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Why Do Computers Depreciate?

Michael J. Geske, Valerie A. Ramey, and
Matthew D. Shapiro

Personal computers rapidly lose economic value. Within two years after purchase, the price of a used computer falls to one-third 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. That new computers are cheaper and better than older computers has distinct effects on the value of older computers. First, the value of old computers falls to bring the value of the computing power they can deliver in line with its current replacement cost. Technical change that reduces the price of producing computers with constant specifications reduces the

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value of older computers, but it does not affect their productivity. Second, technical change can also improve the specifications of new computers. Such improvements in new computers can depress the value of older computers by making them obsolete. Even though older computers might be able to do existing tasks perfectly well, they can 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., compact disc [CD] readers, Internet adapters). The development of new operating systems or software is likely promoted by reductions in the costs of hardware. Hence, the declines in constant-quality replacement cost and obsolescence are distinct but interrelated processes that have separate effects on the value of older computers.

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 Accounts are based, for example, on changes in the price of new computers. In this paper, we estimate directly the change in value of personal computers by comparing the price of used computers to the price of the same computer when new. Our data set links 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 1996.) The method of this paper extends the procedure of Ramey and Shapiro (2001), which estimated such changes in value of 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 change in value of existing 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

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[1] Oliner's (1993, 1996) important work on computer depreciation focuses on mainframe computers and computer peripheral equipment. Berndt and Griliches (1993) use hedonic price regressions based on new personal computers (PCs) only. Since this paper was presented at the conference in 2003, Doms et al. (2004) have produced estimates of depreciation using the same data source as used in this research. Wykoff (2003) presents estimates of obsolescence of laptop computers using data on new prices of computers observed at different points in time.

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 change in value 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. Our results suggest that part of the estimated rate of obsolescence is directly related to the decline in the hardware prices. Thus, the estimates imply that a slowdown in the rate of technological progress would reduce the depreciation rate on used computers.

The remainder of the paper is organized as follows. Section 5.1 sketches our theoretical framework. Section 5.2 discusses our data. Section 5.3 outlines our empirical implementation. Section 5.4 presents the estimation results. Section 5.5 presents their implication for user cost. Section 5.6 gives our conclusions.

5.1 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, $q^{\mathrm{NOM}}_{t,t-v}$, nominal ratio of used to new computer prices,

$$(2) \qquad q^{\mathrm{NOM}}_{t,t-v} \equiv \frac{P^{U}_{t,t-v}}{P^{N}_{t-v}},$$

where $P^{U}_{t,t-v}$ is the price of a used piece of equipment at time t that was new at time $t - v$, and P^{N}_{t-v} 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.

What makes $q^{\mathrm{NOM}}_{t,t-v}$ deviate from unity? 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 central processing unit (CPU) or random-access memory (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 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, $q^{\mathrm{NOM}}_{t,t-v} \equiv P^{U}_{t,t-v}/P^{N}_{t-v} = P^{N}_{t}/P^{N}_{t-v}$. In practice, we do not typically observe P^{N}_{t}, the current price of the new good, and instead substitute the constant-quality new (replacement) investment good price index P^{I}_{t}. Hence, if there is no economic depreciation, $q^{\mathrm{NOM}}_{t,t-v} \equiv P^{U}_{t,t-v}/P^{N}_{t-v} = P^{I}_{t}/P^{I}_{t-v} \equiv \exp(\pi^{I}_{t,t-v})$. Note that $\pi^{I}_{t,t-v} = \int_{t-v}^{t} \pi^{I}(s)ds$ denotes the cumulative rate of change of constant quality new investment good prices as defined in the user cost formula in equation (1).

To create a variable that adjusts for this change in the price of new goods, define q as

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

$$(3) \qquad q_{t,t-v} \equiv \frac{P^U_{t,t-v}}{P^N_{t-v}} \exp(-\pi^I_{t,t-v}) = q^{\mathrm{NOM}}_{t,t-v} \exp(-\pi^I_{t,t-v}).$$

Under the special circumstances just outlined, $q_{t,t-v}$ would be equal to 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. The variable 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

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

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, that is, 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. In the following, we discuss in detail how we implement this empirical strategy.

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

$$(5) \qquad \delta = \delta_v + \delta_0 + \delta_s.$$

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. All three components of depreciation are measured relative to replacement

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[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 1. 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.

cost, so they account for declines in value in excess of the declining costs of producing computers of constant quality.

Scrappage is another source of user cost. Old computers are often discarded or given away. Our data set, which contains information on the value of computers that are sold, does not provide any information about computers that are disposed of by other methods. Because the value of scrapped computers is zero (or even negative if there is a cost of disposal), our estimates will not account for the entire user cost of the computers. Doms et al. (2004) use the same data as used in this study, together with parametric assumptions about scrappage rate, in order to account for this important component of user cost. Though our data do not provide new estimates of scrappage rates, we present some calculations based on presumed scrappage rates to provide a full picture of user cost.

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

$$(6)\qquad q^{\mathrm{NOM}}_{t,t-v} = \exp\left[\int_{t-v}^{t} \pi^{I}(s)ds\right] \cdot \exp\left\{-\int_{t-v}^{t} [\delta_0(s) + \delta_v(s) + \delta_s(s)]ds\right\}$$

or

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

that is, q equals cumulative economic depreciation. The use of the contemporaneous arbitrage between new and used prices to quantify depreciation in equations (6) provides a link to the intertemporal arbitrage in the user cost relationship in equation (1).

It is important to emphasize that technological change can impact user cost through two very different channels. First, technological changes can make new capital goods *cheaper* over time. 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 lead to obsolescence of old capital by making 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, technological progress can make existing capital obsolete. There are three separate effects within this channel. First, new capital might perform the same tasks *faster, better,* or *with less labor input.* Second, the new capital may be able to work with *complementary inputs,* such as software, in a manner that is impossible for the old capital. Third, the new capital may have better *network abilities,* such as sharing documents, exchanging data, and connecting to the Internet. All three of these effects are potentially important for computers. The IBM AT computer that this paper might have been written with fifteen 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 fifteen-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 fifteen-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 data set. Hence, even though the old AT could have once performed the task and is still physically operational, that is, has not depreciated physically, its productivity has declined. As technology evolves, a serviceable old technology becomes unproductive as the network and infrastructure for operating it vanish.[6]

Obsolescence as a result of technological change 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. One of the main goals of this paper is to measure this type of obsolescence and to quantify its role in the user cost of computers.

5.2 Data

The data consist of information on used computers gathered from the Orion Computer blue books. The Orion Research Corporation (various years) 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 thirty days. Computers that 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 com-

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

puter 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 model, including monitor type and size (if one was included in the purchase price of the computer), speed, amount of 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.

We limit our analysis to 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 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. After deleting computer models with missing data, we have 3,112 observations. Some models are observed in several years; we have observations on 1,170 distinct models. We observe used prices in years from 1990 to 2001 (excluding 1991 and 1994, years for which we could not obtain the source data). 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 median new price of a computer was $2,490. Used prices range from $7 to $14,140. The median used price is $333. The computers ranged in speed from 8 to 933 megahertz (MHz), with the median computer having a 100 MHz processor. Random access memory (RAM) varies from 512 kilobytes (KB) to 256 megabytes (MB), with a median of 16 MB. Hard drive space ranged from 1 to 40 gigabytes (GB). The median size is 1 GB. We exclude diskless machines from the sample.

These data are summarized in tables 5.1, 5.2, and 5.3. Table 5.1 shows the attributes by year when the computer was new. Several aspects are noteworthy. The rate of quality improvement in computers is striking. From 1984 to 2001 (with adjustments for 2001 where the medians are affected by the small numbers of computers produced in 2001 and resold in the same year), the median RAM in our sample rose 250 times, the median speed rose 87 times, and the median hard drive capacity rose 1,000 times. At the same time, the median price fell 72 percent. Interestingly, median prices rose during the 1980s and then started plummeting during the 1990s. The

Table 5.1 **Attributes of new computers, by year produced**

Year	N	RAM	Speed	Hard disk	Has CD	Compaq	CPU	Price
1984	16	0.512	8	30	0	1	286	5,145
1985	7	0.512	8	30	0	1	286	4,799
1986	37	1	20	70	0	1	386	7,999
1987	58	1	20	60	0	1	386	7,495
1988	38	1	20	40	0	1	386	5,190
1989	89	2	33	320	0	1	386	12,499
1990	136	4	25	120	0	1	386	9,999
1991	154	4	25	120	0	0.52	486	2,560
1992	354	4	33	120	0.02	0.75	486	2,359
1993	319	8	50	270	0.18	0.88	486	2,480
1994	205	8	66	540	0.44	0.41	486	2,490
1995	206	16	100	1,000	0.59	0.64	PI	3,040
1996	217	16	133	1,600	0.42	0.88	PI	2,930
1997	330	32	200	2,500	0.72	0.59	PI	2,470
1998	559	32	300	4,300	0.72	0.76	PII	1,999
1999	291	128	500	13,000	0.80	0.54	PIII/IV	1,899
2000	94	128	650	10,000	0.85	0.72	PIII/IV	1,431
2001	2	96	700	30,000	1	1	PIII/IV	1,525

Notes: Year = year when new; 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); CPU = generation of processor: 386 = 80386, 486 = 80486, PI = Pentium I, PII = Pentium II, PIII/IV = Pentium III or IV (median); Price = price of new computer, nominal dollars (median).

Table 5.2 **Attributes of used computer, by year sold**

Year	N	RAM	Speed	Hard disk	No CRT	Has CD	Compaq	Age	CPU	Price	q (BEA)	q (hedonic)
1990	26	1	20	65	1	0	1	3	386	3,840	0.68	0.82
1992	73	2	20	84	0.95	0	0.95	3	386	1,470	0.42	1.03
1993	118	4	25	120	0.83	0.01	0.81	2	386	574	0.23	0.44
1995	155	4	33	120	0.81	0.06	0.80	4	486	499	0.30	0.55
1996	233	4	33	270	0.67	0.17	0.76	4	486	417	0.39	0.51
1997	284	8	50	340	0.70	0.24	0.79	4	486	340	0.44	0.55
1998	382	8	75	650	1.00	0.38	0.75	4	PI	320	0.43	0.47
1999	553	16	150	1,800	0.82	0.50	0.73	2	PI	327	0.33	0.44
2000	595	32	200	3,000	0.67	0.56	0.67	2	PI	132	0.16	0.23
2001	693	32	300	4,300	0.61	0.65	0.67	3	PII	239	0.36	0.40

Notes: Year = year when sold; 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); No CRT = 1 if used computer sold without a monitor; 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 (median); q = resale price over acquisition price, reflated by BEA price index for computers or reflated by estimated hedonic price index (median).

Table 5.3 **Attributes of used computers, by age when sold**

Age	*N*	RAM	Speed	Hard disk	No CRT	Has CD	Compaq	CPU	Price	*q* (BEA)	*q* (hedonic)
1	666	32	300	4,300	0.54	0.63	0.70	PII	934	0.62	0.66
2	606	32	200	3,200	0.59	0.63	0.67	PI	562	0.47	0.58
3	500	16	166	2,000	0.77	0.54	0.75	PI	306	0.34	0.46
4	349	8	66	630	0.92	0.38	0.70	PI	220	0.29	0.38
5	273	8	50	340	0.89	0.24	0.74	486	155	0.22	0.35
6	237	4	33	270	0.87	0.20	0.74	486	70	0.14	0.27
7	198	4	33	240	0.90	0.07	0.76	486	25	0.10	0.19
8	141	4	33	210	0.97	0.01	0.80	486	17	0.08	0.17
9	89	4	33	120	1	0	0.83	486	14	0.07	0.18
10	35	2	20	84	1	0	1	386	16	0.07	0.23
11	19	1	16	40	1	0	1	386	47	0.07	0.27
12	13	1	20	60	1	0	1	386	15	0.04	0.17
13	7	1	16	40	1	0	1	386	9	0.03	0.16
14	2	0.512	12	30	1	0	1	286	15	0.09	0.30

Note: See notes to table 5.2.

speed up in technological progress during the late 1990s is also evident from the table.

Tables 5.2 and 5.3 show the data from the vantage point of when the computer was sold. Table 5.2 shows the attributes by the year that it was sold. The values for *q* (the ratio of used to new price, adjusted for the change in the price of new computers) show that in most years, the average computer sold used had lost close to 70 percent of its value. (See table 5A.1 for averages.) Table 5.3 shows the attributes by the age when it was sold. One-year-old computers lost 34 percent of their real value on average, and two-year-old computers lost 42 percent of their value, as shown by the values of *q* in the last column.

5.3 Empirical Framework

5.3.1 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, that is, hedonic, price index can be used to adjust the acquisition price of a used computer to make it comparable to a new computer.

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 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 (2003). The estimates (fitted values) were extremely noisy. (Estimation error is also given substantial attention by Pakes.) Our data set is not designed for estimating hedonic models along lines Pakes suggests, that is, 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. Therefore, we use time dummy estimates, which a recent National Academy panel has labeled as *Griliches-neutral* (see Schultze and Mackie 2002, 151).

Table 5.4 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.

5.3.2 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 $\int_{t-v}^{t} \pi^I(s)ds = \log(P^I_t / P^I_{t-v})$, the basic equation is

$$\log(q^{\text{NOM}}_{t,t-v}) = \log\left(\frac{P^I_t}{P^I_{t-v}}\right) - \int_{t-v}^{t} [\delta_0(s) + \delta_v(s) + \delta_s(s)]ds \tag{7}$$

or

$$\log(q_{t,t-v}) = -\int_{t-v}^{t} [\delta_0(s) + \delta_v(s) + \delta_s(s)]ds, \tag{7'}$$

where $\log(q_{t,t-v}) = \log(P^U_t / P^N_{t-v}) - \log(P^I_t / P^I_{t-v})$. Recall that the used and new prices, P^U_t and P^N_{t-v}, are specific to a particular observation, while the constant-quality price index P^I_t is either a function of time only (in the case of the Bureau of Economic Analysis [BEA] index) or of time and attributes of the computer (in the case of our hedonic index). We will estimate relationship (7) or (7′) over our sample of computers.

We observe the same computer models 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

Table 5.4 New computer price hedonic equation—Dependent variable: $\log(P_t^N)$

log of CPU speed	0.410 (0.070)	Year 1990	–0.800 (0.120)
log of RAM	0.250 (0.035)	Year 1991	–1.697 (0.123)
log of hard disk size	0.127 (0.029)	Year 1992	–2.148 (0.133)
CPU 386	0.045 (0.100)	Year 1993	–2.619 (0.146)
CPU 486	0.273 (0.103)	Year 1994	–2.849 (0.153)
CPU Pentium I	0.516 (0.120)	Year 1995	–3.240 (0.173)
CPU Pentium II	0.164 (0.151)	Year 1996	–3.515 (0.186)
CPU Pentium III or IV	0.419 (0.169)	Year 1997	–3.974 (0.199)
Compaq	0.138 (0.037)	Year 1998	–4.282 (0.207)
Has CD drive	–0.041 (0.023)	Year 1999	–5.015 (0.229)
Year 1985	–0.004 (0.074)	Year 2000	–5.336 (0.242)
Year 1986	–0.184 (0.117)	Year 2001	–5.439 (0.254)
Year 1987	–0.376 (0.117)	Constant	7.225 (0.208)
Year 1988	–0.526 (0.139)	No. of observations	3,112
Year 1989	–0.432 (0.152)	R^2	0.68
		SEE	0.35

Notes: Dependent variable is the log of the price of computer when new. Excluded CPU is 80286. Excluded year is 1984. Standard errors corrected for heteroscedasticity and clustering by model are in parentheses.

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. These disturbances are implicit in the integrals of the components of depreciation in the preceding expressions. They will be made explicit in what follows. 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.[7]

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[7] For many models, we observe linked new-used prices at different dates when the used computer was sold. In our econometric specifications, it is reasonable to assume that these observations within model are correlated across time. Accordingly, we correct standard errors in our regression estimates for clustering by model.

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

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

$$\log(q_{t,t-v}) = \alpha_0 + \sum_{v=1}^{V-1} \tilde{\alpha}_v \tilde{D}_v + \varepsilon, \tag{8}$$

where α_0 is instantaneous (time-zero) 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. The variable ε is a mean zero, idiosyncratic disturbance. The αs in this regression correspond in most cases to the negative of the δs 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

$$\log(q_{t,t-v}) = \alpha_0 + \sum_{v=2}^{V} \alpha_v D_v + \varepsilon, \tag{9}$$

where the α_v are the annual rates of depreciation between ages $v - 1$ and v. Note that equation (9) fits the data identically to equation (8), but is easier to compare with annual estimates of depreciation. There 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, so that age 1 depreciation is not separately identified from the α_0.

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

$$\log(q_{t,t-v}) = \alpha_0 + \sum_{k=1}^{K} \alpha^k v^k + \varepsilon, \tag{10}$$

where K is the order of the polynomial, v^k is the kth power of age, and α^k are parameters. With K equal to 1, we have standard case of constant geometric depreciation, that is, that the coefficients α_v in equation (8) are equal. This specification identifies age-related depreciation for all ages.

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. As discussed in the introduction, computers can lose productivity because of changes in technology. This reduction in productivity relates not to the physical operation of the computer, but to its interoperability with other computers or with current software. 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 (9) or (10) as

$$\log(q_{t,t-v}) = \mathrm{f}(\mathrm{age}) + \mathbf{X}'\boldsymbol{\beta} + \varepsilon, \tag{11}$$

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

To indicate 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 decline of replacement cost of hardware helps drive the development of new software. Incompatibilities with such new software accelerate the obsolescence of older computers. Recall that $q_{t,t-v}$ controls for the direct effect of the change in technology on the cost of production of computers. Hence, $\mathbf{X}'\boldsymbol{\beta}$ accounts for further effects of technology on the value of used computers that are no longer on the technological frontier.

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. We also consider a composite of these measures, defined as a weighted sum, where 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 5.4.

Table 5.5 reports the mean values of these measures of obsolescence by year sold and age when sold.[8] Table 5.5 shows how rapidly attributes of

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[8] 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

Table 5.5 **Attributes of used computers relative to current new models**

	Deviation from median attribute of new computers				
	Composite	RAM	Speed	Hard disk	CPU lag
Year sold					
1990	0.506	1.301	0.290	0.483	1.2
1992	0.425	0.785	0.471	0.281	1.0
1993	0.637	1.041	0.656	0.845	1.6
1995	1.109	1.477	1.189	1.988	1.4
1996	1.018	1.164	1.188	1.887	1.1
1997	1.238	1.658	1.380	2.025	0.9
1998	1.131	1.228	1.398	1.975	1.6
1999	1.399	2.039	1.440	2.354	2.1
2000	1.077	1.497	1.279	1.403	1.6
2001	1.020	1.228	1.094	2.082	1.3
Age sold					
1	0.332	0.478	0.357	0.521	0.7
2	0.606	0.826	0.678	0.954	1.0
3	0.930	1.205	1.030	1.622	1.3
4	1.209	1.566	1.351	2.078	1.6
5	1.520	1.958	1.704	2.610	1.8
6	1.765	2.278	1.986	3.003	2.2
7	2.133	2.765	2.386	3.644	2.6
8	2.313	3.005	2.587	3.949	2.8
9	2.401	3.105	2.684	4.126	2.9
10	2.512	3.512	2.733	4.040	3.0
11	2.583	3.665	2.758	4.215	3.1
12	2.818	4.047	2.999	4.537	3.5
13	3.125	4.545	3.309	4.972	3.7
14	3.151	4.135	3.624	4.965	4.0

Notes: 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 5.4. The CPU lag is the number of generations the CPU of the 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.

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 52 percent smaller. The value metric of the composite attribute shows a 33 percent decline. For older ages, the decline is rapid and continues for all but the oldest ages.

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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.

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 previously in the specification of the hedonic model. The last column of table 5.5 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.

5.4 Estimates of Depreciation

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 [9] and [10]) and how this function shifts when the controls for obsolescence are included (equation [11]).

5.4.1 Age-Related Depreciation

Table 5.6 reports estimates of age-related depreciation for the dummy variable specification (9) and the polynomial specification (10). 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 q on the left-hand side and no price variable on the right-hand side. The last two columns relax this restriction.

Table 5.6 present estimates using two measures of the price of new computers, the BEA deflator for computers, denoted P_t^{BEA}, and the hedonic price index reported in table 5.4, denoted P_t^{HED}. The index 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 5.6 reports the age-dummy estimates of age-related depreciation using the BEA deflator to measure price change on new computers. All specifications also include a dummy variable that is 1 if the used computer is sold without a cathode ray tube monitor (CRT). The CRT represents a substantial—approximately one-quarter—fraction of the value.[9]

The constant of –0.280 indicates instantaneous depreciation of more

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[9] The value of the CRT enters multiplicatively in the specification. An alternative would be to enter it additively, though that would be more awkward econometrically. We do not know anything about the quality or value of the original CRT. Our specification assumes that it varies proportionately with the value of the computer.

Table 5.6 **Explaining the resale price of computers, by age—Dependent variable: $\log(q^{\text{NOM}}_{t,t-v}) = \log(P^{U}_{t,t-v}/P^{N}_{t-v})$**

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Age = 2	–0.287			–0.206				
	(0.027)			(0.024)				
Age = 3	–0.261			–0.170				
	(0.038)			(0.035)				
Age = 4	–0.090			–0.077				
	(0.043)			(0.042)				
Age = 5	–0.191			–0.044				
	(0.047)			(0.048)				
Age = 6	–0.341			–0.207				
	(0.054)			(0.054)				
Age = 7	–0.423			–0.299				
	(0.055)			(0.053)				
Age = 8	–0.247			–0.155				
	(0.066)			(0.067)				
Age = 9	–0.227			–0.036				
	(0.067)			(0.068)				
Age = 10	–0.306			0.148				
	(0.177)			(0.147)				
Age = 11	0.354			0.335				
	(0.209)			(0.174)				
Age = 12	–0.498			–0.408				
	(0.194)			(0.156)				
Age = 13	–0.195			–0.128				
	(0.232)			(0.161)				
Age = 14	0.902			0.557				
	(0.260)			(0.235)				
Age		–0.244	–0.242		–0.134	–0.200	–0.074	–0.133
		(0.008)	(0.020)		(0.009)	(0.019)	(0.030)	(0.035)
Age^2			–0.000			0.007	–0.005	0.006
			(0.002)			(0.002)	(0.002)	(0.002)
$\log(P^{\text{BEA}}_{t}/P^{\text{BEA}}_{t-v})$	1.0	1.0	1.0				1.465	
							(0.066)	
$\log(P^{\text{HED}}_{t}/P^{\text{HED}}_{t-v})$				1.0	1.0	1.0		1.164
								(0.075)
No CRT	–0.425	–0.412	–0.412	–0.368	–0.377	–0.360	–0.398	–0.346
	(0.030)	(0.029)	(0.029)	(0.030)	(0.030)	(0.030)	(0.029)	(0.031)
Constant	–0.180	–0.052	–0.054	–0.225	–0.138	–0.038	–0.081	–0.045
	(0.020)	(0.022)	(0.032)	(0.026)	(0.028)	(0.035)	(0.032)	(0.037)
R^2	0.60	0.59	0.59	0.36	0.34	0.35	0.86	0.85
SEE	0.57	0.58	0.58	0.58	0.59	0.58	0.57	0.58

Notes: Dependent variable is the log of the ratio of the used to new price, P^{BEA}_{t} and P^{HED}_{t} are the BEA's and the authors' hedonic price indexes for new computers. In columns (1) through (6), the price index for new computers is included in the regression with a coefficient of 1. Taking the price index to the left-hand side of the equation makes the dependent variable of the log of q. Standard errors corrected for heteroscedasticity and clustering by model are in parentheses. Age dummies are defined so the coefficient is the annual age-related depreciation (log difference). Age (v) is measured in years. No CRT is a dummy for the used computer being sold without a monitor. No. of observations = 3,112.

than 28 percent. Depreciation is 29 percent in year two, 26 percent in year three, 9 percent in year four, and 19 percent in year five. (These rates are measured as log differences. In tables 5.9, 5.10, and 5.11, we convert the estimates to levels and compute percent changes.) 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 negligible 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 24 percent is very high—much higher than is plausible for physical deterioration. Together with the constant of 41 percent, these estimates fit the facts that computers lose over half their value over the first two years of their lives.

The estimates in columns (4), (5), and (6) based on our hedonic price index yield similar patterns of age-related depreciation but point estimates that correspond to about half the annual rate of depreciation.[10] The average geometric rate of depreciation is 13 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 1 for each of the measures of new computer price change. For the BEA index, the unrestricted coefficient jumps to nearly 1.5 with a substantial downward effect on the 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 1 when price change is measured with our hedonic index in column (8), it is much closer to 1. Consequently, the annual rate of depreciation is affected less. 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.

5.4.2 Obsolescence

As discussed previously, 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 5.7. The first column of table 5.7 includes the quadratic in age specification from table 5.6, column (6), for reference.

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

Table 5.7 **Explaining the resale price of computers, by age and obsolescence—Dependent variable: $\log(q^{\mathrm{NOM}}_{t,t-v}) = \log(P^{U}_{t,t-v}/P^{N}_{t-v})$**

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Age	–0.200	–0.001	–0.021	–0.093	–0.037	–0.060	–0.105
	(0.019)	(0.022)	(0.023)	(0.020)	(0.022)	(0.023)	(0.034)
Age^2	0.007	0.001	0.002	0.008	0.006	0.007	0.008
	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.002)	(0.002)
Hard disk deviation		–0.055			–0.016		
		(0.022)			(0.021)		
RAM deviation		–0.041			0.064		
		(0.031)			(0.028)		
CPU speed deviation		–0.383			–0.208		
		(0.058)			(0.058)		
Composite deviation			–0.538			–0.145	–0.145
			(0.046)			(0.057)	(0.056)
CPU lag = 1				0.014	0.035	0.045	0.014
				(0.030)	(0.030)	(0.032)	(0.032)
CPU lag = 2				–0.459	–0.400	–0.374	–0.424
				(0.045)	(0.053)	(0.054)	(0.057)
CPU lag = 3				–1.204	–1.052	–1.043	–1.107
				(0.072)	(0.092)	(0.091)	(0.096)
CPU lag = 4				–1.240	–1.057	–1.029	–1.139
				(0.111)	(0.119)	(0.116)	(0.135)
$\log(P^{\mathrm{HED}}_{t}/P^{\mathrm{HED}}_{t-v})$	1.0	1.0	1.0	1.0	1.0	1.0	0.871
							(0.065)
No CRT	–0.360	–0.229	–0.231	–0.270	–0.248	–0.255	–0.253
	(0.030)	(0.034)	(0.035)	(0.029)	(0.030)	(0.031)	(0.031)
Constant	–0.038	–0.138	–0.121	–0.217	–0.250	–0.233	–0.221
	(0.035)	(0.037)	(0.040)	(0.031)	(0.030)	(0.032)	(0.032)
R^2	0.35	0.42	0.42	0.49	0.50	0.49	0.49
SEE	0.58	0.55	0.55	0.52	0.51	0.51	0.51

Notes: Dependent variable is the log of the ratio of the used to new price. P^{HED}_{t} is the authors' hedonic price indexes for new computers. In columns (1) through (6), the price index for new computers is included in the regression with a coefficient of 1. Taking the price index to the left-hand side of the equation makes the dependent variable the log of q. Standard errors corrected for heteroscedasticity and clustering by model are in parentheses. Age (v) is measured in years. 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 5.4 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. No CRT is a dummy for the used computer being sold without a monitor. No. of observations = 3,112.

Obsolescence of Attributes

Columns (2) and (3) of table 5.7 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 used (see the preceding). 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 jointly significant incremental explanatory power and, except for RAM, are individually statistically significant. The obsolescence of the attributes has negative effects on depreciation. The effects of obsolescence can be quantitatively significant. For example, having a CPU that is half the median speed lowers the value of the used computer by 19 percent, all other things equal.

Imposing the restriction that these measures enter as the weighted sum in column (3) has only a negligible effect on the fit. The estimated effect of obsolescence on depreciation is substantial. The average two-year-old computer has a composite obsolescence of 0.61, that is, the hedonic value of the hard disk/speed/RAM bundle has fallen by 61 percent (see table 5.5). Multiplying this amount by the coefficient of –0.538 yields a predicted depreciation from obsolescence of 33 percent.

Controlling for these measures of obsolescence has a substantial effect on the estimates of the age-related depreciation, whether entered individually in column (2) or as a composite in column (3). Age-related depreciation is estimated to be small and insignificant. Hence, controlling for obsolescence essentially eliminates the age-related component of depreciation.

Distance of Used CPU from Frontier

We construct a variable *CPU lag* that 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 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 5.7, column (4) reports estimates for CPU lag entered as dummy variables for lagging one to four generations. The zero lag is the omitted category; there are no computers in our sample sold with a lag of five generations. This set of variables has more explanatory power than the measures of attributes. A lag of 1 has little effect on value, a lag of 2 reduces it by almost half, and a lag of 3 or 4 eliminates most of value.

Columns (5) and (6) of table 5.7 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 speed variable remains significant, as does the composite attribute, these variables add little to the explanatory power of the CPU lag dummies. The coefficient of RAM has the "wrong" sign, but given its interaction with other factors such as CPU generation, this coefficient should not be overinterpreted.

5.4.3 Specification Test

Recall that in the last two columns of table 5.6, 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 5.7, column (7) reports an estimate that allows us to test this restriction. When the coefficient of $\log(P_t^{\mathrm{HED}}/P_{t-v}^{\mathrm{HED}})$ is freely estimated, it is 0.871, with a standard error of 0.05, close to the theoretically mandated value of 1. Hence, the attributes we include in the equation are appropriately controlling for change in value insofar as they are correlated with the change in replacement cost measured by the deflator.

5.4.4 Age-Related Depreciation Revisited

Once obsolescence is taken into account, age-related depreciation of the personal computers that were resold is negligible. This result does not mean that the effect of age on the entire cohort of computers is negligible. By concentrating only on those computers that are resold, we neglect the effect of age on the probability of the computer being scrapped. To see how we should amend our estimates, consider the equation that relates the average price of computers in the entire cohort to those that are sold used,

$$\bar{p}(v) = S(v) \cdot p(v) + [1 - S(v)] \cdot 0, \tag{12}$$

where $\bar{p}(v)$ is the average price of the entire cohort at age v, $p(v)$ is the price observed in the used computer market, and $S(v)$ is the probability of survival to age v. It is assumed that scrapped computers have zero value. Taking logarithms of equation (12) and then differentiating with respect to age, we obtain

$$\frac{\partial \ln[\bar{p}(v)]}{\partial v} = \frac{\partial \ln[p(v)]}{\partial v} + \frac{\partial \ln[S(v)]}{\partial v}. \tag{13}$$

The first term on the right-hand side comes directly from our estimate of the effects of age on used price. The second term is the percent change in the probability of survival with respect to age. As Oliner (1996) points out, it is the negative of the hazard rate of scrappage with respect to age.

The survival function for computers depends both on physical failure as well as technological obsolescence. Physical failure is only a small part of scrappage. Electronic components are typically assumed to follow a "bathtub" model of reliability, which is well approximated by a Weibull distribution (Wilkins 2002). A few months of decreasing failure rates are followed by several years of low, constant failure rates, with increasing failure rates during the end-of-life, wear-out phase.

The most important factor driving scrappage is technological obsolescence. According to Matthews et al. (1997), the average life-span of a personal computer is around five years. Our data suggests that the survival distribution must have a long-tail because we have a number of much older computers in our sample. To capture the mean age of scrappage of five years as well as the long tail, we assume that the survival function is governed by a two-parameter Weibull distribution

Table 5.8 **Estimated scrappage rates for installed computers (hazard rates for Weibull distribution with $\beta = 2$ and $\eta = 5.64$)**

Age	Hazard rate (%)
1	6
2	13
3	19
4	25
5	31
10	57

Notes: Authors' calculations. These hazard rates are parameterized to match the scrappage rate of personal computers. They need to be added to the decline in value of installed computers to account fully for user cost. See section 5.4.4 for details.

$$f(v) = \frac{\beta}{\eta}\left(\frac{v}{\eta}\right)^{\beta-1} e^{-(v/\eta)^{\beta}} \tag{14}$$

with $\beta = 2$ and $\eta = 5.64$.[11] The implied hazard rates for this distribution are given by

$$h(v) = \frac{\beta}{\eta}\left(\frac{v}{\eta}\right)^{\beta-1}. \tag{15}$$

The hazard rates at different ages for this distribution are given in table 5.8. The numbers in table 5.8 give the rate at which surviving computers are scrapped as of various ages. In order to characterize the depreciation rates of the entire cohort of computers instead of just the installed computers on which we base our analysis, these numbers must be added to the depreciation rates estimated based on the sample of used equipment.

5.4.5 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 four generations is about the same as those lagging three generations. 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. This finding could be accounted for by survivorship

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[11] Doms et al. (2004) use a similar distribution. For a very useful discussion of the Weibull distribution, see http://www.weibull.com.

bias in these very old models or the value of being able to run older applications.

5.5 Decomposing the Decline in Value of Used Computers

Using the estimates from the last section, we can now decompose the decline in computer value into its key components: (a) the change in price of new computers; (b) instantaneous depreciation; (c) age-related depreciation; and (d) obsolescence. Specifically, the decline in value of used computers can be decomposed as

$$(16)\qquad \log(q^{\text{NOM}}_{t,t-v}) - \log\left(\frac{P^{\text{HED}}_{t}}{P^{\text{HED}}_{t-v}}\right) = \log(q^{\text{NOM}}_{t,t-v}) - \pi^{I}_{t,t-v}$$

$$= \log(q_{t,t-v}) = -(\delta_0 + \delta_v + \delta_s) + \varepsilon,$$

that is, instantaneous depreciation, age-related depreciation, obsolescence, and a residual. Tables 5.9, 5.10, and 5.11 summarize the key findings of the paper through this decomposition of user cost. For these tables, we convert the variables on the left-hand side and the fitted value on the right-hand side of equation (16) to levels by exponentiation, compute percent changes for individual observations, and then average. Tables 5.9, 5.10, and 5.11 then report the average cumulative or annualized percent change in value. The average exponentiated values differ from the exponentiation of the averages because of heterogeneity. The appendix tables give the averages in terms of logarithms, the units in which equation (16) is estimated.

Table 5.9 gives the cumulative and annualized values of the variable by age sold. The average nominal decline in value for a used computer relative to its nominal acquisition cost in our sample is 77 percent.[12] The decline in replacement cost is 66 percent, on average, over the interval between acquisition and sale, or 32 percent per year of age. The decline in q is 41 percent over this interval, or 18 percent per year.[13] Hence, the decline in replacement cost looms very large in the loss in value of used computers.

The last three columns of table 5.9 decompose the q, the discount of used price relative to new price adjusted for the change in replacement cost. On average, age-related depreciation δ_v is 7 percent cumulatively and 3 percent per year of age. This accords with the prior that deterioration of computers is negligible. Instantaneous depreciation of 21 percent is substantial

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[12] The annual rate of decline per year of age is 45 percent. The average cumulative change in value is –2.19 in logarithms (see table 5A.1). Exp(–2.19) is 0.11, which corresponds to an 89 percent decline in value. The difference between the 77 percent value in table 5.9 and this value illustrates the importance of taking into heterogeneity in taking averages.

[13] The percent changes in table 5.9 are multiplicative and corrected for heterogeneity, so they do not add up either across columns or down rows. The log changes in the appendix tables are additive. Note that the first three columns in the appendix tables do not add to the last three columns because of the residual in equation (16) except for the averages.

Table 5.9 **Explaining the price of used computers, by age**

				Depreciation		
Age sold (v)	Nominal q [$\log(q^{\mathrm{NOM}}_{t,t-v})$]	New price [$\log(P^{\mathrm{HED}}_{t}/P^{\mathrm{HED}}_{t-v})$]	q [$\log(q_{t,t-v})$]	Age-related (δ_v)	Age-zero (δ_0)	Obsolescence (δ_s)
			Cumulative decrease in value (%)			
Average	77	66	41	7	21	28
1	48	32	2-	5	21	4
2	69	54	33	9	21	12
3	82	70	41	11	21	20
4	87	78	44	12	21	30
5	91	85	44	11	21	39
6	95	90	52	9	21	52
7	98	94	65	6	21	62
8	99	95	71	1	21	68
9	99	97	71	–5	21	70
10	99	98	67	–14	21	68
11	99	98	60	–25	21	70
12	100	98	74	–39	21	76
13	100	99	79	–57	21	77
14	99	99	62	–80	21	77
			Annual rate decrease in value per year of age (%)			
Average	45	32	18	3	10	8
1	47	32	20	5	21	4
2	46	33	20	4	11	7
3	46	33	19	4	7	8
4	43	32	17	3	6	9
5	42	32	14	2	5	10
6	42	32	15	2	4	12
7	44	33	17	1	3	14
8	43	32	17	0	3	14
9	42	32	15	–1	3	13
10	41	33	13	–1	2	11
11	36	30	9	–2	2	11
12	38	30	11	–3	2	11
13	37	29	11	–4	2	11
14	32	26	7	–4	2	10

Notes: The percent decreases are calculated by exponentiating the logarithmic values and then averaging. The first panel contains averages of cumulative percent decreases. The second panel contains averages of percent decreases per year of age. The first column is change in nominal q, the second column is the change in the new price holding attributes constant, the third column is the change in q (the difference of the first two columns), and the last three columns give the estimates of components of depreciation from the regression in table 5.7, column (6).

Table 5.10 **Explaining the price of used computers, by year**

				Depreciation		
Age sold (v)	Nominal q [$\log(q^{\mathrm{NOM}}_{t,t-v})$]	New price [$\log(P^{\mathrm{HED}}_{t}/P^{\mathrm{HED}}_{t-v})$]	q [$\log(q_{t,t-v})$]	Age-related (δ_v)	Age-zero (δ_0)	Obsolescence (δ_s)
Cumulative decrease in value (%)						
Average	77	66	41	7	21	28
1990	41	38	4	9	21	11
1992	71	77	–35	9	21	8
1993	79	64	40	8	21	24
1995	80	73	25	8	21	26
1996	79	66	37	8	21	19
1997	80	71	30	7	21	21
1998	76	63	39	6	21	27
1999	76	72	36	6	21	40
2000	81	67	57	8	21	30
2001	74	60	51	8	21	25
Annual rate decrease in value per year of age (%)						
Average	45	32	18	3	10	8
1990	20	19	1	4	11	3
1992	35	40	–8	3	8	3
1993	54	38	26	4	12	11
1995	39	32	11	3	7	7
1996	41	29	16	3	8	5
1997	41	32	13	3	8	5
1998	41	28	18	3	10	6
1999	49	42	11	3	11	15
2000	53	35	28	3	10	9
2001	41	25	21	3	9	7

Note: See notes to table 5.9.

but is much less than 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 about 40 percent.

The majority of economic depreciation, 28 percent of value cumulatively or 8 percent per year of age, is attributable to our observed indicators of obsolescence. Recall that this loss of value owing to obsolescence of used computers is above and beyond the loss of value because of the decline in the replacement cost of a computer of constant quality, which is controlled for by the log ($P^{\mathrm{HED}}_{t}/P^{\mathrm{HED}}_{t-v}$) term in equation (16) shown in the third column of table 5.9.

Table 5.9 also shows the user cost decomposition by age sold. Age-related depreciation depresses value in the first years of the computers life by a modest amount. It accounts for approximately a 10 percent cumulative decline in value in the first two to three years of life. The rate of decline in value

Table 5.11 **Obsolescence (δ_s), by year, age sold, and CPU type: Cumulative decrease in value (%)**

	1990	1992	1993	1995	1996	1997	1998	1999	2000	2001
Age sold										
1	–2	0	10	3	3	6	0	10	0	2
2	18	8	21	6	7	8	5	36	12	3
3	3	–1	31	20	8	12	7	43	36	14
4	1	3	27	27	20	13	28	45	44	38
5	42	12	42	35	29	26	41	62	45	45
6	42	14	48	38	36	31	54	71	62	47
7		43	41	46	35	39	58	75	71	62
8		43	73	53	48	39	70	76	75	71
9			73	46	54	51	67	76	76	76
10				75	48	56	76	76	75	77
11				75	76	51	76	78		
12					76	77	76	77		
13						77	77	78		
14							77			
CPU										
80,286	41	41	72	74	75	76	76			
80,386	1	1	38	44	45	48	74	76	75	
80,486	–2	–2	1	8	9	14	45	75	75	76
Pentium I				5	4	8	4	43	43	44
Pentium II							0	3	3	5
Pentium III/IV									1	3

Notes: Cumulative obsolescence (percent decrease) based on estimates from table 5.7, column (6). See also notes to table 5.9.

attributable solely to age then gets smaller. At high age, the quadratic term dominates, so the age-specific component adds to value. As noted previously, this finding can arise from selectivity or a premium (other things equal) for old models that can operate old software. Given the thinness of markets for very old computers, the results for the earlier ages where the linear term dominates are of greater interest and are also more reliable.

Obsolescence increases substantially with age. The rate of increase, shown in the lower panel of the table, increases for moderate age, but then levels off. Obsolescence accounts for most of the decline in q at all ages once instantaneous depreciation is taken into account. This finding is clearest in the logarithmic results shown in table 5A.1, which are additive across columns and down rows. For example, a five-year-old computer changes in value by –0.82 on log scale. Of this, –0.12 owes to age-related depreciation, –0.23 owes to instantaneous loss of value, and –0.55 owes to obsolescence.[14]

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[14] Note that these figures do not sum to –0.82 because of the residual in equation (16), which only averages to zero for the whole sample, not for a particular age.

Finally, note again that results are for depreciation of installed computers. To obtain an estimate of total depreciation per period, the scrappage rates in table 5.8 need to be added to the rates in the bottom panel of table 5.9.

Table 5.10 shows the cumulative components of user cost by year sold. The corresponding results in logarithms are reported in table 5A.2. Our hedonic price index declines on average of 32 percent per year.[15] Our estimate bounces around somewhat from year to year. There is no clear trend in the rate of change of the index. While the estimates of obsolescence also have a lot of variation from year to year, its rate increases somewhat over 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 5.11 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 bottom panel shows 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 several years of the introduction. The 80286 had experienced substantial obsolescence at the beginning of the sample. (The 80386 was introduced in the mid-1980s.) The obsolescence of the 80386 becomes significant in 1993. The 80486 does not become significantly obsolete until 1998, while the Pentium I becomes significant obsolete one year later in 1999. We do not discern a pattern of faster or slower obsolescence of computers over time.

5.6 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 key components of the user cost of installed computers.

The typical computer, when it is sold, has experienced about a 77 percent decline in value compared to its price when new. About half of this decline in value can be accounted for by the decline in replacement cost of com-

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[15] The BEA price index for personal consumption of computers declined at an annual rate of 25 percent over the 1990 to 2001 time period. We do not have an explanation of the differences in these rates.

puters of constant quality. That is, even if nothing intrinsic has happened 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 decline in the used price relative to the new price), age-related depreciation is small. 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 *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. 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. 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.

Without the decline in replacement cost, it is unlikely that obsolescence would have proceeded so quickly. 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.

Appendix

Table 5A.1 **Explaining the price of used computers, by age**

				Depreciation		
Age sold (v)	Nominal q [$\log(q^{\text{NOM}}_{t,t-v})$]	New price [$\log(P^{\text{HED}}_{t}/P^{\text{HED}}_{t-v})$]	q [$\log(q_{t,t-v})$]	Age-related ($-\delta_v$)	Age-zero ($-\delta_0$)	Obsolescence ($-\delta_s$)
			Cumulative change in value (log levels)			
Average	–2.19	–1.46	–0.73	–0.08	–0.23	–0.42
1	–0.70	–0.42	–0.29	–0.05	–0.23	–0.05
2	–1.30	–0.81	–0.50	–0.09	–0.23	–0.15
3	–1.91	–1.22	–0.69	–0.11	–0.23	–0.26
4	–2.31	–1.53	–0.78	–0.12	–0.23	–0.38
5	–2.76	–1.94	–0.82	–0.12	–0.23	–0.55
6	–3.35	–2.33	–1.03	–0.10	–0.23	–0.81
7	–4.11	–2.78	–1.33	–0.06	–0.23	–1.07
8	–4.60	–3.10	–1.49	–0.01	–0.23	–1.22
9	–5.02	–3.49	–1.53	0.05	–0.23	–1.27
10	–5.35	–3.97	–1.38	0.13	–0.23	–1.21
11	–4.93	–3.88	–1.05	0.22	–0.23	–1.27
12	–5.70	–4.25	–1.46	0.33	–0.23	–1.45
13	–6.09	–4.51	–1.58	0.45	–0.23	–1.49
14	–5.31	–4.28	–1.03	0.59	–0.23	–1.49

Note: See notes to table 5.9.

Table 5A.2 **Explaining the price of used computers, by year**

				Depreciation		
Age sold (v)	Nominal q [$\log(q^{\text{NOM}}_{t,t-v})$]	New price [$\log(P^{\text{HED}}_{t}/P^{\text{HED}}_{t-v})$]	q [$\log(q_{t,t-v})$]	Age-related ($-\delta_v$)	Age-zero ($-\delta_0$)	Obsolescence ($-\delta_s$)
			Cumulative change in value (log levels)			
Average	–2.19	–1.46	–0.73	–0.08	–0.23	–0.42
1990	–0.57	–0.49	–0.08	–0.09	–0.23	–0.15
1992	–1.31	–1.55	0.24	–0.10	–0.23	–0.10
1993	–1.89	–1.27	–0.63	–0.08	–0.23	–0.34
1995	–2.01	–1.62	–0.39	–0.09	–0.23	–0.35
1996	–1.97	–1.41	–0.56	–0.08	–0.23	–0.25
1997	–2.08	–1.63	–0.45	–0.07	–0.23	–0.27
1998	–2.01	–1.45	–0.56	–0.06	–0.23	–0.42
1999	–2.38	–1.68	–0.71	–0.06	–0.23	–0.65
2000	–2.57	–1.46	–1.10	–0.08	–0.23	–0.47
2001	–2.16	–1.26	–0.90	–0.08	–0.23	–0.38

Note: See notes to table 5.9.

References

Berndt, Ernst R., and Zvi Griliches. 1993. Prices indexes for microcomputers: An exploratory study. In *Price measurements and their uses,* ed. Murray F. Foss, Marilyn E. Manser, and Allan H. Young, 63–93. Chicago: University of Chicago Press.

Doms, Mark E., Wendy E. Dunn, Stephen D. Oliner, and Daniel E. Sichel. 2004. How fast do personal computers depreciate? Concepts and new estimates. In *Tax policy and the economy.* Vol. 18, ed. James Poterba, 37–79. Cambridge, MA: MIT Press.

Jorgenson, Dale W., and Zvi Griliches. 1967. The explanation of productivity change. *Review of Economic Studies* 34 (July): 239–80.

Hall, Robert E. 1968. Technical change and capital from the point of view of the dual. *Review of Economic Studies* 35 (January): 34–46.

———. 1971. The measurement of quality changes from vintage price data. In *Price indices and quality change,* ed. Zvi Griliches, 240–71. Cambridge, MA: Harvard University Press.

Hall, Robert E., and Dale W. Jorgenson. 1967. Tax policy and investment behavior. *American Economic Review* 57 (April): 391–414.

Hulten, Charles. 1996. Quality change in capital goods and its impact on economic growth. NBER Working Paper no. 5569. Cambridge, MA: National Bureau of Economic Research, May.

Hulten, Charles, and Frank Wykoff. 1981. The estimation of economic depreciation using vintage asset prices. *Journal of Econometrics* 15 (April): 367–96.

———. 1996. Issues in the measurement of economic depreciation. *Economic Inquiry* 34:10–23.

Jorgenson, Dale W. 1996. Empirical studies of depreciation. *Economic Inquiry* 34 (January): 24–42.

Matthews, H. Scott, Francis C. McMichael, Christ T. Hendrickson, and Deanna J. Hart. 1997. Disposition and end-of-life options for personal computers. Green Design Initiative Technical Report no. 97-10. Pittsburgh, PA: Carnegie Mellon University.

Oliner, Stephen. 1993. Constant-quality price change, depreciation, and retirement of mainframe computers. In *Price measurements and their uses,* ed. Murray F. Foss, Marilyn E. Manser, and Allan H. Young, 19–61. Chicago: University of Chicago Press.

———. 1996. New evidence on the retirement and depreciation of machine tools. *Economic Inquiry* 34:57–77.

Orion Research Corporation. (Various years). *Orion computer blue book.* Durango, CO: Orion Research Corporation.

Pakes, Ariel. 2003. A reconsideration of hedonic price indices with an application PC's. *American Economic Review* 93 (December): 1578–96.

Ramey, Valerie A., and Matthew D. Shapiro. 2001. Displaced capital: A study of aerospace plant closings. *Journal of Political Economy* 109 (October): 958–92.

Schultze, Charles, and Christopher Mackie. 2002. *At what price? Conceptualizing and measuring cost-of-living and price indexes.* Washington, DC: National Academies of Science.

Wilkins, Dennis. 2002. The bathtub curve and product failure behavior. *Hotwire* 22 (December): http://www.weibull.com/hotwire/issue22.

Wykoff, Frank C. 2003. Obsolescence in economic depreciation from the point of view of the revaluation term. Pomona College. Unpublished Manuscript.