2001	2002	2003	2004	**2005**
0	$5,000	$5,500	$6,100	$7,300	**$7,750**
1	4,200	4,800	5,600	6,050	**6,500**
2	3,600	4,000	4,750	5,250	**5,850**
3	2,500	3,100	3,900	4,150	**4,775**
4	1,7000	1,850	2,600	2,950	**3,000**
5	**600**	**900**	**1,200**	**1,780**	**2,125**

decline (usually) in price resulting from aging at a point in time minus an increase (usually) in price resulting from the passage of time, given age.

Suppose one inserts ±p(1, 2001) into equation (6), then Δ can be decomposed into two parts:

(7) Δ p(0, 2001) = [p(0, 2001) – p(1, 2001)] – [p(1, 2002) – p(1, 2001)].

The tableau illustrates the decomposition of Δ in equation (7) into the two parts, a vertical step, the change in price with age, and a horizontal step, the change in price with the passage of time. Let D be depreciation and let R be revaluation then:

(8) D = [p(0, 2001) – p(1, 2001)]   R = [p(1, 2002) – p(1, 2001)]

The total price change is in equation (7) is:

(9) $\Delta\, p(s, t) = D(s)\,\big|_{\Delta t=0} - R(t)\,\big|_{\Delta s=0}$

Total price change is depreciation minus revaluation. In the example price falls by $800 from age given date and rises by $600 from passage of time, given age. The net effect is a fall in price of $200. Alternatively we could move horizontally and then vertically, so that we have Δ = 500 – 700 = - 200.[17]

Clearly from equations (7) and (8) while the depreciation term and the revaluation terms are completely different they each contain multiple effects. In particular, suppose we explicitly designate the vintage of the asset where v = t – s. Indexing vintage, as well as age and date, we re-write (6) as:

(10) Δ p(2001, 0, 2001) = p(2001, 0, 2001) – p(2001, 1, 2002)

[17] These differences reflect the approximations caused by the discrete analysis. Obviously, both steps occur simultaneously. The differences are resolved by the calculus.

Here the first index in the parentheses following each price term represents the vintage, the second term indexes age and the third indexes the date or year. The history of an asset requires that as it ages time passes, but its vintage remains the same. When we re-write the term for depreciation in (8), without changing the actual prices used at all, however, the role of vintage becomes clearer:

(11) $D = [p(2001, 0, 2001)] - p(2000, 1, 2001)]$.

Similarly, revaluation is:

(12) $R = [p(2000, 1, 2001) - p(2001, 1, 2002)]$.

Note that $\Delta = D - R$, is unchanged from equation (8), except that we explicitly allow for vintage. One can now see that depreciation, the change in price with age given date, involves two distinct forces. First, price changes (falls usually) as a result of an aging effect, an effect we call *deterioration.* Second, depreciation includes the fact that the one-year-old asset is an older vintage in year 2001 than the new vintage 2001 asset. Effects of vintage also cause depreciation, and we call this effect *obsolescence.* Note that this definition of economic depreciation is correct for the tax code because depreciation results from "wear, tear and obsolescence."

The pure aging effect (deterioration) actually results from several different forces. Some services are used up or, in the language of national income accounts, consumed. The asset has fewer periods of service to deliver (unless it has an infinite life). The likelihood of down time may have increased. The cost of repairs may have increased (or decreased). The quality of the service flow may have degenerated and the cost of operations may have increased. Anything we can think of resulting from aging applies, but not effects associated with the passage of time or the introduction of new vintages.

The vintage effect (obsolescence) is associated only with differences between a vintage 2000 asset and a vintage 2001 asset; not with aging *per se*. Was the year 2000 better for cabernet sauvignon wine grapes and thus cabernet sauvignon wines than the year 2001? Do vintage-2001 computers have larger memory than vintage-2000 computers? If we let Θ represent vintage effects (obsolescence) and Γ aging effects (deterioration), then

(13) $D = \Theta + \Gamma$

The revaluation term also contains two types of effects, vintage effects, Θ, and the passage of time effects, say Λ,[18] so that:

(14) $R = \Theta + \Lambda$

We have already described vintage effects, but the time effect Λ also requires some analysis. Time effects are not simply inflation. Inflation is a time-specific effect, but it should be excluded from time effects that influence the relative demand for and supply of the asset. Pure inflation, a decline in the price of the numeraire, has no effect, assuming money neutrality, on underlying optimization policies.[19] There are still other effects that do influence the market for the asset. Output decay is a good example of conditions that may change between periods that will influence Λ and will change the economic conditions that determine the relative price of the asset used as an input. This is not, however, depreciation, because by construction specific vintage effects and aging effects have already been excluded.

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[18] It is now necessary to define the pure time-effect, Λ. We call this term the *capital gain or loss*.
[19] Expectation and uncertainty effects can cause real effects on markets; but that is beside the point.

The combined effects on asset price change Δ are:

(15) $\Delta = D - R = [\Theta + \Gamma] - [\Theta + \Lambda] = \Gamma - \Lambda.$

Unfortunately, Hall's Impossibility Theorem tells us we cannot with price data alone isolate each term Θ, Γ and Λ. We have only two degrees of freedom to obtain information about the three effects. This is why we settle for D and R. However, a solution to the identification problem in some cases may be available.[20] The solution is based on hedonics.

Section 4—A brief update on price hedonics

An extensive literature on price hedonics reveals its widespread use in studying quality change and yet it remains controversial. Extensively developed and championed by Griliches and his colleagues and students in the academy, hedonics has taken some time to play a significant role in U.S. official statistical agencies. Though Griliches' work on hedonics started in the mid 1950s, as late as (1990) Robert J. Gordon and others were critical of official price indexes for computers not adequately corrected for quality change. Partly as a result of a nearly fifty-year-long debate among academic and statistical-agency economists hedonics now are used. Hedonics is especially helpful in correcting for quality change for products like computers and electronics where large technological changes frequently occur. One might have thought that was the end of the debate, but that is not so.

[20] Hall (1971), Berndt and Griliches (1993) and Berndt, Griliches, and Rappaport (1993) employ hedonics in order to estimate quality change using this framework.

As recently as 2002 the National Academy of Sciences (NAS) presented a report by a distinguished panel of experts that, while endorsing hedonics as a promising research tool, expressed reservations about statistical agencies' actually employing the procedure. The hedonics approach, the NAS report argued, was not ready for prime time. Hulten (2002) notes the intellectual leap of faith required by the general public, especially political and national leaders, to accept abstract regression methods in the production of national statistics. It is evident that enough skepticism about government-produced data periodically comes out of the popular press. As Hulten argues, it is one thing for field agents to try to collect data and quite another, from a public perception point of view, for statisticians to generate data from abstract, esoteric procedures.[21] While academic and government statisticians who specialize in analyzing price indexes may have become comfortable with hedonic results, especially compared to the matched-model alternative, the public may not be ready.

Of course, the fact that the Boskin Commission was being used as a political foil to possibly reduce the growth rate of Social Security benefits helped to produce more heat than light in the public debate. It also didn't help matters that the community of hedonic researchers had still not achieved a consensus on the efficacy of the procedure.

[21] One need only recall with bemusement the public outcry when the Boskin Commission (1996) announced the presence of about a 1.1 percent upward "bias" in the CPI. Journalists asked why BLS was biased and why had they failed to get it right. Were they incompetent, stubborn or even corrupt? Katharine Abraham, Director of BLS, was grilled by the Senate for not adopting modern techniques. All of this was, while unfortunate, absolute nonsense. Statisticians, including the Boskin Commission and agency researchers, meant bias in a purely statistical sense. This in no way impugned the agency statisticians who were producing the numbers. In fact, of course, many of the most important research papers on CPI bias had been produced by the statistical agency researchers, including those at BLS, for some time.

While Griliches had successfully employed the method as early as 1957, another eighteen years elapsed before Sherwin Rosen (1974) developed theoretical conditions in which hedonic methods produced identifiable coefficients. It turns out that a rather restrictive set of market conditions are necessary for hedonic regression to produce identifiable parameter estimates. Unfortunately the Rosen article was a little too obtuse so that Rosen's caveats were paid lip service and largely ignored. The hedonic method did seem to be producing sensible results about the extent to which price changes reflect quality change. Hedonics is easy to use; and once you see it in operation it is relatively straight forward.

The soft underbelly of the hedonic method, though, was the evident instability of estimated regression coefficients—the effects of individual characteristics seemed to be quite sensitive to modeling and sampling. Also, some economists were concerned about the theoretical underpinnings of the model. Rosen had shown that only in a world in which suppliers are very limited in the market can one be sure that estimated coefficients reflected identifiable underlying parameters. Diewert in (2002) develops a consumer optimization model from which one can derive a hedonic equation. Diewert provides therefore a consumer-theory rational for price variations to reflect variations in "quality" as measured by variations in the quantities of characteristics. Unfortunately, as Diewert recognizes, since he does not model the supply side, the coefficients are not necessarily equilibrium values for both supply and demand sides.

Fortunately for hedonics' users, Arial Pakes (2002) proposes a potential way out of the problem. Pakes notes that based on Rosen's model, one should not expect estimated coefficients to be stable. He points out that if producers employ different marketing strategies, then this can lead to instability of estimated characteristic coefficients. However, Pakes argues that the resultant hedonic prices will still correctly reflect the market prices. In other words, while the coefficients are unstable the hedonic price estimates can still be used to estimate the effect overall of quality change on prices. Given this result we shall employ the idea of a hedonic estimated price below.

Section 5 Using hedonic prices to isolate vintage effects from revaluation

The revaluation component of price change consists of two distinct effects, obsolescence and capital gain or loss. Suppose we insert ±p(2000, 2002), the price of a one-year-old vintage 2000 asset in year 2002 into the revaluation term, equation (12):[22]

(16) $R = [p(2000, 2002) - p(2001, 2002)] + [p(2000, 2001) - p(2000, 2002)]$

One can assume that equation (16) occurs for new assets as well, since revaluation is independent of age and applies only to inter-temporal effects, and the following expression is a little more natural:

(17) $R = [p(2001, 2002) - p(2002, 2002)] + [p(2001, 2001) - p(2001, 2002)]$.

The first term in square brackets on the right-hand side of equation (17) consists of a change in price as a result only of a change in vintage given date at 2002. This is the obsolescence effect. The second term in square brackets is capital gain or loss without a vintage effect.

Strictly speaking p(v=2001, s=0, t=2002) does not exist: certainly in the case of wines, a vintage is absolutely tied to a date. This fact results in the identity problem of effects as-

[22] I delete the age term since it remains unchanged in the revaluation effect.

sociated with v, s, and t explained by Hall. Hall points out, though, that price hedonic regression provides a partial solution. The efficacy of price hedonic regression depends on the gradual adoption in new-asset markets of new characteristics. This means that, over the years of a sample, new assets with some old-vintage characteristics are sold on the market alongside new assets with the newer vintage characteristics. From data on new-asset prices and with overlapping vintage characteristics, price hedonics can answer the question: What would the price of a new vintage-t asset be in period t+1? For instance, the price of a new vintage-2001 asset in year-2002 can be estimated using price hedonic regression.

From equation (17) and an estimated hedonic price for a vintage t-1 asset in period-t one can estimate the separate effects of obsolescence Θ and capital gain or loss Λ, because equation (17) can also be written as

(18) $R = \Theta(v)\,\big|_{\Delta t=\Delta s=0} + \Lambda(t)\,\big|_{\Delta v=\Delta s=0}$.

Note that obsolescence, from the revaluation term is:

(19) $\Theta = [p(2001, 2002) - p(2002, 2002)]\,\big|_{\Delta\Lambda = \Delta T = 0}$.

Since obsolescence also appears in the economic depreciation term, this estimate of Θ can be used to estimate the obsolescence portion of the depreciation term.

This model has a number of advantages. First, if one knows economic depreciation, then one can isolate out the obsolescence effect and identify the deterioration effect. Second, if one can find a way of estimating deterioration, say by motion studies of used assets, by maintenance and repair records on assets, or by observation of retirement patterns and heterogeneity characteristics of cohorts, then one can combine the obsolescence estimate with this new measure of deterioration to obtain an estimate of economic depreciation. Another advantage to identifying obsolescence and deterioration is that one can test the essence of the Griliches concern: To what extent does the market deplete the practical productive efficiency of used assets when depreciation is caused by obsolescence as opposed to deterioration? If one can answer this question, then one might be able to resolve the debate about the efficacy of net vs. gross capital stocks.

One can match estimates of the pattern of obsolescence taken from a sequence of equation (19) over vintages with various assumptions about deterioration to obtain lower bounds on rates of depreciation. Starting with a one-horse-shay deterioration pattern, the pattern of economic depreciation only gets steeper as one accelerates the possible pattern of deterioration. One can combine one-horse-shay or hyperbolic patterns of deterioration over several useful lives in order to see what the entire economic depreciation pattern might look like.

Naturally, since the pure inter-temporal effect Λ is $R - \Theta$, one can estimate Λ as well. This term, frequently confused with inflation is important because it contains output decay as well other purely inter-temporal effects on asset price such as devaluation of the unit of account, pure inflation. If one corrects Λ for inflation, the result is the change in relative price over time of a fixed-quality asset.

Section 6 Empirical illustration with laptop computers

The data

Dell in recent years has been issuing announcements of its new computer models on its web site. The sequence of advertisements vary somewhat, but they usually include prices and many characteristics of the new models, emphasizing new and, in Dell's view, characteristics that will appeal to their target audience. Based on such announcements that appeared in selected months from January 1998 to April 2002, we were able to construct 55 observations. Each observation specifies the announced price of the computer and the features included in the advertisement. Since these are announcements of the most recent new laptop computers from Dell and since each advertisement is dated we have the date the asset is marketed at this particular price as well. In addition to price and date of sale, we have information on as many as 11 characteristics, though some characteristics are not mentioned in some advertisements. Table 1 contains a small sample of observations to illustrate the nature of the data.

We have data for 18 different months during the interval from January 1998 to April 2002. Remarkably over this four-year, four-month interval substantial changes in most characteristics took place. For instance, in late 1997, based on the January 1998 advertisement, the top-of-the-line Dell laptop, the Inspiron-3000 selling for $3,399, had a Pentium-I chip with .233 gigahertz, 32 megabytes of memory, a 2.1 gigabytes hard drive and a 13-inch screen. The operating system was pre-microsoft-2000; there was no 56-K modem. Neither DVD nor read-write (RW-CD) capacity was available.

Table 1 Sample of the data

------ some of the 18 hedonic characteristics* ------										
Price	Time	Mod	Proc	GHz	Mem	GByts	Screen	OpSys	CDRW	Video
$1299	53	I-2650	IV	1.600	512	20.0	14	XP	1	8
5109	52	I-8200	IV	2.000	1000	60.0	15	XP Pro	1	64
2118	41	I-8000	III	0.900	64	10.0	15	2000	1	16
2599	34	LC600	III	0.700	64	6.0	14	2000	0	0
1899	22	I-3700	C	0.333	32	4.8	13	1998	0	--
2500	14	I-7000	II	0.333	64	4.8	14	1998	0	--
3598	2	I-3000	I	0.266	32	2.1	13	1998	0	--

Legend: Time: the date the advertisement appeared. 52=4/02, 1=12/97.
Mod: model. I is Inspiron and L is Latitude.
Proc: processor. IV is Pentiurn-IV and so on C is Celeron. GHz: processor gigahertz.
Mem: memory in megabytes
GByts: gigabytes of hard drive.
Screen: screen in inches
OpSys: operating system (Microsoft).
CDRW: Compact Disk read-write capability.
Video: Quality of video capability.
Note: Other characteristics included 56-K modem; DVD capacity; weight; warranty in months; 3-COM.

By April 2002, the Inspiron-8200 model selling for $2,876 sported a 1.6 gigahertz Pentium-IV processor, 512 megabytes of memory, a 20 gigabyte hard drive and a 15-inch screen. It had capacity for a read-write CD, and an advanced DVD system with up to 64-video capacity. Dell included Microsoft XP-Pro operating system and a 56-K modem. Not all characteristics uniformly improved. Some improved by leaps and some regressed. For example, the warranty offer fell from 36 months for some early vintages to 12 months for some recent vintages. Of course in each period different systems were available, so that there is considerable overlap of characteristics over the time period. This overlap is essential for hedonics. There was also quite a bit of movement in prices over the nearly four-and-a-half years. Prices for the 55 observations ranged from $999 to $5109. The mean price was $2,403.81 with a standard deviation $927.74.

Hedonic price estimates

We ran a variety of hedonic regressions, varying the functional forms, characteristics, and observations. We ran linear, log-log, and semi-log forms. The data included two model designations: Inspiron models and Latitude models. Some regressions excluded the Latitude models; some did not. Some characteristics were too infrequently reported to be useful. Availability of technical support for instance, was mentioned sometimes but too infrequently. Two of the Latitude observations appeared to be outliers, a vintage April-2002 L-C840 and a vintage April-1998 L-CP, so we ran some regressions without these two observations.

In any case, Table 2 reports results for two regressions, both linear, one on 53 observations and 11 variables and one on 44 observations (latitude models excluded) and 13 variables. The latter had 31 degrees of freedom. The coefficients of determination are .95335 and .96419 respectively. We only included variables that had t-statistics larger than 1.5.

The estimated coefficient of screen size had the tightest fit based on the t-statistic. The processor power, in gigahertz, had by far the largest positive coefficient, and, the dummy variable representing the presence of the Microsoft-XP had the largest negative coefficient. The latter may reflect in part a marketing strategy or the market's negative reaction to the new operating system.

Implied obsolescence

The first step in estimating the pattern of obsolescence implied by the data is to specify the exact characteristics of each new vintage laptop computer. Table 3 contains assigned values for the twelve variables other than vintage, from the right-hand side of the regression in Table 2, for eleven select dates. We selected values that appear to be top-of-the-line values in each particular period.

We have selected only those dates for which new vintages were significantly different, in terms of the variables in the equation, from the previous vintage. (At this point we report on results for the second column of regression results from Table 2, Inspiron laptops only.) From the regression results of Table 2 and the vintage-specific characteristics in

Table 2 Illustrative hedonic regression results

	Linear			Linear	
	With Latitudes ↓#4 & 45			Inspiron only	
Variable	Coefficient	t-statistic		Coefficient	t-statistic
Date	-82.75	13.55		-58.66	9.50
D: I≥8000	Xxx	xxx		-481.79	3.81
D: I<4000	Xxx	xxx		-171.84	1.86
D: L-CS	899.09	7.38		Xxx	xxx
D: L-CP(i)	546.33	3.86		Xxx	xxx
D: Pent-IV	-923.80	3.18		Xxx	xxx
D: Pent-I	Xxx	xxx		414.97	2.78
processor GHz	2590.22	5.71		1105.60	3.43
hard drive GBz	34.03	5.26		43.75	7.61
screen inches	196.32	25.5		204.97	22.27
D: 56k modem	342.36	3.04		637.70	4.77
D: Microsoft XP	-1120.53	7.49		-1108.74	7.17
D: CD-RW	Xxx	xxx		-295.48	2.22
Weight	-17.91	1.56		-19.89	1.63
3COM	761.08	5.56		715.54	5.26
Video capacity	Xxx	xxx		9.15	2.41
**** Equation statistics ****					
No. of observations	53			44	
Degrees of freedom	42			31	
Standard Error	220.81			212.92	
R-bar-squared	.94224			.95033	
Durbin Watson	2.196			2.542	

Table 3 Definition of Vintage by Characteristics
In Linear Regression Equation on Inspiron Laptops

Vintage	Model	Model	Chip	Prcsr	H-D	Scrn	56K	XP	CD/RW	Wgt	3COM	Video
	I-8	I<4	P-I	GHz	GBz	Inch	D8	D9	D13	Lbs.	D	size
3/02	1	0	0	2.000	60	15	1	1	1	7.62	1	64
10/01	1	0	0	0.860	30	15	1	1	1	3.80	1	16
4/01	1	0	0	0.700	10	15	1	0	1	3.80	0	16
3/01	0	0	0	0.600	6	14	1	0	1	3.80	0	16
9/00	0	0	0	0.600	6	14	1	0	0	5.20	0	2
6/00	0	0	0	0.500	6	14	0	0	0	6.25	0	2
2/00	0	0	0	0.466	5	14	0	0	0	6.25	0	2
1/99	0	0	0	0.366	4.8	14	0	0	0	6.25	0	2
4/98	0	1	0	0.266	3.2	13	0	0	0	6.90	0	2
1/98	0	1	1	0.266	2.1	13	0	0	0		0	0
12/97	0	1	1	0.233	2.0	12	0	0	0		0	0

Table 3, one can ask the following questions: (1) What would a vintage t-1 asset cost in period t when new? What would be the price of a new vintage t-x asset, for all x, in period-t? We answer these questions for one date. (We chose the end of the sample period, April-2002). This procedure results in two new sequences of prices, both derived from the hedonic regression technique. The first is the set of prices in each period, since period-1, of assets that differ from the previous period's vintage only in vintage characteristics, holding both age and date constant. The second set is prices at one point in time, April-2002, of assets that differ only by vintage. From these sequences of hedonic prices one obtains the pure Θ-pattern, obsolescence unpolluted by wear-and-tear effects or by date effects.

In Table 4 we present the results for ten of the Table 3 vintages. (The earliest vintage observation is lost in this procedure, because we are asking what would the price be of the previous period's vintage, v=t-1, were it to be sold after the new vintage-t asset is on line, but assuming the previous vintage asset is new and selling in period-t.) Column two of Table 4 indexes the vintage of the asset, in the period it is first marketed.[23] (Column one is a counter.) Only selected vintages are presented in Table 4 and the intervals between vintages shown are not equal.

Vintage is followed in column three by the price of each vintage asset in its vintage year based on the regression. For instance, the item in cell column 3 of row 4 is the price, $1,862.11, of a vintage April, 2001 asset in period 40—April, 2001. The coefficients for

[23] Date April 2002 is indexed as 52. February 2002 is 51. The earliest vintage in the data set is December 1997 and is indexed as 1.

Table 4 Hedonic prices, revaluation and vintage effects
Revaluation decomposed into obsolescence and capital gain/loss
(Insprion laptops)

	Date*	Price	Revaluation	hedonic prices		decomposition of revaluation	
#	T	v=t	p(t) – p(t-1)	v=t-1	v=t-x, t=52	Θ	Λ
1	52	$4761.81	$2642.95	$1825.55	$4761.81	$2936.26	-293.31
2	47	2118.86	306.67	1460.21	1825.55	658.65	-351.97
3	41	1812.19	-49.93	1803.45	1166.90	8.74	-58.66
4	40	1862.11	-491.44	2001.58	1158.17	-139.47	-351.97
5	34	2353.55	593.16	1584.40	1297.63	769.14	-175.99
6	31	1760.39	-153.31	1679.05	528.49	81.34	-234.65
7	27	1913.70	-643.30	1794.39	447.15	119.31	-762.61
8	14	2557.00	42.34	1986.70	327.84	570.29	-527.96
9	5	2514.66	-680.08	3018.75	-242.45	-504.09	-175.99
10	2	3194.74	205.48	2930.59	261.64	264.14	-58.66

* These are the values of the dates used in the regressions; 2 is January, 1998 and 52 is April, 2002.

each characteristic (as specified in Table 2) come from the regression results. Column four is the revaluation term,

$R = p(t) \mid_{v=t} - \; p(t\text{-}1) \mid_{v=t-1}.$

Revaluation is the first difference by rows of column 3 prices.[24]

The next two columns, five and six, are hypothetical prices based on hedonics. Column five is the price of a vintage-(t-1) Dell laptop when new in period t. Column six is the price of each vintage Dell laptop when new in April-2002. Specifically, column six is the price of a vintage t-x asset in period t where t=April-2002 and x consists of selected months running back through January-1998. For instance row 5 of column 6, $1,297.63, is the price of a January-2001 vintage asset if were to be marketed new in April-2002. The difference between this price and the price of the new April-2002 vintage asset in April-2002 is pure obsolescence, given age and date. Thus, $4,761.81 minus $1,297.63 is the price increase between January-2001 and April-2002 resulting only from technological change in one year and two months.

Finally, in the last two columns, seven and eight, the revaluation term, column four, is decomposed into obsolescence and capital gain/loss as explained in Section 4. Recall that

(20) $\Theta = [p(v) - p(v\text{-}1)] \mid_{\Delta s=\Delta t=0}$ and $\Lambda = [p(t) - p(t\text{-}1)] \mid_{\Delta s=\Delta v=0}$

Some interesting results are evident from Table 4. The revaluation term, column four, jumps around quite a bit. Sometimes revaluation is positive and sometimes negative. This reflects the fact that revaluation is caused by a host of effects; effects that, as shown

[24] See equation (17) for the revaluation term.

above, can be decomposed into a vintage term (obsolescence) and a passage of time term (capital gain or loss). These forces include shifts in supply and demand for the asset as well as changes in markets for its complements and substitutes. This also includes change in the prices of various outputs for which the asset is an input. These forces include, but are not restricted to, technological innovation and inflation. Innovation can drive down the prices of earlier vintage assets and inflation can drive them up. Clearly some of these forces push prices down and others push them up.

Vintage effects (quality change) ordinarily raise prices of new assets over time, e.g., the obsolescence component of revaluation is ordinarily positive, because quality is improving and fixed-vintage assets will sell for less in subsequent periods when they have to compete with the newer, more advanced vintages. Ordinarily each new vintage of asset costs more than the last, because the new ones have superior characteristics. However, the sequence of computer prices of a fixed-vintage asset, constant quality, is falling with the passage of time. This latter effect is seen in the last column of Table 4. Figure 3 illustrates the estimated and actual prices for observations from the data.

One can illustrate the relationship between price and vintage at a point in time, from Table 4, by plotting p(v=t-x)/p(v=t) against v(t-x)/v(t). See Figure 4—this is the actual pattern of obsolescence implied by equation (19) and hedonic regression results for Inspiron laptop computers. The obsolescence rates during 1998 to 2002 seem to me to be surprisingly rapid. In April of 2002, a new laptop with the characteristics of 3-year, 2-months

Figure 3 Hedonic prices and actual "average" prices

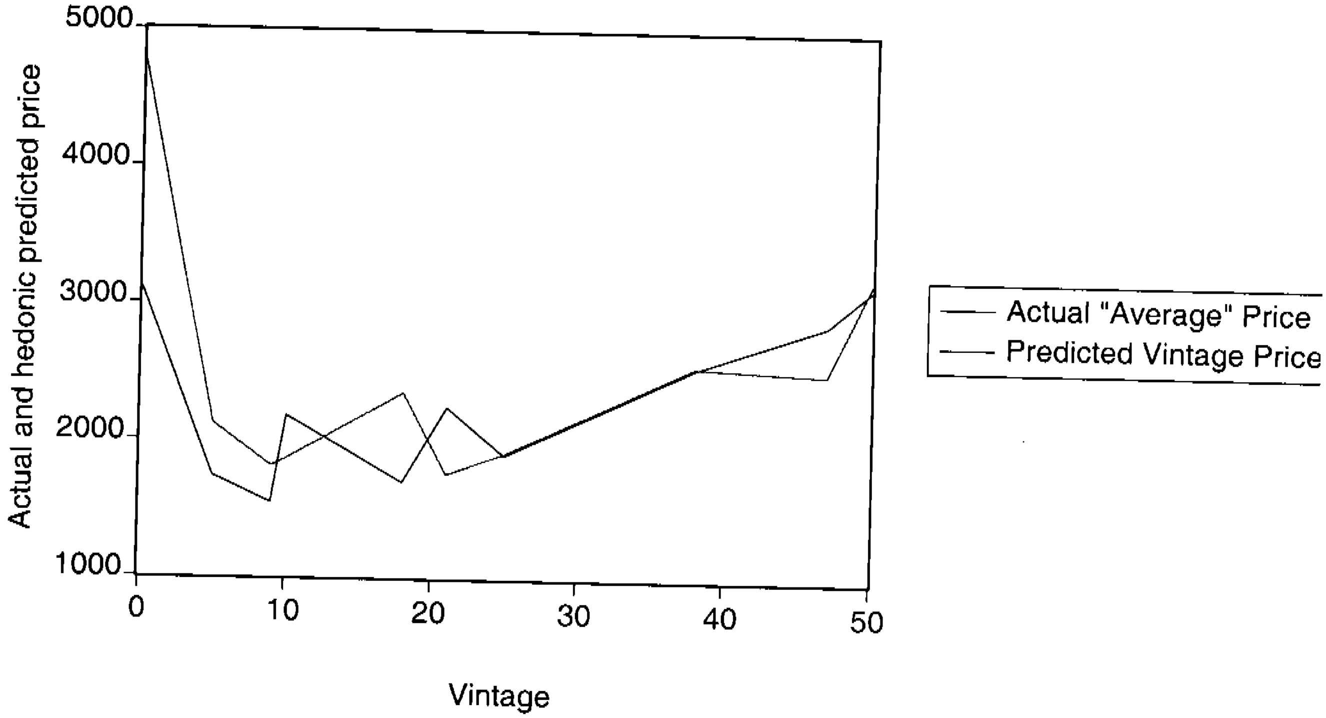
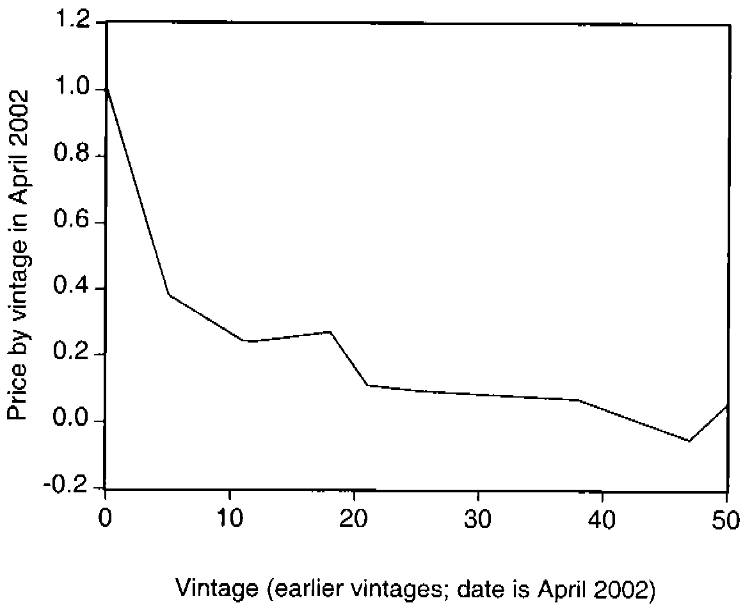


Figure 4 Relative price by vintage in April 2002



earlier vintage, February 1999, would have had a negative price. A laptop less than six months obsolete was worth less than 40 percent of a new one.

Implications of obsolescence for economic depreciation

Economic depreciation is the sum of obsolescence and deterioration

(21) $D(v, t) = \Theta(v) \big|_{\Delta t = \Delta s = 0} + \Gamma(s) \big|_{\Delta t = \Delta s = 0}$

To learn more about obsolescence in order to use it to analyze depreciation, we estimate a constant rate of obsolescence model:

(22) $\text{Log } p_i(v) = \alpha + \beta\, v_i + \mu.$

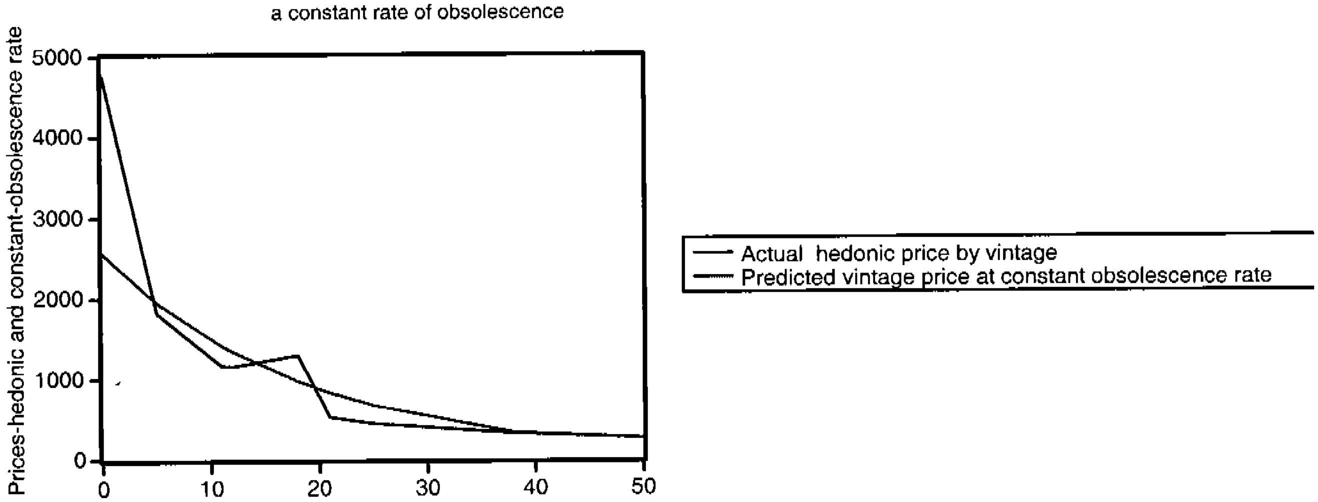
The vintage prices used to estimate the unknowns in equation (22) are from column 5 of Table 4. Table 5 summarizes the statistical results of the regressions. Figure 5 illustrates the hedonic prices and the prices predicted by the obsolescence equation for Inspiron from Table 5 by vintage. Figure 6 illustrates the same sequences normalized on a new vintage April 2002 asset price both for the actual vintage prices and the vintage prices predicted at the constant obsolescence rate. The constant rate pattern, as can be seen from Figure 6, is much slower, less bowed, than the actual observed pattern.

The constant rates of obsolescence, .0535 and .1354, from the two illustrated models can be used to produce obsolescence sequences, for 48 months. These two sequences, reproduced in Table 6, are illustrated in Figure 7. As a result of obsolescence alone, at these rates, depreciation is between 80 percent and 50 percent after 1 year (12 months). By April 2002 a vintage April 2000 asset, even if brand new, was worth between 30 percent

Table 5 Estimated Rates of Obsolescence

Estimators based on obsolescence results computer from Table 2 regressions					
	With Latitude and Inspiron			Inspiron laptops	
Variable	coefficient	t-statistic		Coefficient	t-statistic
Constant	1.2540	1.1112		5.0652	16.567
Vintage	0.1354	5.1878		0.0535	6.184
***** equation statistics *****					
No. of observations	5			9	
Degrees of freedom	3			7	
Standard error	0.3605			0.3892	
R-squared	0.8997			0.8453	
R-bar-squared	0.8663			0.8232	
Durbin Watson	3.2980			1.9754	

Figure 5 Hedonic and fitted prices assuming
a constant rate of obsolescence



Vintage (Up to 50 months from April 2002)

Figure 6 Obsolescence patterns
actual and constant rate

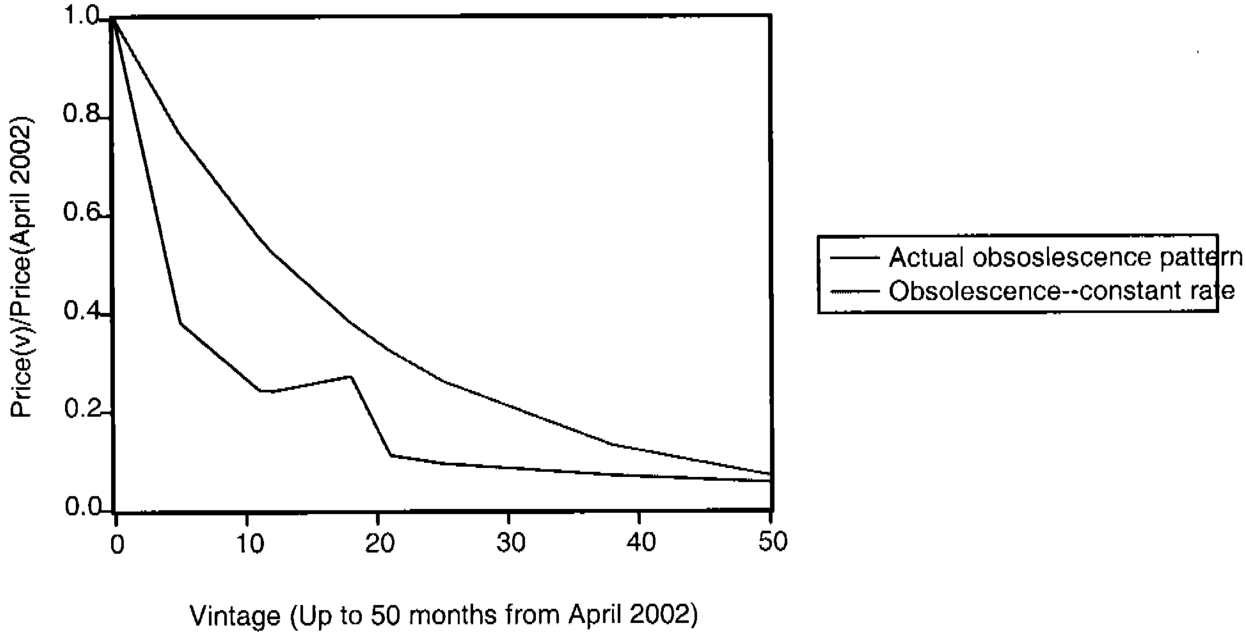
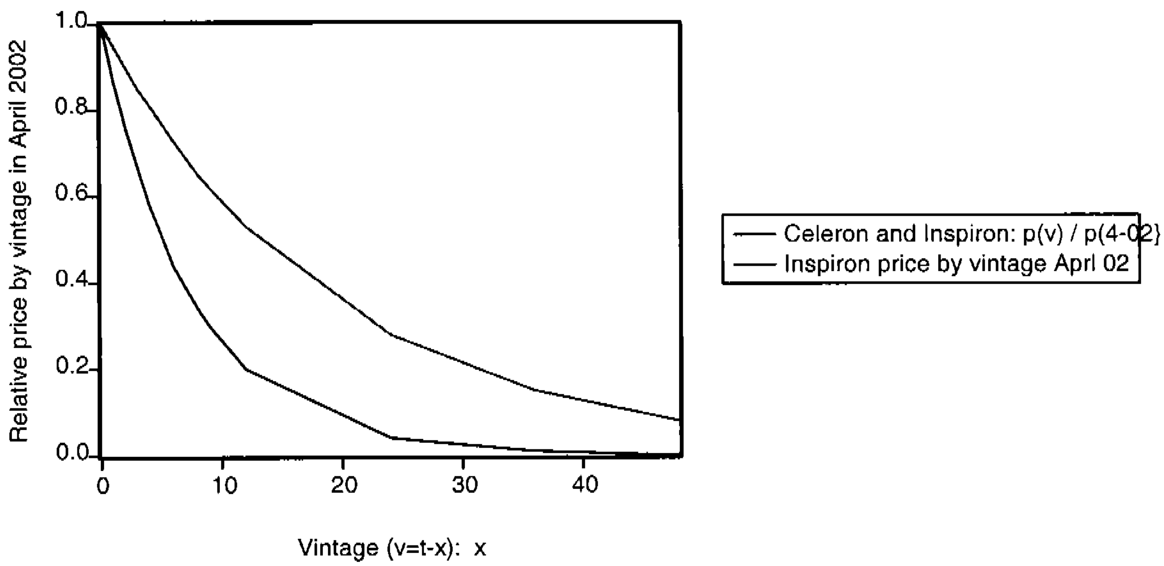


Table 6 The Obsolescence component of depreciation assuming constant rates from Table 5 regressions

	Obsolescence patterns	
	Vintage: t-x where t=1 (April 2002)	
	x indexes vintages by months	
	Latitude and Inspiron	Inspiron
Vintage (v=t-x): x	P(v)/p(0)	P(v)/p(0)
0	1.00	1.00
1	.87	.95
2	.76	.90
3	.67	.85
4	.58	.81
5	.51	.77
6	.44	.73
7	.39	.69
8	.34	.65
9	.30	.62
12	.20	.53
24	.04	.28
36	.01	.15
48	.00	.18

Figure 7 Obsolescence constant rates:
With and without Celeron



and 5 percent of its original value. After 48 months the earlier vintage-asset has lost between 82 percent and 100 percent of its value.

Integrating obsolescence with possible deterioration models is an exercise in speculation, since we have little evidence on laptop computer deterioration patterns *per se*. It is, nonetheless, instructive to observe that even if deterioration follows a one-horse-shay pattern, then the depreciation pattern will be quite steep once one takes obsolescence into account.

For illustrative purposes four deterioration schemes, two one-horse-shay patterns and two hyperbolic patterns, are assumed. Each deterioration pattern is assumed to have either a 5-year (60 months) or a 10-year life (120 months). This means that zero deterioration occurs for 5 or 10 years. Even with no deterioration for 60 to 120 months economic depreciation has reduced relative asset prices by 96 to 100 percent by the time the one-horse-shay collapses to dust.

The hyperbolic pattern, a two parameter function, depends on the assumed asset life, L, and on a "decay" (or in the lexicon here a deterioration) parameter, β.[25] When β is between zero and one, the pattern tends to be humped. With higher β-values the hyperbolic

[25] At this point terminology can be confusing. If one thinks of "decay" as a physical process, then it is a quantity concept and not part of depreciation *per se*, which is a price concept. I use the term deterioration to refer to the effect on asset price of aging. Under duality, the relative efficiencies, quantity concepts, equal relative user-costs, so that in equilibrium decay and deterioration may be equal.

can accommodate straight line and even approximate geometric. The hyperbolic function is:[26]

(23) $p(t-s)/p(t) = (L - s)/(L-\beta s)$

For any given (assumed) asset life, L, the hyperbolic pattern of deterioration obviously is more rapid than the one-horse-shay, so integrating it with the obsolescence pattern has some impact on depreciation before the end of life. The beta coefficient used by BLS for machines is .5; so we start with that value. A β value of .5 produces a humped shape.

Table 7 contains information on 4 different deterioration patterns—two one-horse-shay and two hyperbolic, each at L = 60 months (a five-year life) and L = 120 months (a ten-year life). Combining obsolescence and deterioration produces economic depreciation. Since the one-horse-shay does not kick in until the end of asset life, the depreciation pattern is the obsolescence pattern until the last month. When L = 60 months and the one-horse-shay finally collapses, only 4 percent of its original value remains. Where L = 120 months, only 1.6 percent of the asset remains by the end of life after obsolescence.

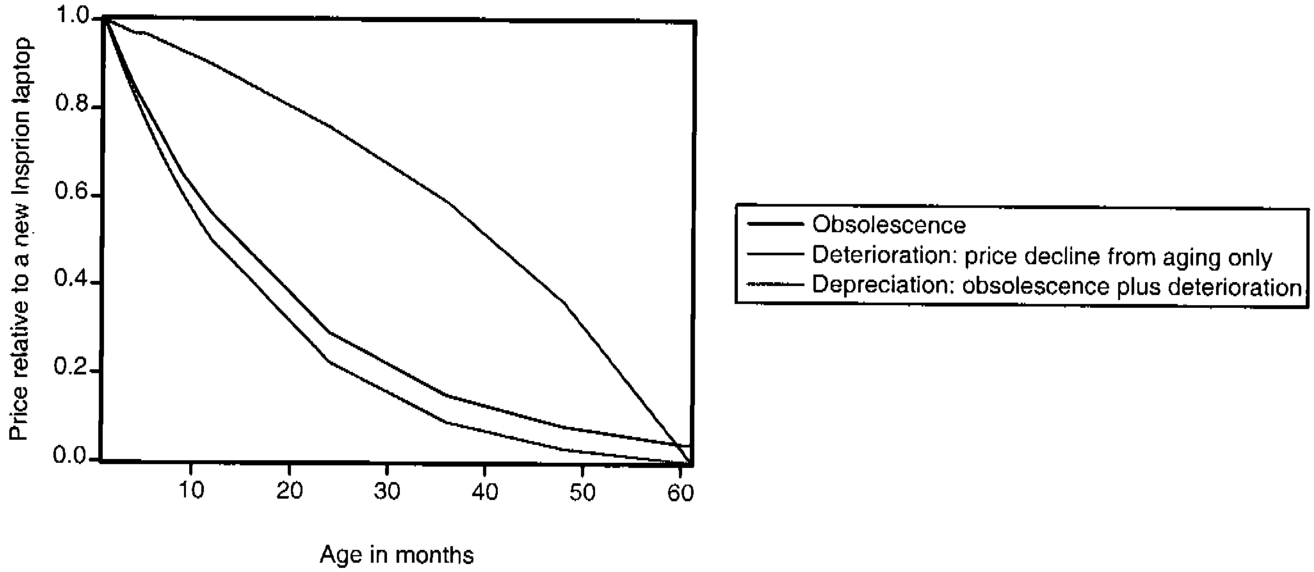
Assuming a hyperbolic deterioration pattern with β = .5O, the overall depreciation pattern is basically a steeper shadow of the obsolescence pattern. The depreciation rate for geometric obsolescence at rate 5.38 percent per month and hyperbolic deterioration with β = .50 and an asset life of 60 months (5 years) is illustrated in Figure 8. The red humped

[26] The Bureau of Labor Statistics employs the hyperbolic function. See Harper (1982). See also Hulten (1990b) fn. 8 for the properties of the hyperbolic.

Table 7 Relative prices of Inspiron laptop computers by age:
Economic depreciation by month

Depreciation: obsolescence (Θ) plus deterioration (Γ) = depreciation For 4 deterioration schemes								
	$D = \Theta + \Gamma$: Γ is one-horse-shay			$D = \Theta + \Gamma$: Γ is hyperbolic β = .5				
		Depreciation					depreciation	
Month	Θ	L=60	L=120	Θ	Γ L=60	Γ L=120	L = 60	L=120
1	1.00	1.00	1.00	1.00	1.00	1.00	1.000	1.000
2	.95	.95	.95	.95	.99	.996	.940	.944
3	.90	.90	.90	.90	.98	.992	.883	.891
4	.85	.85	.85	.85	.97	.987	.830	.841
5	.81	.81	.81	.81	.97	.983	.780	.794
6	.77	.77	.77	.77	.96	.979	.732	.749
7	.73	.73	.73	.73	.95	.974	.687	.707
8	.69	.69	.69	.69	.94	.970	.645	.667
9	.65	.65	.65	.65	.93	.966	.605	.629
10	.62	.62	.62	.62	.92	.961	.568	.594
11	.59	.59	.59	.59	.91	.957	.532	.560
12	.56	.56	.56	.56	.90	.952	.499	.528
24	.29	.29	.29	.29	.76	.894	.223	.261
36	.15	.15	.15	.15	.59	.829	.090	.127
48	.08	.08	.08	.08	.36	.756	.029	.061
60	.04	.04	.04	.04	.03	.674	.001	.029
61	.04	.00	---------	.04	.00	--------	.000	-------
72	.0224		.0224			.580		.013
84	.0118		.0118			.471		.0056
96	.0062		.0062			.345		.0021
108	.0033		.0033			.195		.0006
120	.0017		.0017			.017		.00003
121	.0016		.0016			.000		.00000

Figure 8 Depreciation: obsolescence + deterioration
deterioration hyperbolic beta .5
obsolescence constant rate

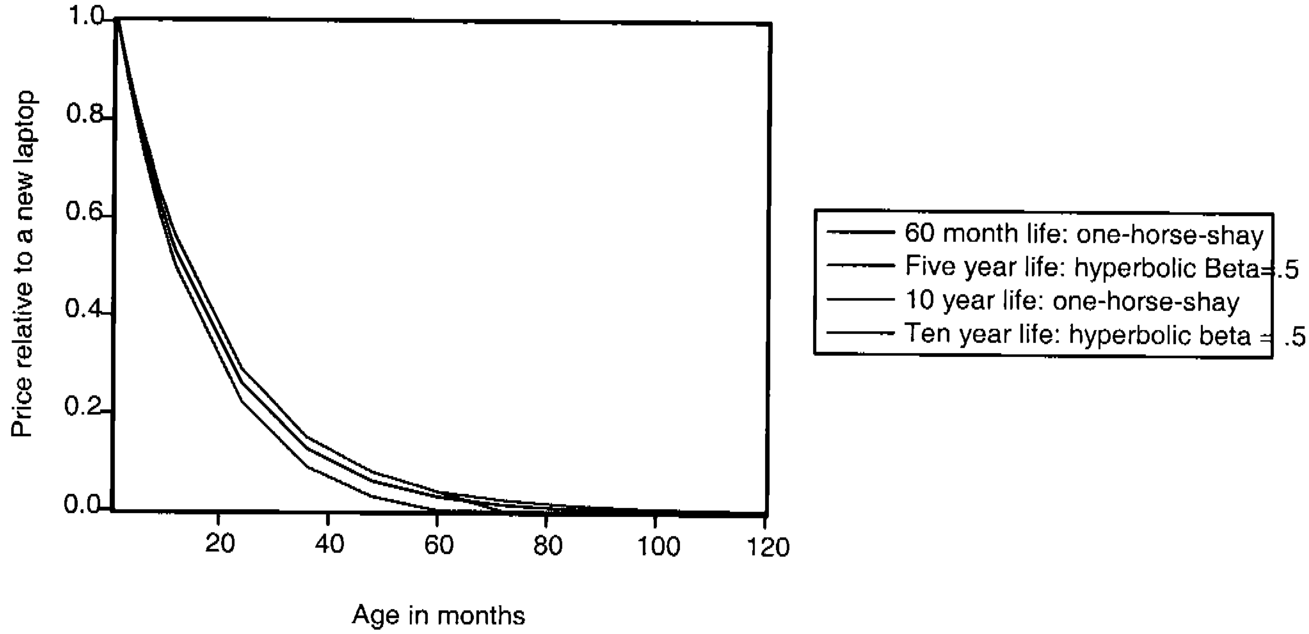


curve is deterioration and the blue geometric curve is obsolescence. The green approximately-geometric curve mirrors the obsolescence pattern.

Finally in Figure 9 we reproduce all four depreciation patterns. It is evident from this figure that obsolescence completely dominates depreciation. The choice of asset life, even between five and ten years and even assuming one-horse-shay or hyperbolic, extremely sluggish deterioration patterns, makes no real difference in the depreciation process. This figure seems to beg the question of why gross stocks are produced. Only if obsolescence is irrelevant and if deterioration is extremely sluggish is the depreciation pattern hump shaped like the red curve in Figure 8. Could it be that those who believe that asset depreciation patterns should be hump shaped, do not think obsolescence should be taken into account? Perhaps the Griliches argument, as long as the old professor continues to do what he has always done, even if a new, superior-vintage, recent graduate is teaching advanced material, the old professor is just as productive, carries the day. Still, one might ask, "Will students pick the old, obsolete professor when they have a choice of a new, superior young gun?" My view is that Zvi Griliches may have been a rare exception to the rule that students would prefer to learn the newest techniques (at least if they are indeed superior!). Most of us choose the most recent vintage laptop computer and put the old one in the attic where its productive efficiency becomes zero.

We might have applied a more interesting deterioration pattern assuming a heterogeneous cohort of new computers, say, acquired when new by a large firm, rather than to a single laptop unit. In this case, the deterioration pattern would have to account for early loss of

Figure 9 Four depreciation patterns
One-horse-shay (L = 5, 10 years)
Hyperbolic (L=5, 10 years and beta = .5)



shorter-lived computer models, in-use decay of the performance of some computers, frequency of breakdown, costs of loss time, and some pattern of retirements about the "average" life. Since all of this would be speculative, I do not do this here.

Section 7 Summary and conclusions

While one would not take seriously the statistical results from such a small sample of information on Inspiron laptop computers, I think it has been shown that one can approximate the obsolescence portion of depreciation from new-asset prices. In the case of products for which technological change has played a major role, obsolescence may be quite important, even dominant, relative to deterioration. Our example indicates that by the time an asset actually drops off production, it may be worth considerably less than newer assets with which it must compete as an input to production processes.

Several important questions are raised by this analysis. How do various forces associated with obsolescence, deterioration and capital gains influence asset values and usage? Separating these effects out and observing each, subject of course, to the approximate nature of price hedonics, may allow us to determine how markets and owners respond when different types of effects reduce the relative value of new and used assets. If we can answer this question, then perhaps we can close in on resolving some capital measurement disputes.

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