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Why Do Computers Depreciate?

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ABSTRACT

The value of installed computers falls rapidly and therefore computers have a very high user cost. The paper provides a complete account of the non-financial user cost of personal computers—decomposing it into replacement cost change, obsolescence, instantaneous depreciation, and age-related depreciation. The paper uses data on the resale price of computers and a hedonic price index for new computers to achieve this decomposition. Once obsolescence is taken into account, age-related depreciation—which is often identified as deterioration—is estimated to be negligible. While the majority of the loss in value of used computers comes from declines in replacement cost, this paper shows the second most important source of decline in value is obsolescence.

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Personal computers rapidly lose economic value. Within two years after purchase, the price of a used computer has typically fallen to well under half of its price when new. This rapid loss in value occurs even though the two-year-old computer can do exactly the same computations it did when it was new and suffers only small changes in reliability, physical appearance, or in other observable attributes. The two-year-old computer can typically produce the same documents, run the same regressions, and connect to the same server as it did when new. Hence, by most measures, it can produce the same output. Thus, economic depreciation takes place with little or no physical deterioration or loss of productive capacity.

The general source of this economic depreciation is not a puzzle. New computer models are typically both cheaper and more powerful than older ones. Hence, the value of old computers falls to bring the value of the computing power they can deliver in line with its current replacement cost. Computers also become obsolete because they become incompatible with new operating systems or software, or do not have hardware that becomes standard in new models (e.g., CD readers, Internet adapters).

Though the economics of depreciation of computers is relatively clear, there are substantial gaps in measuring this phenomenon. Specifically, we know of no research that explicitly links new and used personal computer prices to measure depreciation rather than presuming a rate of depreciation from the change in prices of new computers.[1] The estimates of depreciation of computers in the National Income and Product are based, for example, on

[1] Oliner's (1992, 1993) important work on computer depreciation focuses on mainframe computers and computer peripheral equipment. Berndt and Griliches (1993) use hedonic price regressions based on new PCs only.

changes in the price of new computers. In this paper, we estimate directly the depreciation in value of personal computers by comparing the price of used computers to the price of the same computer when new. The data set we have collected has matched new and used prices of several thousand computers, the years sold when new and used, the age, and a precise description of important characteristics. The richness of our data allows us to overcome a common problem in the measurement of depreciation—that the effects of vintage, age, and time are typically not separately identified. [See Hall (1968), Hulten (no date).] The method of this paper adapts the procedure of Ramey and Shapiro (2001), which estimated such rates of depreciation in value for used equipment as a function of age and measures of flexibility of the equipment in alternative uses, by including measures of the obsolescence of the used equipment. This paper also presents estimates of a hedonic price index of new computers that is an important ingredient in the calculation of depreciation and user cost.

Precise measurement of the depreciation of used computers, as well as a precise decomposition of its sources, is important for addressing several economic issues. First, depreciation estimates are a necessary ingredient in the measurement of the value of the capital stock. Personal computers have become an increasing fraction of both business and household capital. As measures of depreciation are important for estimating the net value of capital, our estimates should be useful for this purpose.

Second, it is important to understand the rate of depreciation of computers to understand investment in new computers. The user cost of computers is among the highest for any type of equipment because of the rapid fall in replacement cost and the high rate of economic depreciation. For investment to be positive, computers must have very high marginal products to balance the high cost of owning them. That is, computers are purchased with the knowledge that investment in them will have to be amortized over a short period of years. This paper will provide a decomposition of the user cost of computers into change in replacement cost and economic depreciation, with economic depreciation decomposed into age-related deterioration and into obsolescence.

Third, to calculate an index of capital services for total factor productivity measurement, it is necessary to have a reliable estimate of the user cost of the various types of capitals (Jorgenson and Griliches, 1967). Given the importance of information technology investment in the recent acceleration in total factor productivity, having a good estimate of the user cost of computers can make an important contribution to measuring the pace of technological change.

Fourth, the estimates of the impact of obsolescence on the value of installed capital can provide valuable insights into the propagation and effects of new technologies.

The remainder of the paper is organized as follows. Section 1 sketches our theoretical framework. Section 2 discusses our data. Section 3 outlines our empirical implementation. Section 4 presents the estimation results. Section 5 presents their implication for user cost. Section 6 gives our conclusions.

1. Theoretical Framework

The work of Hall and Jorgenson (1967) on user cost and the work of Hall (1968, 1971), Hulten and Wykoff (1981, 1996)), Oliner (1993), Jorgenson (1996) and others on depreciation provides the framework for this analysis. Consider first the definition of user cost,

$$R^K \equiv P^I(r + \delta - \pi^I)\,, \tag{1}$$

where P^I is the constant-quality price of new investment goods in period t, r denotes the nominal opportunity cost of funds, δ is the depreciation rate, and π^I is the rate of change of P^I. The user cost relationship is derived from an intertemporal arbitrage between purchasing new equipment currently versus purchasing new equipment in the future, in which the capital stock evolves according to $\dot{K} = I - \delta K$ where I is gross investment.[2] Absent adjustment costs, the marginal product of having a unit of capital installed at time t should equal the user cost, that is, the sum of the opportunity costs of funds, the economic depreciation, and the capital loss from selling the equipment in the future.

This paper will use a second arbitrage, between new and used equipment, to quantify the economic depreciation component of user cost. Specifically, the paper will use the wedge between the new and used price of the same computer to quantify economic depreciation. Consider, $q_{t,t-v}^{NOM}$, nominal ratio of used to new computer prices,

$$q_{t,t-v}^{NOM} \equiv \frac{P_{t,t-v}^{U}}{P_{t-v}^{N}}, \tag{2}$$

where $P_{t,t-v}^{U}$ is the price of a used piece of equipment at time t that was new at time t-v and P_{t-v}^{N} is the price of the equipment when it was new. Note that in our analysis, the prices refer to a specific piece of equipment, not to a price index. Why would $q_{t,t-v}^{NOM}$ not be identically one? Suppose that the only change in the environment were the change in the replacement cost of new equipment. That is, suppose that the same piece of equipment were available at time t as at time t-v and there were no technological change except for potentially a change in the cost of the new equipment. (In the computer example, this would correspond to a decline in the price of a CPU or RAM of a given quality.) Moreover, suppose that the used piece of equipment suffered no deterioration whatsoever, and that there were no costs of adjustment, installation, or resale. In

[2] This equation may be derived from a continuous time dynamic optimization problem. It can also be viewed as an approximation from a discrete time problem. In the case of computers,

this case, contemporaneous arbitrage would require that the price of the used computer fall by the amount that replacement cost had declined. That is, with no economic depreciation, $q_{t,t-v}^{NOM} \equiv \frac{P_{t,t-v}^{U}}{P_{t-v}^{N}} = \frac{P_{t}^{N}}{P_{t-v}^{N}}$. In practice, we do not typically observe P_t^N, the price of the new good currently, and instead substitute the constant-quality new (replacement) investment good price index P_t^I. Hence, if there is no economic depreciation $q_{t,t-v}^{NOM} \equiv \frac{P_{t,t-v}^{U}}{P_{t-v}^{N}} = \frac{P_{t}^{I}}{P_{t-v}^{I}} \equiv \exp(\pi_{t,t-v}^{I})$. Note that $\pi_{t,t-v}^{I} = \int_{t-v}^{t} \pi^{I}(s)ds$ denotes the cumulative rate of change of constant quality new investment good prices as defined in the user cost formula (1).

Define (real) q as

$$q_{t,t-v} \equiv \frac{P_{t,t-v}^{U}}{P_{t-v}^{N}} \exp(-\pi_{t,t-v}^{I}) = q_{t,t-v}^{NOM} \exp(-\pi_{t,t-v}^{I}) . \tag{3}$$

Under the special circumstances just outlined, real $q_{t,t-v}$ would be one and user cost would come only from the change in replacement cost.

Now consider the more general case, where new and used equipment are not perfect substitutes because of economic depreciation. Real q measures the fraction of original real value left, so under the assumption of exponential but not necessarily constant decay, it is linked to the depreciation rate δ by

$$q_{t,t-v} = \exp(-\delta_{t,t-v}) , \tag{4}$$

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though, the rates δ and π are so large that the approximation is not very good.

where $\delta_{t,t-v} = \int_{t-v}^{t} \delta(s)ds$ and $\delta(s)$ is the depreciation rate at instant s. We will decompose economic depreciation into three components.

Age-related depreciation or *deterioration*, denoted δ_v, captures the wedge in value between new and used equipment that is strictly a function of age. It is frequently modeled as a geometric function of time. We will consider that specification, as well as more general cases.[3]

Age-zero depreciation, denoted δ_0, captures the loss in value the instant that a piece of equipment is sold. This instantaneous depreciation can arise from lump-sum costs of adjustment, installation costs, and transactions costs.[4] Additionally, it may also represent the discount from customization, i.e., that a purchaser of a new computer may get to choose its precise configuration while the buyer of the used computer does not.[5]

Obsolescence, denoted δ_s, represents the change in value of used computers because they have fallen behind the current technology. Our empirical strategy is to use measures of obsolescence to quantify δ_s. We discuss in detail below how we implement this empirical strategy.

We will treat the three components of depreciation as additive, so

$$\delta = \delta_v + \delta_0 + \delta_s . \tag{5}$$

[3] Deterioration may also be a function of intensity of use. Depreciation in use does not appear, however, to be an important factor for computers, and is not considered in this paper.
[4] Adjustment costs are another reason for q to differ from one. We believe these are well-captured by the instantaneous depreciation.
[5] The instantaneous depreciation could also represent a lemons discount owing to adverse selection. As with the case of machine tools (Ramey and Shapiro, 2001), we argue that lemons discounts are unlikely to be substantial in the used PC markets because PCs rarely are lemons, and because the rare lemon is easy to detect.

Obsolescence is in no sense a residual. The average discount of used relative to new computers that we cannot account for with observed measures of obsolescence or with age will be counted as age-zero depreciation.

We can combine equations (3), (4), and (5) to characterize the decomposition of the components of nominal q as

$$q_{t,t-v}^{NOM} = \exp[\int_{t-v}^{t} \pi^I(s)ds] \cdot \exp[-\int_{t-v}^{t} (\delta_0(s) + \delta_v(s) + \delta_s(s))ds] \tag{6}$$

or

$$q_{t,t-v}^{NOM} \cdot \exp[-\int_{t-v}^{t} \pi^I(s)ds] = q_{t,t-v} = \exp[-\int_{t-v}^{t} (\delta_0(s) + \delta_v(s) + \delta_s(s))ds], \tag{6'}$$

that is, (real) q equals cumulative economic depreciation. The use of the contemporaneous arbitrage between new and used prices to quantify depreciation in (6) provides a link to the intertemporal arbitrage in the user cost relationship (1). In particular it makes clear the distinction between two different effects of technological change on user cost. First, technological changes can make new capital goods *cheaper* over time. The price decline in computers has been dramatic. This first channel for technological change is captured by π^I in the user cost expression. When the price of replacement investment goods is falling, this channel adds substantially to user cost even if there is no deterioration or obsolescence. Second, technological change can make new capital goods *better* over time. This change does not directly reduce the intrinsic productivity of existing capital; it can still perform its previous functions (e.g., a steam locomotive can still pull a train in the age of diesel). Nonetheless, with significant enough technological progress, existing capital may become obsolete. This process can be quite fast for computers given the importance of networks in the broad sense (e.g., operating common software, exchanging data, as well as connection to the Internet). As technology evolves, a serviceable old technology becomes unproductive as the network and infrastructure for operating it vanish.[6]

2. Data

Our data consist of information on used computers gathered from the Orion Computer Blue Books. The Orion Research Corporation has been publishing used pricing guides for a wide range of consumer products since 1973. The products covered by the guides include audio/visual equipment, cameras, musical instruments, copiers, vintage collectibles, and televisions. They have been publishing their computer price guide quarterly since 1982. The Orion Blue Books are currently used by retail dealers, insurance companies, computer manufacturers (including Dell, Gateway, and Micron), and the Internal Revenue Service to provide an accurate reflection of the used computer market.

Orion determines used computer prices through surveys given to used computer dealers nationwide. Dealers are asked to provide the asking price, selling price, and days the computer was in stock before it was sold. The used price listed in the book is the average price of a computer that was sold in less than 30 days. Computers which were sold after being on the market for longer periods did not have their selling prices included in this computation. The Orion Blue Books also include a retail price (price when new) of the used computers listed in the book. Using computer company advertisements in back issues of PC Magazine and PC World we were able to determine that the retail price listed reflects the new price of the computer approximately nine months to one year after the model was first introduced. The range of dates the specific computer model was manufactured is also given, as are the specific attributes of the

[6] To pursue the rail analogy, steam engines are not productive without water towers.

model, including monitor type and size (if one was included in the purchase price of the computer), speed, amount of random access memory (RAM), hard drive storage space, type of hard drive, type and speed of CD-ROM or DVD-ROM, Ethernet card or modem, and type of processor (Pentium, Celeron, 286, AMD Athelon, etc.). They include prices from nearly 700 manufacturers, including all major computer companies.

For our study, we focused on data for Compaq and Gateway computers. Many manufacturer listings in the blue books were inconsistent from year to year in which models were included in the pricing, making analysis of the same model's used price over a long period of time difficult. This problem was encountered for many major computer manufacturers listings, including IBM and Dell. Compaq and Gateway have a thorough listing of prices across numerous models and over a long time period, making it well suited for our analysis. We coded data beginning with the Winter 1990 Blue Book, and proceeded yearly until the Winter 2001 edition.[7]

We coded the attributes of the computer available from the blue books. These include the dates the model was sold, the new price, the used price, and some characteristics of the computer. These include the amount of RAM, the size of the hard drive, the speed of the CPU, the type of CPU, the speed of the CD drive (if any), and the make. Though we have more detailed information, we have coded the CPUs as follows: Intel 286, 386, 486, Pentium I, Pentium II, Pentium III, Pentium IV or AMD Athelon and non-Intel processors other than AMD Athelon.

After deleting computers with missing data, we have 3,135 observations. We observe used prices in years from 1990 to 2001. The computers we observe were produced between

1984 and 2001. The computers range in price when new from a minimum of $499 to a maximum of $32,880. The average new price of a computer was $3,428. Used prices range from $7 to $14,140. The average used price is $526. The computers ranged in speed from 12 MHz to 933 MHz, with the median computer having a 100 MHz processor. Random access memory (RAM) varies from 256 KB to 512 MB, with a median of 16 MB. Hard drive space varied greatly, with some computers sold without hard disks, and some containing 40 GB.[8] The median size 1 Gb.

These data are summarized in Tables 1, 2 and 3. Table 1 shows the attributes by year when the computer was new. Table 2 shows the attributes by the year that it was sold. Table 3 shows the attributes by the age when it was sold. The tables demonstrate the dramatic improvement in the observable attributes over the period of the sample.

3. Empirical Framework

3.1. *Hedonic model for new computer prices*

For goods such as computers, where the quality of new goods is changing rapidly, much of the decline in the resale price of existing capital derives from competition with new models that are both better, and possibly cheaper, than the older models. This environment does not alter conceptually the user cost framework, but it does provide a substantial measurement challenge. A constant quality, e.g. hedonic, price index can be used to adjust the acquisition price of a used computer to make it comparable to a new computer.

[7] We were unable to obtain the Winter 1991 and Winter 1994 Blue Book editions from Orion, and thus the used prices from these years are not present in our data set.
[8] We exclude diskless machines from the sample.

While not the focus of the paper, we use our data set to estimate a hedonic model of new computer prices. We regress the log of new computer prices, $\log(P^N_{t-v})$, on a constant, year dummies, and attributes to measure the quality. These attributes include the log of the CPU speed, the log of the size of the hard disk drive, the log of the size of the random access memory (RAM), a dummy for whether the computer has a CD drive, a dummy for whether the computer is made by Compaq, and a set of dummies for six generations of CPU (Intel 80286, 80386, 80486, Pentium I, Pentium II (and non-Intel competitors AMD K-6, Celeron, Duron, Cyris), and Pentium III or IV or AMD Athelon).

We experimented with allowing the prices of the attributes to vary with time as recommended by Pakes (2001). The estimates (fitted values) were extremely noisy. (Estimation error is also given substantial attention by Pakes.) Therefore, we present time-dummy estimates, which a recent National Academy panel has labeled as *Griliches-neutral* (see Schultze and Mackie, 2002, p.151). Our data set is not designed for estimating hedonic models along lines Pakes suggests, i.e., it is relatively small and not designed explicitly so that competing models of different attributes are marketed simultaneously, so it is not a good test bed for Pakes's recommended procedure.

Table 4 reports the estimates of the hedonic equation for new computer prices. Even this simple model explains two-thirds of the variance of the log of price. The year dummies show a sharp and relatively steady rate of decline in prices.

3.2. *Modeling depreciation*

The estimation equation we consider follows from taking logarithms of both sides of equation (6) or (6') and then considering alternative functional forms for the various components of depreciation. Noting that cumulative change in constant value replacement cost is

$\int_{t-v}^{t} \pi^I(s)ds = \log(P_t^I / P_{t-v}^I)$, the basic equation is

$$\log(q_{t,t-v}^{NOM}) = \log(P_t^I / P_{t-v}^I) - \int_{t-v}^{t} (\delta_0(s) + \delta_v(s) + \delta_s(s))ds$$

or

$$\log(q_{t,t-v}) = -\int_{t-v}^{t} (\delta_0(s) + \delta_v(s) + \delta_s(s))ds$$

where $\log(q_{t,t-v}) = \log(P_t^U / P_{t-v}^N) - \log(P_t^I / P_{t-v}^I)$. Recall that the used and new prices, P_{t-v}^N and P_{t-v}^N, are specific to a particular observation, while the constant-quality price index P_t^I is either a function of time only (in the case of the BEA index) or of time and attributes of the computer (in the case of our hedonic index). We will estimate this relationship over our sample of computers.

We observe the same computer at two points in time, so our data have a panel structure. Note, however, that the theoretically-mandated specification above takes the difference (used versus new price) as the dependent variable rather than differencing an expression in the level of price, so the coefficients of time-invariant parameters (such as characteristics of the computer) are identified, and time-invariant unobserved effects of the computer remain in the disturbances.[9] Though we observe different computers at different points in time, our econometric specification is a cross-section of changes of price from new to used because we do not follow particular computers at more than two points in time.

The following subsections consider alternative parameterizations of the economic depreciation function.

3.3.1. Age-related depreciation

To model age-related depreciation, we consider several functional forms for how the value of $q_{t,t-v}$ depends on the age of the computer. In the most general formulation, we allow depreciation to be a general function of the age *v* of the computer. To do so, consider the relationship

$$\log(q_{t,t-v}) = \alpha_0 + \sum_{v=1}^{V-1} \tilde{\alpha}_v \tilde{D}_v + \varepsilon \tag{7}$$

where α_0 is instantaneous depreciation, $\tilde{\alpha}_v$ is the cumulative age-related depreciation as of age *v*, and $\tilde{D}_v$ are dummies that equal one for observations with age *v* and zero otherwise, and *V* is the maximum age of a piece of equipment in our sample.[10] The variable ε is a mean zero, idiosyncratic disturbance. The α's in this regression correspond in most cases to the negative of the δ's in the depreciation model of the theoretical section.

In the estimates, we consider a different formulation. Let D_v be a dummy variable that equals one for a piece of equipment of age *v or greater* and zero otherwise. We will estimate the relationship

$$\log(q_{t,t-v}) = \alpha_0 + \sum_{v=2}^{V} \alpha_v D_v + \varepsilon \tag{8}$$

where the α_v are the annual rates of depreciation between ages *v*-1 and *v*. Note that equation (8) fits the data identically to equation (7), but is easier to compare with annual estimates of depreciation. Note also that the age 1 depreciation cannot be separately identified from the α_0

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[9] These disturbances are implicit in the integrals of the components of depreciation in the expressions above. They will be made explicit in what follows.

[10] The are a few observations in our sample where the year when new is the same as the year when sold. We have coded these as one-year old pieces of equipment.

We also consider the restriction that the annual rate of depreciation is constant or a polynomial function of age. Specifically, we estimate

$$\log(q_{t,t-v}) = \alpha_0 + \sum_{k=1}^{K} \alpha^k v^k + \varepsilon \tag{9}$$

where K is the order of the polynomial, v^k is the k^{th} power of age, and α^k are parameters. With K equal to one, we have standard case of constant geometric depreciation, i.e., that the coefficients α_v in equation (8) are equal. This specification has the advantage that it allows us to separately identify age 1 depreciation from α_0.

3.3.2. Obsolescence

We then generalize equations (8) and (9) to allow for shifters of the discount for used capital relative to new capital. Ramey and Shapiro (2001) emphasize how specificity of capital can lead to such discounts over and above physical depreciation. Personal computers are highly fungible across industry and activity, so these considerations seem very unlikely to be relevant. Computers may, however, be less fungible over time. The IBM AT computer that this paper might have been written with 15 years ago would have gotten the job done almost as well as the Pentium IV laptop. Certainly, the current statistical software and word processing software is easier to use and runs faster, but the 15-year-old technology would have sufficed to get the job done, presumably with no effect on the quality of the analysis or quality of the writing. Using the 15-year-old technology to write this paper *now* would, however, be considerably more difficult. Media for storing and transferring data have changed. Old software does not work with new printers. The old computer cannot run new software, and new software might have been necessary to read a dataset. Hence, even though the old AT could have once performed the task and is still physically operational, i.e., has not depreciated physically, its productivity has declined.

This reduction in productivity relates not to the physical operation of the computer, but to its interoperability with other computers. Even before the Internet, such network economies related to common software, media, and data formats drove much of the value of computers.

Increasing incompatibility with the current state of technology is a source of obsolescence and therefore of user cost that is not well modeled either as physical deterioration or as a reduction in the price of new computers owing to the decline in production costs of delivering computing power. This paper will attempt to measure obsolescence and quantify its role in the user cost of computers. Specifically, we augment equation (8) or (19) as

$$\log(q_{t,t-v}) = f(age) + X'\beta + \varepsilon \qquad (10)$$

where *f(age)* is the dummy-variable or polynomial function of age discussed above, *X* is a vector of measures of obsolescence, β is a vector parameters to be estimated.

To measure obsolescence, we consider how the attributes of the used computer—the speed of its CPU, the amount of its RAM, and the size of its hard disk—stand in relationship to attributes of current new computers. Again, current software and operating systems are designed to make use of power and capacity of current new computers. Often, the owner of an older computer does not have the choice of running new software.

The specific measures we consider are the deviation of the logarithm of the computer's speed, RAM, or disk size from the median log speed, RAM, or disk size of current new computers.[11] We also consider a composite of these measures, defined as a weighted sum, where

[11] Because of heaping of attributes, the log of the median equals the median of the log.

the weights are the coefficients of the attributes in a hedonic regression of new computer prices. The estimates of these hedonic coefficients are given in Table 4.

Table 5 reports the means values of these measures of obsolescence by year sold and age when sold.[12] Table 5 shows how rapidly attributes of computers get out of date. At an age of one year, the RAM of a used computer is 48 percent that below the median RAM of a new computer, its speed is 36 percent slower, and its hard disk is 55 percent smaller. The value metric of the composite attribute shows a 32 percent decline. For older ages, the decline is rapid and continues for all but the oldest ages.

The other measure of distance of the used computer from the current technological frontier is how many generations its CPU is behind the generation of the best CPU available in new computers. We classify CPUs according to the six generations discussed above in the specification of the hedonic model. The last column of Table 5 reports the average number of generations a used computer is behind the frontier by year sold and by age. There is an upward trend in number of generations the CPU is behind with year sold. In earlier years, there are fewer generations of CPUs available. With age sold, the number of generations behind increases from just under one on average for one-year old computers to four generations for the oldest ones.

[12] We have few observations on new computers produced in 2001 because very few were resold within the year. The median RAM of the 2001 computers that we observe actually fell from 2000. *For this calculation only*, we recode the median RAM in 2001 to equal 128MB, the same value as in 2000. For all earlier years, there are sufficient observations of new computers in our sample to get reliable estimates. Note that the observations of new computers are perhaps not a representative sample. To get into the sample as a new computer, the computer must have a resale price. If prices of computers for which there is a secondary market differs systematically from the representative new computer, this feature of the data set leads to a potential source of bias.

Finally, software compatibility is an important issue for obsolescence of hardware. It is the combination of hardware and software that creates computer output. Thus, introduction of new software can lead to induced demand for upgraded hardware. The operating system in particular is central since other software introductions usually follow the introduction of a new operating system.

In order to determine which types of new operating systems might have hastened the obsolescence of old computers, we read industry magazine articles over our period of study. We looked for examples of new systems that were (1) considered to be major breakthroughs in terms of what they would allow a computer to do; and (2) would only function well on frontier or near-frontier hardware. We found two new operating systems that met these requirements. They were Windows 3.0, introduced in 1990, and Windows 95, introduced in 1995. According to PC Magazine (July 1990, p. 33): "Windows 3.0 is graphical user interface that will completely change the face of MS-DOS computing" and "It will run on low-end machines, but a 286 or better–and lots of RAM–is recommended." Windows 3.1, introduced in April 1992 further increased the quality of the operating system by adding the important Object Linking and Embedding capability. Similarly, Windows 95 was considered to be major breakthrough that required an upgrade. According to Datamation (Dec. 15, 1994, p.32): "Windows 95 requires at least 8 MB to 16MB of RAM, plenty of hard disk space and at least a 486 DX2 processor to run as efficiently as advertised by Microsoft."

On the other hand, other new operating systems introduced during our period of study (1990-2001) did not meet this requirement. According to PC Magazine (June 30, 1998, p. 100), Windows 98 was not a major architectural change, so one did not need to upgrade. According to

Home Office Computing (Dec. 1999, p. 72), Windows 2000 combined the best of Windows 98 and NT, but was probably not enough to induce one to switch from either operating system.

Hence, the introduction of Windows 95 is likely to be the most important structural break in for software in our sample. Accordingly, we construct an indicator for Windows 95 incompatibility and include it in our analysis of obsolescence. Based on our review of the technology discussed above, the Windows 95 incompatibility variable is defined as one in years 1995 and after for computers that have pre-80486 CPUs or have less than 8MB of RAM.

4. Estimates

In this section we present estimates of the depreciation of personal computers based on estimating how resale price falls as a function of the age of the computer [equations (8) and (9)] and how this function shifts when the controls for obsolescence are included [equation (10)].

4.1. *Age-related depreciation*

Table 6 reports estimates of age-related depreciation for the dummy variable specification (8) and the polynomial specification (9). The left-hand side variable is logarithm of nominal q. The right-hand side variables include the change in the new price index. In columns (1) through (6), the coefficient of the price index is constrained to equal 1, so the regressions have implicitly the log of real q on the left-hand side and no price variable on the right-hand side. The last two columns relax this restriction.

Table 6 present estimates using two measures of the price of new computers, the Bureau of Economic Analysis (BEA) deflator for computers, denoted P_t^{BEA}, and the hedonic price index reported in Table 4, denoted P_t^{HED}. P_t^{BEA} is a function only of year, while P_t^{HED} is a function of year and the attributes of the computer included in the hedonic equation, so it is more closely matched to the specific computers in our sample than the BEA index.

The first column of Table 6 reports the age-dummy estimates of age-related depreciation using the BEA deflator to measure price change on new computers. The constant of –0.622 indicates instantaneous depreciation of more then 62 percent. The annual rates of depreciation are between 22 and 43 percent for the years two through six. Later years have lower rates on average and they are more variable. Though the restriction that the annual rates of depreciation are equal, which is imposed in column (2), is rejected at any standard level of statistical significance, there is only a very modest reduction in R^2 from imposing the restriction. Allowing a quadratic term in column (3) yields a significant coefficient, but adds only modestly to the goodness of fit. The annual rate of depreciation of 34.2 percent is very high—much higher than is plausible for physical deterioration. Together with the constant of 34.0 percent, these estimates fit the facts that computers loss over half their value over the first two years of their lives.

The estimates in columns (4), (5), and (6) based our hedonic price index yield similar patterns of age-related depreciation, but point estimates that correspond to about half the annual rate of depreciation.[13] The average geometric rate of depreciation is 16.6 percent based on the estimates with our hedonic price index, which, though lower than the estimates based on the BEA price index, is still very high relative to our priors about the deterioration of computers.

The last two columns present an informal specification check. We relax the restriction that the coefficient is one for each of the measures of new computer price change. For the BEA index, the unrestricted coefficient jumps to nearly two with a substantial downward effect on the

[13] The R^2 falls because the implicit left-hand side variable is more variable.

annual rate of depreciation. (With a bigger coefficient on price change, which increases with age, the coefficient of age takes on a lower value.) Though the coefficient of price change differs from one when price change is measured with our hedonic index in column (8), it is much closer to one. Consequently, the annual rate of depreciation is affected less. Based on this greater stability of the estimation equation and that our price index can be much better matched to the specific observations because it is a function of attributes as well as time, we use our hedonic price index in the remainder of our estimation. We will return to the specification test based on inclusion of the price index in the estimation equation once we have considered the measures of obsolescence.

4.2. *Obsolescence*

As discussed above, an advantage of our data set is its rich detail about the characteristics of the computers sold. By including measures of computer characteristics in our specifications, we can separate the effects of age, time, and obsolescence. We explore the effect of several measures of obsolescence of personal computers on the discounts of used computers relative to their reflated acquisition cost. These results are reported in Table 7. The first column of Table 7 includes the quadratic in age specification from Table 6, Column (6), for reference.

4.2.1. Obsolescence of attributes

Columns (2) and (3) of Table 7 present estimates for the determination of depreciation for used computers by age and by these measures of obsolescence, as measured as deviation of the attribute of the computer from the median new computer at the time when it was sold (see above). Column (2) includes the speed, RAM, and hard disk measures separately. Column (3) includes the composite measure based on the weighted sum of the three separate measures. In column (2), the obsolescence measures based on the individual attributes have significant incremental explanatory power and are, except for the hard disk, statistically significant. The obsolescence of RAM and CPU speed have negative effects on depreciation, and substantial coefficients. For example, having a CPU that is half the median speed lowers the value of the used computer by about 21 percent.

Imposing the restriction that these measures enter as the weighted sum in column (3) has only a negligible effect on the fit.[14] The estimated effect of obsolescence on depreciation is substantial. The average two-year old computer has a composite obsolescence of 0.59, that is, the hedonic value of the hard disk/speed/RAM bundle has fallen by 59 percent (see Table 5). Multiplying this amount by the coefficient of –0.639 yields a predicted depreciation from obsolescence of -0.377.

These measures of obsolescence have a substantial effect on the estimates of the age-related depreciation, whether entered individually in column (2) or as a composite in column (3). Relative to the estimates from column (1), age-related depreciation has fallen dramatically and is only marginally statistically significant. Hence, controlling for obsolescence essentially eliminates the age-related component of depreciation.

4.2.2. Distance of Used CPU from Frontier

We construct a variable "CPU lag" which indicates how many generations the computer's CPU is behind the frontier. If the computer has the latest CPU, then this variable is equal to 0. The

[14] The sample is large enough, however, that the linear restriction implied by (4) versus (3) can be rejected at any standard level of significance.

number of generations the CPU is behind the frontier is broadly a measure of incompatibility of an existing computer with current software and operating systems.

Table 7, Column (4) reports estimates for CPU lag entered as dummy variables for lagging one to five generations (zero lag omitted). This set of variables has more explanatory power than the measures of attributes. With the exception of the lag five, the magnitude of impact of lags on depreciation increases with the lag.

Columns (5) and (6) of Table 7 present estimates where both CPU lag and the measures of obsolescence of the CPU speed, RAM, and hard disk are included as explanatory variables. Though the RAM and speed variable remain significant, as does the composite attribute, these variable add little to the explanatory power of the CPU lag dummies. The coefficient of hard disk has the "wrong" sign, but given hard disk size's interaction with other factors such as CPU generation and speed of computer, this coefficient should not be overinterpreted.

4.2.3. Obsolescence and Operating System

As discussed in the previous section, the introduction of the Windows 95 operating system in 1995 made previous generations of computers incompatible with the state-of-the-art operating system. To study how this affects the price of used equipment, we construct a dummy variable that is one in 1995 and thereafter for computers with pre-80486 CPUs or less than 8MB of RAM, and zero otherwise.

Including this dummy as a measure of obsolescence leads to the surprising result reported in Table 7, Column (7) that Windows 95 incompatibility carries a premium in the resale market.[15] There are several possible explanations of this premium. Perhaps individuals did not want to switch to Windows 95, so computers with older systems installed (as opposed to new ones that would come with Windows 95) had a scarcity value. Additionally, the used market was flooded with high-quality, pre-Windows 95 machines from business that needed to upgrade, and that the increase in quality of the used computer pool rather than the increase in supply dominated the change in price. Because Windows 95 triggered replacement of machines by businesses, the quality of those sold as a consequence would have been higher than were they replaced on a normal cycle in ways not captured by the other covariates. If so, this result is an example of Pakes's (2001) point that hedonic relationships capture equilibrium prices, not just the utility value of attributes.

4.3. *Specification test*

Recall that in last two columns of Table 6, when the restriction that the new price change has a unit coefficient is relaxed, the restriction is rejected. If the measures of age and obsolescence are correctly accounting for depreciation, then the new price change should have unit effect on the nominal used/new price ratio. Table 7, Column (8) reports an estimate that allows us to test this restriction. When the coefficient of $\log\left(P_t^{HED} / P_{t-v}^{HED}\right)$ is freely estimated, it is 1.005, with a standard error of 0.041, both economically and statistically indistinguishable from the theoretically mandated value of one. This result strongly suggests we have produced estimates of depreciation that are coherent with the user cost model.

[15] The premium is for all other factors held constant. Since the Windows 95 incompatible computers have low values of the other attributes, they do not sell at an overall premium.

4.4. *Age-related depreciation revisited*

Once obsolescence is taken into account, age-related depreciation of personal computers is negligible. In contrast, when obsolescence is not controlled for, age-related depreciation is substantial. Given that the physical deterioration and failure rates of computers are very small, our finding of low rates of age-related depreciation once obsolescence is controlled for brings the econometric estimates in line with what one would expect. The results also demonstrate the risk of estimating depreciation from age alone, and then identifying that estimate with loss of productive efficiency. Computers lose value long before they become unable to do the tasks for which they were designed.

Even controlling for obsolescence, computers have a substantial instantaneous depreciation of 40 percent. We attribute this instantaneous depreciation to installation and resale costs, and the value of customizing a new system to the specifications of a buyer.

4.5. *Premia for oldest computers*

Though there are powerful factors pushing down the price of used computers, there are aspects of our results that older is not uniformly less valuable. First, the quadratic term in age-related depreciation is positive, so the rate of depreciation falls with age. In the next section, we will see that the quadratic term indeed dominates the negative linear term for the older vintages. Second, the coefficient of the CPU generation for lagging five generations is smaller in absolute value than the previous generation. Finally, as noted above, Windows 95 incompatibility has a positive coefficient. Hence, for surviving older models, there are factors pushing against deterioration and obsolescence that add to value. Ramey and Shapiro (2001) found similarly that there was a premium for some very old machine tools that were no longer manufactured.

5. Estimates of User Cost

Using the estimates from the last section, we can now decompose the decline in computer value into its key components: (i) the change in price of new computers; (ii) instantaneous depreciation; (iii) age-related depreciation; and (iv) obsolescence. Specifically, non-financial user cost can be decomposed as

$$\log(q_{t,t-v}^{NOM}) - \log(P_t^{HED} / P_{t-v}^{HED}) = \log(q_{t,t-v}^{NOM}) - \pi_{t,t-v}^{I} = \log(q_{t,t-v}) = -(\delta_0 + \delta_v + \delta_s) + \varepsilon, \qquad (11)$$

that is, instantaneous depreciation, age-related depreciation, obsolescence, and a residual. Tables 8, 9, and 10 and Figure 1 summarize the key findings of the paper through this decomposition of user cost. Table 8 gives the cumulative and incremental values of the variable by age sold. That is, the top panel gives the cumulative log change in the variables by age; the bottom panel gives the differences in these variables for each extra year of age.

The average nominal discount of the resale price of a computer in our sample relative to its nominal acquisition cost is –2.39 on the log scale. In terms of levels, this corresponds to resale price of 9.2 percent of the price when new.[16] Over the interval between acquisition and sale, the log constant-quality replacement price of new computers changed –1.40, which corresponds to a 75 percent decline in the level of the price. Hence, this component of user cost can account for the majority of the decline in the value of computers.

What explains the remaining –0.99 log difference (corresponding to a decline in real q to 0.372 in levels) of the user cost on average? On average, age-related depreciation is 0.02, that is, positive, but negligible. This accords with the prior that deterioration of computers is negligible.

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[16] To convert to levels here, we simply take the antilogarithm of the log differences, i.e., exp(-2.39) equals 0.092. These figures are presented to give a feel for the log differences. Note that

Instantaneous depreciation of –0.40 in log difference is substantial, but consistent with what is found for other capital goods. For example, Ramey and Shapiro (2001) find that the instantaneous discount for forklifts, the most fungible of the aerospace equipment they study, was also –0.40.

The majority of economic depreciation, –0.61, is attributable to our observed indicators of obsolescence.

Table 8 also shows the user cost decomposition by age sold. Because the residual only averages to zero over the whole sample, these lines also included the average residual. Age-related depreciation depresses value in the first four years of the computers life by a modest amount—1 to 3 percent cumulatively. But by age five, the age-related factor is positive. It gets very large due to the quadratic specification. For high ages, we do not put too much weight on the point estimate because the sample gets small and idiosyncratic.

Obsolescence increases substantially with age. The rate of increase, shown in the lower panel of the table, increases for moderate age, but then decreases. The rate of obsolescence averages 15 percent per year. The high rate of obsolescence during the period of study is in large part the outcome of the unique interaction of hardware and software in computers. During this time period, technological change in hardware manufacturing drastically lowered the cost of RAM, speed and hard disk space. The lower cost by itself would not cause obsolescence. For example, the real price of new microwaves has also fallen over time, but obsolescence of existing microwaves has been minimal because the only network component of microwaves is electricity, which has not changed. In contrast, the lower cost of computer hardware spurred software designers to write more versatile programs that were more demanding on the hardware.

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because of Jensen's equality, transforming the averages is not the same as taking the averages of

The newer software does not run well on the limited capabilities of older machines. Moreover, one cannot simply set up two or more older machines to achieve the same capabilities of a newer machine: if a program needs 400 Mhz to run well, setting up two 200 Mhz machines will not solve the problem.

Figure 1 shows the results in the top panel of Table 8 (excluding the residual). The one-time, instantaneous depreciation of –0.40 is shown by the dark area [blue when viewed in color]. Age related depreciation is not discernable for early ages, and then turns positive for older ages [red]. The medium shaded area [green] below the instantaneous depreciation is obsolescence and the bottom, lightly-shaded area [purple] is replacement cost change. Obsolescence and replace cost change are the largest components of user cost, and they increase substantially with age. For ages three through seven, when computers are typically sold, slightly more than half of user cost comes from replacement price change, about a quarter from obsolescence, and the balance from instantaneous depreciation.

Table 9 shows the cumulative components of user cost by year sold. (Incremental obsolescence by year is mainly dominated by composition of computers sold, and is not reported.) Note that cumulative obsolescence increases with time. Recall that the coefficients of the measures of obsolescence are time-invariant, so this increase in obsolescence with time is coming from the declining relative attributes of used computers. Given that personal computers were relatively new products at the beginning of our sample, this pattern is not surprising, and would not be expected to apply to mature products.

Table 10 takes a closer look at obsolescence by time, age, and CPU generation. The top panel shows how the increase in obsolescence with age gets more pronounced over time. The

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the transformed values.

bottom panel shows the how obsolescence increases over time within generation of CPU. There is a distinct pattern of slow aging of CPUs until the next generation is introduced, and then higher rates of obsolescence within a year or two of the introduction. We do not discern a pattern of faster or slower obsolescence of computers over time.

6. Conclusion

This paper has sought to provide a detailed answer to the question of why computers lose their economic value so quickly. In order to answer the question, we gathered data on the characteristics of over 3,000 computers, including the new and used price, detailed features of the computer, and age. By linking the ratio of the used and new price of the computer to observable characteristics, we were able to estimate the key components of the user cost of computers.

The typical computer, when it is sold, has experienced about a 90 percent decline in value compared to its price when new. Over half of this decline in value can be accounted for by the decline in replacement cost of computers of constant quality. That is, even if nothing intrinsic has happen to the computer, it can be replaced at much lower cost. What accounts for the remaining decline in the value of this computer? This paper shows that obsolescence accounts for most of the remaining decline. Though instantaneous depreciation is important (accounting for a 20 percent share in the decline in the used price relative to the new price), age-related depreciation is negligible. By using a parsimonious set of variables to quantify obsolescence, we can account for the remaining quarter of the decline in the value of computers to when they are sold new, or over half of the drop in the real q of a three-year old computer. Without accounting for obsolescence, the estimated age-related depreciation is between 15 and 25 percent per year.

Therefore, the standard procedure of attributing all age-related depreciation to deterioration can be seriously misleading.

The paper has identified the forward movement in the technological frontier as the source of obsolescence. The interactions of the improvements in hardware with the design of software magnify the effects of technological progress. If the rate of technological progress in the production of computer hardware slows down, one would expect the rate of obsolescence of used computers to decrease as well.

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Table 1. Attributes of New Computers by Year Produced

Year	N	RAM	Speed	Hard disk	Has Cd	Compaq	Price
1984	16	0.512	12	30	0	1	4937
1985	11	0.512	12	30	0	1	4143
1986	37	1	20	70	0	1	7950
1987	62	1	20	50	0	1	6620
1988	40	1	20	40	0	1	5764
1989	96	2	25	120	0	1	11731
1990	144	4	25	120	0	1	8737
1991	161	4	25	120	0	0.54	4075
1992	358	4	33	120	0.02	0.75	3352
1993	319	8	50	270	0.18	0.88	2611
1994	204	8	66	540	0.45	0.41	2575
1995	206	16	100	1000	0.59	0.64	3198
1996	217	16	133	1600	0.42	0.88	3092
1997	330	32	200	2500	0.72	0.59	2568
1998	558	32	300	4300	0.72	0.76	2164
1999	280	128	500	13000	0.79	0.56	1958
2000	94	128	650	10000	0.85	0.72	1634
2001	2	96	700	30000	1	1	1525

N = number of observations; RAM = Random access memory, megabytes (median); Speed=Clock speed of CPU, megahertz (median) Hard disk=Size of hard disk, megabytes (median); Has CD=1 if has a CD drive (mean); Compaq=1 if a Compaq computer and 0 if a Gateway (mean); Price=price of new computer, nominal dollars (mean).

Table 2. Attributes of Used Computer by Year Sold

Year	N	RAM	Speed	Hard disk	Has Cd	Compaq	Age	CPU	Price	q (BEA)	q (Hedonic)
1990	27	1	20	70	0	1	2	386	4517	0.59	0.72
1992	75	2	20	80	0	0.95	3	386	1984	0.33	1.01
1993	136	4	25	120	0.01	0.83	2	386	658	0.21	0.47
1995	169	4	33	120	0.05	0.82	4	486	502	0.25	0.60
1996	234	4	33	270	0.17	0.76	4	486	548	0.32	0.52
1997	283	8	50	340	0.24	0.78	4	486	559	0.33	0.58
1998	382	8	75	650	0.38	0.75	4	PI	478	0.33	0.46
1999	553	16	150	1800	0.50	0.73	2	PI	433	0.31	0.49
2000	595	32	200	3000	0.56	0.67	2	PI	357	0.24	0.35
2001	681	32	300	4300	0.65	0.68	3	PII	414	0.35	0.42

N = number of observations; RAM = Random access memory, megabytes (median); Speed=Clock speed of CPU, megahertz (median) Hard disk=Size of hard disk, megabytes (median); Has CD=1 if has a CD drive (mean); Compaq=1 if a Compaq computer and 0 if a Gateway (mean); Age=Age of the computer when sold, years (median); CPU=generation of processor: 386=80386, 486=80486, PI= Pentium I, PII=Pentium II (median); Price=Retail price of used computer, dollars (mean); q=Resale price over acquisition price, reflated by BEA price index for computers, or reflated by estimated Hedonic price index (mean).

Table 3. Attributes of Used Computers by Age When Sold

Year	N	RAM	Speed	Hard disk	Has Cd	Compaq	CPU	Price	q (BEA)	(Hedonic)
1	666	32	300	4300	0.62	0.70	PII	1109	0.57	0.68
2	606	32	200	3200	0.62	0.69	PI	724	0.42	0.56
3	500	16	166	2000	0.53	0.75	PI	418	0.28	0.46
4	349	8	66	630	0.38	0.70	PI	348	0.23	0.42
5	273	8	50	340	0.23	0.75	486	246	0.19	0.43
6	237	4	33	270	0.19	0.75	486	185	0.13	0.36
7	198	4	33	240	0.07	0.77	486	79	0.07	0.26
8	141	4	33	210	0.01	0.81	486	51	0.05	0.21
9	89	4	33	120	0	0.83	486	42	0.04	0.20
10	35	2	20	84	0	1	386	42	0.03	0.23
11	19	1	16	40	0	1	386	43	0.04	0.27
12	13	1	20	60	0	1	386	22	0.02	0.18
13	7	1	16	40	0	1	386	12	0.02	0.13
14	2	0.512	12	30	0	1	286	15	0.04	0.24

See notes to Table 2.

Table 4: New Computer Price Hedonic Equation
Dependent variable: $\log(P_t^N)$

log of CPU speed	0.378
	(0.027)
log of RAM	0.263
	(0.017)
log of Hard disk	0.114
	(0.009)
CPU 386	0.089
	(0.053)
CPU 486	0.307
	(0.058)
CPU Pentium I	0.556
	(0.072)
CPU Pentium II	0.224
	(0.084)
CPU Pentium III or IV	0.359
	(0.094)
Compaq	0.136
	(0.017)
Has CD drive	-0.040
	(0.018)
Year 1985	-0.019
	(0.140)
Year 1986	-0.082
	(0.117)
Year 1987	-0.283
	(0.107)
Year 1988	-0.422
	(0.116)
Year 1989	-0.330
	(0.109)
Year 1990	-0.701
	(0.103)
Year 1991	-1.565
	(0.106)
Year 1992	-2.014
	(0.106)
Year 1993	-2.472
	(0.108)
Year 1994	-2.703
	(0.111)
Year 1995	-3.077
	(0.117)

[Table 4, continued]

Year 1996	-3.350
	(0.119)
Year 1997	-3.793
	(0.121)
Year 1998	-4.095
	(0.123)
Year 1999	-4.735
	(0.132)
Year 2000	-5.034
	(0.138)
Year 2001	-5.153
	(0.285)
Constant	7.228
	(0.117)
Observations	3135
R^2	0.67
SEE	0.36

Note: Excluded CPU is 80286.

Table 5. Attributes of Used Computers Relative to Current New Models

	Deviation from Median Attribute of New Computers				CPU
	Composite	RAM	Speed	Hard disk	Generation
Year sold					
1990	0.487	1.304	0.242	0.462	1.1
1992	0.429	0.807	0.469	0.350	1.1
1993	0.696	1.079	0.650	1.462	1.7
1995	1.136	1.537	1.213	2.409	1.5
1996	0.984	1.187	1.194	1.937	1.1
1997	1.186	1.650	1.376	2.039	1.9
1998	1.075	1.228	1.395	1.975	1.6
1999	1.346	2.035	1.437	2.356	2.1
2000	1.040	1.497	1.290	1.396	1.6
2001	0.977	1.230	1.107	2.065	2.3
Age sold					
1	0.322	0.477	0.354	0.549	0.9
2	0.591	0.824	0.692	0.995	1.3
3	0.893	1.201	1.030	1.650	1.8
4	1.167	1.575	1.356	2.112	2.0
5	1.456	1.952	1.696	2.650	2.1
6	1.690	2.272	1.975	3.041	2.4
7	2.038	2.758	2.371	3.664	2.9
8	2.212	2.998	2.555	4.026	3.3
9	2.297	3.106	2.671	4.137	3.4
10	2.418	3.529	2.704	4.122	3.3
11	2.485	3.690	2.675	4.435	3.3
12	2.678	4.047	2.905	4.537	3.5
13	2.945	4.545	3.135	4.972	4.0
14	2.868	4.135	3.219	4.965	4.0

Note: The first four columns report means of log deviation of the attribute of the used computer relative to the median log attribute for the new computer in the year when sold. Composite is the weighted average of Hard disk, Speed, and RAM, with the weights taken from their coefficients in the hedonic regression reported in Table 4. The CPU generation is the number of generations the CPU of used computer is behind the latest CPU being marketed when the used computer is sold. Generations defined as 80286, 80386, 80486, Pentium I, Pentium II, and Pentium III or IV.

Table 6. Explaining the Resale Price of Computers by Age

Dependent variable: $\log(q_{t,t-v}^{NOM}) = \log\left(\frac{P_{t,t-v}^{U}}{P_{t-v}^{N}}\right)$

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Age=2	-0.418			-0.245				
	(0.035)			(0.035)				
Age=3	-0.430			-0.258				
	(0.037)			(0.037)				
Age=4	-0.211			-0.128				
	(0.043)			(0.043)				
Age=5	-0.250			-0.022				
	(0.050)			(0.050)				
Age=6	-0.399			-0.222				
	(0.055)			(0.055)				
Age=7	-0.525			-0.328				
	(0.060)			(0.060)				
Age=8	-0.358			-0.194				
	(0.068)			(0.068)				
Age=9	-0.314			-0.059				
	(0.084)			(0.084)				
Age=10	-0.305			0.154				
	(0.124)			(0.124)				
Age=11	0.381			0.313				
	(0.176)			(0.177)				
Age=12	-0.544			-0.415				
	(0.223)			(0.223)				
Age=13	-0.209			-0.157				
	(0.290)			(0.290)				
Age=14	0.916			0.552				
	(0.496)			(0.497)				
Age		-0.342	-0.401		-0.166	-0.258	-0.187	-0.207
		(0.004)	(0.015)		(0.004)	(0.015)	(0.023)	(0.024)
Age^2			0.006			0.009	0.000	0.009
			(0.001)			(0.001)	(0.001)	(0.001)
$\log\left(P_t^{BEA}/P_{t-v}^{BEA}\right)$	1.0	1.0	1.0				1.829	
							(0.066)	
$\log\left(P_t^{HED}/P_{t-v}^{HED}\right)$				1.0	1.0	1.0		1.127
								(0.046)
Constant	-0.622	-0.340	-0.240	-0.459	-0.373	-0.218	-0.281	-0.221
	(0.024)	(0.020)	(0.031)	(0.024)	(0.020)	(0.031)	(0.031)	(0.031)
R^2	0.66	0.65	0.66	0.33	0.31	0.32	0.84	0.83
SEE	0.62	0.63	0.63	0.62	0.63	0.62	0.61	0.62

Note: Age dummies are defined so the coefficient is the annual age-related depreciation. P_t^{BEA} and P_t^{HED} are the BEA's and the authors' hedonic price indexes for new computers. Age (v) is measured in years. Standard errors in parenthesis. 3135 observations. For columns (1)-(6), the coefficient of the change in the price index is constrained to be 1.0.

Table 7. Explaining the Resale Price of Computers by Age and Obsolescence

Dependent variable $\log(q_{t,t-v}) = \log\left(\frac{P^U_{t,t-v}}{P^N_{t-v}}\right)$

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Age	-0.258	-0.016	-0.035	-0.094	-0.003	-0.025	-0.057	-0.023
	(0.015)	(0.017)	(0.017)	(0.016)	(0.018)	(0.017)	(0.016)	(0.022)
Age^2	0.009	0.002	0.003	0.008	0.004	0.006	0.005	0.006
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Hard disk deviation		-0.014			0.048			
		(0.013)			(0.012)			
RAM deviation		-0.114			-0.046			
		(0.022)			(0.021)			
CPU speed deviation		-0.432			-0.312			
		(0.032)			(0.030)			
Composite deviation			-0.639			-0.311	-0.490	-0.310
			(0.029)			(0.031)	(0.031)	(0.032)
CPU lag=1				-0.003	0.027	0.060	0.099	0.060
				(0.042)	(0.042)	(0.042)	(0.040)	(0.042)
CPU lag=2				-0.398	-0.293	-0.238	-0.089	-0.238
				(0.047)	(0.049)	(0.049)	(0.047)	(0.049)
CPU lag=3				-1.135	-0.927	-0.868	-0.613	-0.869
				(0.056)	(0.061)	(0.061)	(0.059)	(0.061)
CPU lag=4				-1.520	-1.227	-1.155	-0.810	-1.156
				(0.074)	(0.081)	(0.082)	(0.079)	(0.082)
CPU lag=5				-1.036	-0.758	-0.639	-0.511	-0.639
				(0.214)	(0.213)	(0.215)	(0.202)	(0.215)
Win95 Incompatible							0.576	
							(0.029)	
$\log\left(P^{HED}_t / P^{HED}_{t-v}\right)$	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.005
								(0.041)
Constant	-0.218	-0.258	-0.248	-0.368	-0.388	-0.401	-0.334	-0.401
	(0.031)	(0.029)	(0.029)	(0.042)	(0.041)	(0.041)	(0.039)	(0.041)
R^2	0.32	0.42	0.41	0.48	0.50	0.49	0.55	0.49
SEE	0.62	0.58	0.58	0.55	0.53	0.54	0.51	0.54

Note: Hard disk, RAM, and CPU speed deviation are the median value of those variables for the year when the used computer is sold minus the value of those variables for the used computer. The composite deviation is the weighted value of those variables using the hedonic coefficients reported in Table 4 as weights. The CPU lag variable are dummies for number of generations the CPU of the used computer is behind the most recent CPU in production when the used computer is sold. The generations are defined as 80286, 80386, 80486, Pentium I, Pentium II, and Pentium III or IV. Win 95 incompatible is one for observations 1995 and after with either pre-80486 processors or less than 8MB RAM. Standard errors in parenthesis. 3135 observations.

Table 8. Non-financial User Cost of Computers by Age Sold: Cumulative and Incremental

Age sold	Nominal q	New Price	Real q	Depreciation: Age-related	Depreciation: Age-zero	Depreciation: Obsolescence	Residual
v	$\log(q^{NOM}_{t,t-v})$	$\log\left(\frac{P^{HED}_t}{P^{HED}_{t-v}}\right)$	$\log(q_{t,t-v})$	$-\delta_v$	$-\delta_0$	$-\delta_s$	ε
Cumulative							
Average	-2.39	-1.40	-0.99	0.02	-0.40	-0.61	0.00
1	-0.84	-0.38	-0.46	-0.02	-0.40	-0.09	0.05
2	-1.47	-0.76	-0.70	-0.03	-0.40	-0.22	-0.06
3	-2.12	-1.16	-0.96	-0.02	-0.40	-0.48	-0.05
4	-2.55	-1.46	-1.09	-0.01	-0.40	-0.66	-0.02
5	-2.98	-1.87	-1.11	0.02	-0.40	-0.83	0.10
6	-3.57	-2.23	-1.33	0.05	-0.40	-1.06	0.07
7	-4.31	-2.65	-1.66	0.10	-0.40	-1.38	0.02
8	-4.82	-2.96	-1.86	0.16	-0.40	-1.56	-0.06
9	-5.26	-3.35	-1.92	0.23	-0.40	-1.64	-0.11
10	-5.57	-3.81	-1.76	0.31	-0.40	-1.68	0.01
11	-5.19	-3.74	-1.45	0.41	-0.40	-1.72	0.26
12	-5.96	-4.10	-1.86	0.51	-0.40	-1.86	-0.12
13	-6.35	-4.33	-2.02	0.63	-0.40	-2.07	-0.18
14	-5.56	-4.10	-1.47	0.76	-0.40	-2.05	0.22
Incremental							
Average	-0.40	-0.29	-0.11	0.05	-0.03	-0.15	0.00
1	-0.84	-0.38	-0.46	-0.02	-0.40	-0.09	0.05
2	-0.63	-0.38	-0.24	-0.01	0.00	-0.13	-0.11
3	-0.65	-0.40	-0.26	0.01	0.00	-0.26	0.01
4	-0.43	-0.30	-0.13	0.01	0.00	-0.18	0.03
5	-0.43	-0.41	-0.02	0.03	0.00	-0.17	0.12
6	-0.59	-0.36	-0.22	0.03	0.00	-0.23	-0.03
7	-0.74	-0.42	-0.33	0.05	0.00	-0.32	-0.05
8	-0.51	-0.31	-0.20	0.06	0.00	-0.18	-0.08
9	-0.44	-0.39	-0.06	0.07	0.00	-0.08	-0.05
10	-0.31	-0.46	0.16	0.08	0.00	-0.04	0.12
11	0.38	0.07	0.31	0.10	0.00	-0.04	0.25
12	-0.77	-0.36	-0.41	0.10	0.00	-0.14	-0.38
13	-0.39	-0.23	-0.16	0.12	0.00	-0.21	-0.06
14	0.79	0.23	0.55	0.13	0.00	0.02	0.40

[Table 8, continued]

Notes: Estimates of age-related depreciation and obsolescence from Table 7, Column (6). The variables are related as $\log(q_{t,t-v}^{NOM}) - \log(P_t^{HED} / P_{t-v}^{HED}) = \log(q_{t,t-v}) = -(\delta_0 + \delta_v + \delta_s) + \varepsilon$. Top panel is are cumulative changes; bottom panel is incremental change.

Table 9. Non-financial User Cost of Computers by Year Sold: Cumulative

Year sold	Nominal q	New Price	Real q	Depreciation			Residual
				Age-related	Age-zero	Obsolescence	
t	$\log(q_{t,t-v}^{NOM})$	$\log\left(\frac{P_t^{HED}}{P_{t-v}^{HED}}\right)$	$\log(q_{t,t-v})$	$-\delta_v$	$-\delta_0$	$-\delta_s$	ε
Average	-2.39	-1.40	-0.99	0.02	-0.40	-0.61	0.00
1990	-0.83	-0.47	-0.36	-0.01	-0.40	-0.18	0.22
1992	-1.58	-1.52	-0.06	0.00	-0.40	-0.14	0.49
1993	-2.14	-1.26	-0.88	0.00	-0.40	-0.41	-0.07
1995	-2.27	-1.64	-0.63	0.02	-0.40	-0.49	0.24
1996	-2.17	-1.40	-0.77	0.02	-0.40	-0.37	-0.01
1997	-2.26	-1.59	-0.67	0.03	-0.40	-0.66	0.36
1998	-2.27	-1.41	-0.85	0.04	-0.40	-0.52	0.03
1999	-2.59	-1.56	-1.03	0.03	-0.40	-0.78	0.12
2000	-2.74	-1.36	-1.38	0.01	-0.40	-0.55	-0.44
2001	-2.34	-1.20	-1.14	0.02	-0.40	-0.77	0.02

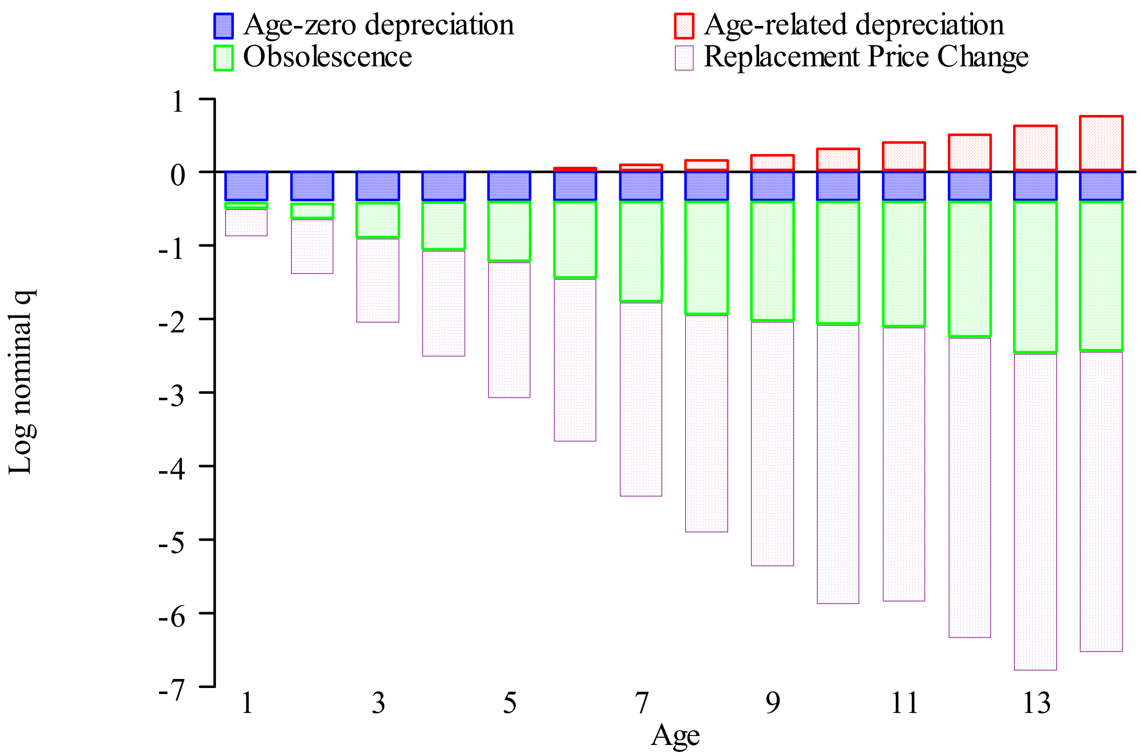
Estimates of age-related depreciation and obsolescence from Table 7, Column (6). The variables are related as $\log(q_{t,t-v}^{NOM}) - \log(P_t^{HED} / P_{t-v}^{HED}) = \log(q_{t,t-v}) = -(\delta_0 + \delta_v + \delta_s) + \varepsilon$.

Table 10. Obsolescence ($-\delta_s$): Cumulative

	1990	1992	1993	1995	1996	1997	1998	1999	2000	2001
Age sold										
1	-0.01	-0.02	-0.20	-0.06	-0.06	-0.07	-0.02	-0.19	-0.01	-0.06
2	-0.28	-0.11	-0.33	-0.15	-0.16	-0.12	-0.15	-0.49	-0.22	-0.13
3		-0.03	-0.51	-0.36	-0.21	-0.42	-0.18	-0.64	-0.51	-0.63
4	-0.08	-0.08	-0.35	-0.51	-0.36	-0.61	-0.47	-0.69	-0.66	-1.13
5	-0.54	-0.24	-0.61	-0.68	-0.53	-0.91	-0.64	-1.18	-0.71	-1.31
6	-0.56	-0.24	-0.79	-0.58	-0.64	-1.03	-0.93	-1.45	-1.19	-1.39
7		-0.60	-0.57	-0.77	-0.56	-1.21	-1.12	-1.67	-1.46	-1.67
8		-0.61	-1.45	-0.97	-0.82	-1.23	-1.49	-1.62	-1.60	-1.83
9			-1.34	-0.76	-1.04	-1.57	-1.31	-1.91	-1.63	-1.93
10				-1.61	-0.81	-1.63	-1.64	-1.90	-1.60	-2.00
11				-1.52	-1.68	-1.56	-1.70	-2.14		
12					-1.57	-1.98	-1.62	-2.08		
13						-1.98	-2.05	-2.12		
14							-2.05			
CPU										
80286	-0.55	-0.55	-1.33	-1.52	-1.56	-1.93	-2.00	-1.43		
80386	-0.06	-0.06	-0.47	-0.68	-0.69	-1.43	-1.51	-2.01		
80486	0.03	0.03	-0.06	-0.20	-0.23	-0.65	-0.71	-1.56	-1.58	-1.90
Pentium I				-0.10	-0.09	-0.11	-0.11	-0.62	-0.64	-1.31
Pentium II							-0.02	-0.09	-0.10	-0.43
Pentium III/IV								-0.18	-0.01	

Note: Cumulative obsolescence based on estimates from Table 7, Column (6). Excludes age-related and age-zero depreciation.

Figure 1. Decomposition of Nominal *q*



Note: Components sum to log nominal *q* (residual excluded). See Table 8. Estimates based on Table 7, Column (6).