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1 Constant-Quality Price Change, Depreciation, and Retirement of Mainframe Computers

Stephen D. Oliner

Over the past two decades, business equipment spending has shifted away from heavy machinery and motor vehicles toward "information-processing" equipment, particularly computers. Indeed, between 1970 and 1990, the Bureau of Economic Analysis (BEA) estimates that constant-dollar investment in office and computing equipment grew at an annual rate of 18.1 percent, far above the 3.3 percent growth averaged for the remaining categories of producers' durable equipment. Given the increasing use of computers by U.S. businesses, estimates of price change for these goods are of substantial importance.

Two distinct facets of price change for computers can be studied. First, how rapidly have the prices of computing equipment fallen over time? Any meaningful answer to this question must adjust for the enormous improvements in the power of computers. Such estimates of constant-quality computer prices are needed not only to deflate investment outlays for computing equipment but also to calculate output in the computer industry and to construct broad indexes of inflation. In recent years, considerable work has been done to estimate constant-quality prices for computing equipment (for a comprehensive review of this literature, see Triplett 1989). Moreover, as described in Cartwright (1986), the results of this work have been used to construct price measures in the national income and product accounts. Nonetheless, this literature is still in its early stages, and much further work is needed to sharpen the

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results obtained to date. In particular, all the recent studies reviewed in Triplett (1989) employ manufacturers' list prices, leaving open the possibility that the resulting estimates do not adequately characterize the behavior of actual transaction prices.

A second aspect of price change for computers concerns the rate at which the value of this equipment declines with age—that is, the rate of depreciation. For a cohort of computers installed at a given time, depreciation of the cohort reflects both the price decline for the equipment remaining in service as the cohort ages and the increase in the proportion of units retired from service, for which price is assumed to be zero. Such estimates of cohort depreciation are a vital input for calculating capital stocks. In contrast to the substantial effort undertaken to estimate constant-quality prices for computers, the literature on depreciation and retirement of these goods is surprisingly sparse. There appears to be no systematic study of retirement patterns. And the most commonly cited estimate of economic depreciation for office and computing equipment, that of Hulten and Wykoff (1981b), is based solely on prices for typewriters (see Hulten and Wykoff 1979, 87), for lack of price data on computers.

This paper provides new estimates of the rate of economic depreciation and the rate of constant-quality price change for a large sample of IBM mainframe computers. These estimates are derived from a rich and virtually untapped source of data, the *Computer Price Guide,* a quarterly bluebook that lists asking prices in the secondhand market for commonly traded models of IBM computer equipment. The paper also analyzes separate data on the installed stock of various IBM mainframe models to derive the implied retirement pattern for these computers and to construct estimates of cohort depreciation. The value of the paper is in bringing new data to the analysis of long-standing and important pricing questions.

The paper is organized as follows. Section 1.1 identifies the primary determinants of price for IBM mainframe computers in the secondhand market. On the basis of this discussion, section 1.2 specifies the "hedonic" price equations used to estimate constant-quality price change and depreciation for my sample of IBM mainframes. Section 1.3 describes the price data in more detail and discusses the construction of other variables used in the econometric work. Section 1.4 estimates constant-quality price change for my sample, using both IBM list prices and the corresponding asking prices in the secondhand market. This section examines whether the results obtained in previous studies with list prices are altered when the analysis is redone with secondhand prices, which should reflect any discounting from list by IBM. Section 1.5 presents the empirical results concerning depreciation and retirement, and section 1.6 uses these results to assess potential biases in BEA's published gross and net capital stocks for office and computing equipment. Section 1.7 summarizes the findings of the paper.

1.1 A Pricing Model for IBM Mainframe Computers

This section lays out a model for the price of IBM mainframe computers. The goal is to motivate the econometric equations used below to estimate price change for these assets. I pay particular attention to the concept of age that belongs in the econometric equations.

Perhaps the most distinctive feature of the secondhand market for IBM mainframes—in fact, for all IBM computing equipment—is that the age of the particular unit for sale is irrelevant to market participants. Indeed, in the *Computer Price Guide*, age is never listed as part of the description of the computer. Thus, two IBM model 360/30 mainframes, one shipped from IBM in 1965 and the other in 1967, are perfect substitutes in the market. This lack of concern for age results directly from IBM's unique policy for maintaining its equipment. Subject to certain conditions, IBM will provide maintenance service for a monthly fee that may vary across models but does not vary across different units of a given model.[1] Effectively, IBM supplies insurance against the purchase of a lemon. The buyer of any IBM mainframe computer can expect it to perform like new by paying a fee that is unrelated to the age of a particular unit. As a result, the market does not care about such age differences.

Although all units of a given model will sell at the same price, a second concept of age is relevant for pricing. Define *model age* as the time that has elapsed since the first shipment of a model. The IBM 360/30 was first shipped in 1965; thus, all 360/30 units had a model age of ten years in 1975. Similarly, all units of the 370/145 model, first shipped in 1971, had a model age of four years in 1975. The 370/145, the younger model, would be expected to command a higher price than the 360/30 at any given time for two reasons. First, the 370/145 is the more powerful computer, thereby generating higher rental income in each period of use. Second, the 370/145 likely has more periods of profitable use remaining before obsolescence causes retirement to occur.

To obtain a mathematical expression that relates IBM mainframe prices to model age and other factors, I begin by assuming that the market for these assets is in equilibrium; the assumption of equilibrium is relaxed later in the section. Let $\mathbf{z}(v)$ denote the vector of characteristics embodied in a mainframe model first shipped in period v, and let $\tau = t - v$ denote the age of this model at time t; $\mathbf{z}(v)$ can thus be written as $\mathbf{z}(t - \tau)$. Next, let $R[\mathbf{z}(t - \tau), t, \tau]$ denote the net rental income generated in period t by a mainframe of model age τ that embodies the vector of characteristics $\mathbf{z}$. $R(\cdot, \cdot, \cdot)$ depends (1) on

1. IBM will offer this contract to any purchaser of IBM computing equipment that is "in good working condition [at the time of sale] and was covered under an IBM maintenance agreement in the previous location" (*Computer Price Guide*, January 1986, 43). Given the adverse effect on resale value of failing to meet these rather mild conditions, almost all IBM equipment qualifies for the maintenance agreement at resale.

$\mathbf{z}(t - \tau)$, because these performance features determine the real services provided by the mainframe; (2) on time, because price changes affect the nominal value of these services; and (3) on a separate argument in τ, as a way of capturing the influence of factors, others than $\mathbf{z}$, that may be correlated with model age.

One factor included in (3) would be differences in IBM maintenance fees across models; for a model nearing obsolescence, the cost of IBM maintenance effectively becomes infinite at the time IBM terminates service contracts for the model. Another age-related factor would be the expense of keeping personnel trained to operate older models that may be used only on an infrequent basis.[2] Finally, as an empirical matter, $\mathbf{z}$ likely omits certain performance characteristics that contribute to value. If these omitted characteristics are correlated with model age, τ will act as their proxy. For all these reasons, a general formulation of net rental income should include a separate argument in model age.

Given this specification of net rental income for IBM mainframes, the purchase price can be expressed as the present value of future net income flows. This price will depend on all the factors that influence rental income and can thus be written $P[\mathbf{z}(t - \tau), t, \tau]$. $P(\cdot, \cdot, \cdot)$ is a general expression for the price of a new or used IBM mainframe computer and can be regarded as a "hedonic" function that relates price to its basic determinants (for an introduction to hedonic functions, see Triplett 1986). $P(\cdot, \cdot, \cdot)$ differs from the hedonic function for other durable goods only in the way that age has been defined. Typically, the measure of age that enters $P(\cdot, \cdot, \cdot)$ is the span of time over which a particular *unit* has been in use. This specification makes sense for goods that deteriorate with use (such as automobiles). However, as argued earlier, this concept of age is irrelevant in the market for IBM computing equipment. Age becomes important for pricing only when used at the level of distinct models, which have different embodied characteristics and input requirements.

Thus far, I have assumed that the market for IBM mainframes is in equilibrium, in that all models lie on a single pricing surface $P[\mathbf{z}(t - \tau), t, \tau]$. That is, after controlling for the effects on price of the characteristics $\mathbf{z}$, time, and model age, there are no price differences across models. Fisher, McGowan, and Greenwood (1983) argued that such an equilibrium seldom prevails for computers, as the prices of existing models are not immediately marked down to compete with the lower constant-quality price of a new model. Dulberger (1989) found empirical support for slow repricing on the basis of list prices

2. Note that I have specified net rental income to be a function of labor costs. Implicitly, I have a "putty-clay" model of computer operations in mind: firms can choose from a range of computers with different labor requirements, but these requirements are fixed once a particular computer has been installed. With fixed proportions ex post, net rental income equals gross income minus required labor costs.

for a sample of IBM and plug-compatible mainframes. Her data suggest that two distinct price regimes tend to exist in that market just after the introduction of a new technology: one regime for models embodying best-practice technology and a higher-priced regime for the set of nonbest models. Eventually, the nonbest models either get repriced down to compete with the best-practice models or leave the market. Although Dulberger's findings suggest that each occurrence of disequilibrium is temporary, nonbest models will, on average, carry a price premium because they spend some time in the higher-priced regime. (Similar evidence of disequilibrium in the market for disk drives is presented in Cole et al. 1986.)

The hedonic function $P(\cdot, \cdot, \cdot)$ can be modified to allow for multiple regimes by introducing an argument that shifts the surface. Let $B(v, t)$ equal one if the vintage v model embodies best technology at time t, and let $B(v, t)$ be greater than one if the model has nonbest technology at time t. Noting that $B(v, t) = B(t - \tau, t)$, the hedonic function that incorporates disequilibrium is

$$(1) \qquad P[\mathbf{z}(t - \tau), t, \tau; B(t - \tau, t)],$$

with $\partial P/\partial B > 0$. Expression (1) captures the idea that nonbest models tend to lie on a higher hedonic surface than best-technology models.

The types of price change studied in this paper can be written as derivatives of the natural log of expression (1). The first is the rate of constant-quality price change over time, $\partial \ln(P)/\partial t$. This partial derivative measures the rate of price change over time conditional on a fixed set of embodied characteristics, a fixed value of model age, and a single hedonic surface. It is a pure measure of inflation that abstracts from changes over time in the mix of mainframes being priced.

The second dimension of price change is the rate of depreciation—the change in asset price with age, holding time fixed. Typically, the rate of depreciation is defined to include all age-related effects on price and would thus be measured in expression (1) as the total derivative

$$(2) \qquad \left.\frac{d \ln(P)}{d\tau}\right| t \text{ fixed} = \frac{\partial \ln(P)}{\partial \mathbf{z}} \cdot \frac{\partial \mathbf{z}}{\partial \tau} + \frac{\partial \ln(P)}{\partial \tau} + \frac{\partial \ln(P)}{\partial B} \cdot \frac{\partial B}{\partial \tau}.$$

Narrower measures of the age-related change in price can also be defined. One such measure is the rate of depreciation that controls for differences across models in the embodied characteristics $\mathbf{z}$. This measure equals the sum of the second and third terms on the right-hand side of equation (2). An even narrower concept of age-related price change is simply the partial derivative of price with respect to τ, the second term on the right-hand side of the equation. Section 1.6 below explores the appropriate choice among these alternative measures.

1.2 The Econometric Model

The previous section identified the variables that affect the price of IBM mainframe computers. These variables include performance characteristics, time, model age, and an index that distinguishes models with best-practice technology from all others. Theory alone, however, cannot determine the form of the estimating equation. Following the tradition in the hedonic literature on computer prices (see Triplett 1989, table 4.2), I adopt the double-log form for the relation between price and the characteristics **z** in the econometric equation. For a single hedonic surface, the double-log assumption yields an estimating equation of the general form

$$\ln P = \alpha + \sum_i \beta_i \ln(z_i) + f(t) + h(\tau), \tag{3}$$

where $f(t)$ and $h(\tau)$ are functions of time and model age, respectively. The usual specification of $f(t)$ in hedonic equations uses a dummy variable for each time period. Because my data set has relatively few observations per period, I economize on degrees of freedom by specifying both $f(t)$ and $h(\tau)$ to be fifth-order polynomials. These polynomials are of high enough order to capture a wide range of time- and age-related price movements. Equation (3) then becomes

$$\ln P = \alpha + \sum_i \beta_i \ln(z_i) + \sum_{j=1}^{5} \gamma_j t^j + \sum_{j=1}^{5} \delta_j \tau^j. \tag{4}$$

For mainframe computers, the consensus view is that two characteristics largely determine the quality of a given model: speed of computation and main memory capacity (again, see Triplett 1989). Although the measurement of memory capacity is straightforward, there is no universally accepted index of speed, in large part because the speed of a processor depends on its mix of tasks. A crude measure of overall speed—which has been adopted in most of the recent empirical studies in this area—is millions of instructions processed per second, the MIPS rating. I specify **z** to consist of the model's MIPS rating and its main memory capacity.

To allow for multiple price regimes, I generalized equation (4) to have different constant terms for best and nonbest models. Moreover, I let the polynomial function in t differ across these two sets of models to accommodate possible shifts over time in the gap between the two price surfaces. Given this generalization, a rule is needed to distinguish models with best-practice technology from all other models. Dulberger (1989) defined best-practice models at time t as those having main memory chips with the greatest density then available. She argued that advances in semiconductor technology, which historically have driven the improvements in performance of computer processors, are highly correlated with increases in chip density. Thus, chip density acts as a proxy for the level of embodied technology.

Following Dulberger's argument, I assigned each model to a technology class on the basis of the density of its memory chip. For example, all models with 64KB (kilobit) chips were placed in a single class, those with 288KB chips were put in a second class, and so on. Given these class assignments, I defined a dummy variable BEST, which took the value of one for models in the class with the densest chip available at the time of the price observation and zero for other models. Now, the generalized version of equation (4) can be written

$$(5) \qquad \ln P = \alpha_1 + \alpha_2 \text{BEST} + \beta_1 \ln(\text{MIPS}) + \beta_2 \ln(\text{Memory}) + \sum_{j=1}^{5} (\gamma_j + \pi_j \text{BEST}) t^j + \sum_{j=1}^{5} \delta_j \tau^j.$$

In the previous section, I argued that prices of mainframe computers likely depend on model age (but not the age of individual units of that model). Price might also be related to a second concept of age, one based on the model's technology class. To illustrate the distinction between these two measures of age, note that IBM began shipping mainframes with 64KB memory chips in 1979. However, the first shipment of its model 3081-K, which also used the 64KB chip, was not until 1982. The age of the 3081-K in 1982 would be zero when defined in terms of the model itself but three years when defined in terms of the technology class. A priori, it is not clear which of these concepts of age is more closely correlated with obsolescence of IBM mainframes, and I use both age measures in the empirical work below.

Finally, I added a dummy variable to equation (5), denoted NEW, that equals one if the price observation refers to a new unit and zero if not. New IBM mainframes often trade in the secondhand market, as dealers place orders with IBM for equipment in short supply and then resell the equipment to firms wanting immediate delivery. From the viewpoint of performance, new and used units are identical. However, tax considerations are likely to make the new unit sell for a higher price in the secondhand market than the same unit used. During most of my sample period, new computing equipment was eligible for an investment tax credit—which ranged up to 10 percent of the unit's purchase price—while the credit was highly restricted for used equipment.[3] Adding the NEW dummy variable to the estimating equation yields

$$(6) \qquad \ln P = \alpha_1 + \alpha_2 \text{BEST} + \beta_1 \ln(\text{MIPS}) + \beta_2 \ln(\text{Memory}) + \sum_{j=1}^{5} (\gamma_j + \pi_j \text{BEST}) t^j + \sum_{j=1}^{5} \delta_j \tau^j + \rho^* \text{NEW},$$

3. The investment tax credit was eliminated in 1986. As an indication that the credit had created a wedge between the prices of new and used units, the *Computer Price Guide* noted in late 1986 that "the difference in value between new and used [units] is going to narrow. . . . From now on, used equipment is going to be a more attractive alternative, at prices closer to list price" (*Computer Price Guide Readers Report*, October 1986, 1).

where τ is defined either by the age of a particular model or by the age of that model's technology class. Equation (6) is the basic equation estimated in the empirical part of the paper.

1.3 Data for Estimating Constant-Quality Price Change and Depreciation

The primary data source for this paper was the *Computer Price Guide*, a bluebook for computing equipment published quarterly since late 1970 by Computer Merchants Inc., a dealer in the secondhand market for this equipment. Each issue of the *Guide* contains price quotes for commonly traded mainframe computers, minicomputers, personal computers, and various types of peripheral equipment. Because the secondhand market for non-IBM equipment is so thin, the *Guide* has listed only IBM equipment since 1978. The data set that I created from the *Guide* includes fifty-two models of IBM mainframe computers, spanning the period from the fourth quarter of 1970 to the fourth quarter of 1986. The IBM 360, 370, 4300, and 30XX families are well represented in the sample.[4]

For each entry in the *Guide*, two prices are shown. The first is the average asking price in the secondhand market during the month or two prior to publication of the *Guide;* this price is a composite of quotes to retail customers seeking immediate delivery. It is not the actual sale price for any particular transaction. The second price provided for each entry is IBM's list price prevailing a few weeks before publication of the *Guide*. Somewhat misleadingly, the *Guide* continues to show a list price for a model even after IBM has ceased production; presumably, the list price shown is the final one at which IBM sold the model. To avoid the use of contaminated data, my empirical work employs the list prices in the *Guide* only for periods before the year of IBM's final shipment. (For the year of final IBM shipment for each model in my sample, see app. table 1A.1.)

Each issue of the *Guide* typically priced different configurations of a particular mainframe model, many of which included peripheral equipment or other attachments to the basic processing unit. To keep the sample as homogeneous as possible, I attempted to price only the model's "minimum configuration," which consists of the central processing unit (CPU), the main memory, and other required components (such as cooling units). As a result, I omitted all entries with peripheral equipment and included entries that had optional attachments to the CPU only when the minimum configuration was not listed.

Besides information on prices, the estimation of equation (6) requires data for age, the BEST dummy, MIPS, and memory size. Memory size, measured

4. Prices from the *Guide* were previously used by Archibald and Reece (1979) to estimate constant-quality price change for large IBM mainframe systems over the period 1970–75. Their study, however, did not attempt to estimate depreciation.

in kilobytes, was taken directly from the *Guide*, which includes this information for every entry. MIPS ratings were obtained from a variety of sources, principally Lias (1980) and issues of *Computerworld*'s "Annual Hardware Roundup." Appendix table 1A.1 lists the MIPS rating for each model in the sample and the source of the rating. Table 1A.1 also lists the date of initial shipment for each model, from which I calculated the model age for each price observation (in quarters). The data needed to calculate the value of BEST and the age of the technology class for each price observation are contained in tables 1A.1 and 1A.2; table 1A.1 shows the technology class for each model, adopting the class codes in Dulberger (1989), while table 1A.2 provides the date of first shipment for each class.[5] Using these tables, I calculated the age of the technology class for each price observation as the pricing date minus the date of first shipment from the model's technology class, in quarters. Table 1A.2 also shows the period over which each technology class represented the best technology, from which I calculated the value of the BEST dummy variable for each observation.[6]

1.4 Constant-Quality Price Change

This section estimates constant-quality prices for IBM mainframe computers, focusing on whether the results are sensitive to the use of list prices in place of actual transaction prices. Ideally, one would assess the bias imparted by list prices by directly comparing the results based on list prices to those based on transaction prices. Unfortunately, transaction prices are proprietary information, so this approach cannot be implemented. Instead, I draw inferences about the behavior of IBM's transaction prices by examining prices in the secondhand market. This procedure implicitly assumes that IBM's transaction prices move closely with secondhand prices, reflecting the ability of firms to buy equipment in either market.

1.4.1 IBM's Discounts on Mainframe Computers

The data in the *Guide* can be used to infer the extent of IBM's price discounts. Let LP(IBM) and TP(IBM) denote, respectively, IBM's list price and

5. There was some ambiguity in defining the date of first shipment for the technology class with magnetic core memory (class 1), the precursor to semiconductor memory. Magnetic core memory was used for the 360 family, but also for earlier models not included in my sample. I set the first shipment date of this technology class equal to the first shipment of the 360s in my sample—April 1965—rather than the first shipment of any processor with core memory.

6. A few models in the 370 family were introduced with relatively low-density chips but were subsequently upgraded to use denser chips. Because the *Guide* does not indicate which version of such models is being priced, I cannot determine the appropriate technology class for price observations after the date of the upgrade. To solve this problem, I assumed that price observations in the *Guide* before the upgrade refer to the lower-density version of the model while prices after the upgrade pertain to the enhanced version. This rule assigns a unique technology class to each price observation.

transaction price for a particular mainframe model. Further, let AP(SHM) and TP(SHM) denote, respectively, the asking price and the transaction price for the same model in the secondhand market. I assume that AP(SHM) = TP(SHM).

For the typical case in which the secondhand market price refers to a used unit while IBM's price refers to a new unit, the latter will include a premium, denoted TAX, equal to the value of the investment tax credit. IBM may be able to extract an additional premium, denoted SVC, equal to the value of the service it provides at the time of sale. A third premium, denoted MAINT, may result from IBM's offer of a year of free maintenance for new units (the *Computer Price Guide Readers Report,* July 1975, 139, documents this IBM practice). Accounting for these premiums, IBM's transaction price will be related to the secondhand asking price as follows:

$$\mathrm{TP(IBM)} = \mathrm{AP(SHM)} + \mathrm{TAX} + \mathrm{SVC} + \mathrm{MAINT}.$$

Dividing each side by IBM's list price and subtracting one from each side yields

$$(7)\quad \frac{\mathrm{TP(IBM)}}{\mathrm{LP(IBM)}} - 1 = \frac{\mathrm{AP(SHM)}}{\mathrm{LP(IBM)}} + \frac{\mathrm{TAX} + \mathrm{SVC} + \mathrm{MAINT}}{\mathrm{LP(IBM)}} - 1.$$

The left-hand side of the equation gives IBM's rate of discount, while the first term on the right-hand side equals the ratio of the secondhand market asking price to IBM's list price, which is provided in the *Guide.* Data for the TAX, SVC, and MAINT premiums are not known for individual models. However, the *Guide* states that, before the elimination of the investment tax credit in 1986, "it was difficult to interest users in a used piece of gear, unless the price was at least 12% to 15% below IBM's list price" (*Computer Price Guide Readers Report,* October 1986, 1). Using this information, I specified the total premium, TAX + SVC + MAINT, to be 15 percent of list price, implying that

$$(8)\quad \begin{aligned} \frac{\mathrm{TP(IBM)}}{\mathrm{LP(IBM)}} - 1 &= \frac{\mathrm{AP(SHM)}}{\mathrm{LP(IBM)}} + \frac{.15 * \mathrm{LP(IBM)}}{\mathrm{LP(IBM)}} - 1 \\ &= \frac{\mathrm{AP(SHM)}}{\mathrm{LP(IBM)}} - .85. \end{aligned}$$

Consequently, I inferred that IBM was discounting from list price whenever the ratio of the *Guide's* asking price for used units to IBM's list price was below 0.85.

Table 1.1 displays this ratio for mainframe models estimated still to be in production at the pricing date (recall that only these models have valid list prices in the *Guide*). Column 1 covers the entire sample period, 1970–86. The first entry in the column represents the average price ratio for models first shipped less than four quarters earlier; the second entry represents the average

Table 1.1 **Average Ratio of *Computer Price Guide* Asking Price to IBM List Price, for Used Units, by Age of Model (standard errors in parentheses)**

	All Models in Production at Pricing Date		All Models in Production at Pricing Date with Ratio ≥ 0.6	
Age in Quarters	1970–86 (1)	1972–84 (2)	1970–86 (3)	1972–84 (4)
0–3	.850	.847	.850	.847
	(.018)	(.023)	(.018)	(.023)
4–7	.787	.795	.813	.817
	(.015)	(.016)	(.013)	(.015)
8–11	.743	.802	.802	.802
	(.026)	(.016)	(.016)	(.016)
12–15	.729	.729	.822	.822
	(.034)	(.034)	(.028)	(.028)
16–19	.453	.453	.621[a]	.621[a]
	(.032)	(.032)		
Average ratio	.758	.766	.816	.813
Sample size	146	116	119	97

[a]Based on a single observation. Standard error is not meaningful.

for models first shipped four to seven quarters earlier, and so on down the column. For models less than four quarters old, the ratio of the secondhand market price to IBM's list price averaged 0.85, indicating that IBM was not discounting from list. However, for older models, the ratio drops steadily and is more than two standard errors below 0.85 in each age group. Column 1, therefore, points to widespread discounting after a model has been available for about one year. Column 2 restricts the sample to 1972–84, the period covered by Dulberger (1989), with little change in the results.

In both columns, the calculated price ratio becomes so small for models aged sixteen to nineteen quarters as to raise questions about the quality of the data. One possible explanation is that the ratios are distorted by the inadvertent use of list prices from the *Guide* for models no longer in production, owing to difficulties in determining exactly when IBM stopped shipping a given model on the basis of publicly available data. In columns 3 and 4, I recalculated the average ratios for each age group after omitting any observation for which the price ratio was below 0.6—that is, for which the discount from list was greater than 25 percent (0.6 − 0.85). All the observations removed by this filter occurred in the four quarters just prior to my estimated ending date of IBM shipments, and two-thirds were within two quarters of this date. The concentration of the low ratios close to the end of IBM's estimated production period supports the view that columns 1 and 2 included list prices for models actually out of production. If the low ratios had been due, instead, to random errors in the data, these ratios would have been spread evenly throughout IBM's production period.

Columns 3 and 4 indicate that, after filtering, the price ratio remains above 0.8 for all but the oldest age group. The ratio for this group is based on a single observation and merits little attention. Focusing on the other age groups, the average ratios for the models aged zero to three quarters and those aged twelve to fifteen quarters are within one standard error of 0.85 and thus provide no significant evidence of IBM discounting. Although the average ratios for the models aged four to seven quarters and those aged eight to eleven quarters are more than two standard errors below 0.85, the point estimates imply IBM discounts from list of less than 5 percent. On balance, these results suggest that IBM's list prices for mainframe computers proxied reasonably well for actual transaction prices, at least until 1986.

1.4.2 Estimates of the Hedonic Pricing Equation

As the next step in the analysis, I compared the estimates of equation (6) based on IBM list prices with those based on prices in the secondhand market. To avoid the use of invalid list prices, I restricted the sample for these regressions to models still in production at the pricing date. In addition, I required that the ratio of asking price to IBM list price be at least 0.6, as in columns 3 and 4 of table 1.1. These two requirements yielded a sample of 145 observations, to which I applied ordinary least squares.[7]

Table 1.2 presents selected estimation results using IBM's list price as the dependent variable. The first column is meant to approximate the hedonic regressions run by Dulberger (1989) and other researchers, who omitted measures of age from the set of regressors. The explanatory variables in column 1 include all those shown in equation (6) except for the fifth-order polynomial in τ. Column 2 adds the polynomial function of model age to the regression, while column 3 instead adds the polynomial with age measured by the model's technology class.

The results in all three columns indicate that MIPS and memory size have positive, highly significant effects on price. The coefficients show that processing speed is a more important determinant of price than is memory capacity, consistent with the findings in Dulberger (1989) and Cartwright (1986). In addition, the terms in BEST and $\Sigma(\text{BEST}*t^j)$ are jointly significant in each regression. This result can be seen in the bottom row of the table, which reports the F-statistic for the null hypothesis that the coefficients on these terms are all zero. In each column, the value of the F-statistic is well above its 1 percent critical value of about 2.95. Thus, along with Dulberger, I find evidence of different list-price regimes for mainframes embodying best and nonbest technology. Moreover, including age as an explanatory variable does not alter this result.

7. This sample of 145 observations is slightly larger than the sample used in col. 3 of table 1.1 because I have included price observations for new equipment.

Table 1.2 OLS Estimates of the Hedonic Price Equation with IBM List Price as Dependent Variable (*t*-statistics in parentheses)

	Age Variable in Regression		
Regressor	None (1)	Model (2)	Tech. Class (3)
ln(MIPS)	0.758	0.777	0.727
	(23.6)	(23.3)	(41.3)
ln(Memory)	0.203	0.188	0.203
	(6.1)	(5.4)	(11.1)
R^2	0.984	0.985	0.996
F-statistic for insignificance of all terms in BEST	4.52	4.09	8.17

Note: Each regression was based on a sample of 145 observations considered to have valid list prices; see the text for specific selection criteria. In addition to ln(MIPS) and ln(Memory), the explanatory variables for each regression included a constant, BEST, NEW, and fifth-order polynomials in Time and BEST*Time. The regressions reported in cols. 2 and 3 also included a fifth-order polynomial in the age variable shown.

Table 1.3 OLS Estimates of the Hedonic Price Equation with Secondhand Market Asking Price as Dependent Variable (*t*-statistics in parentheses)

	Age Variable in Regression		
Regressor	None (1)	Model (2)	Tech. Class (3)
ln(MIPS)	0.806	0.821	0.794
	(33.4)	(32.3)	(37.7)
ln(Memory)	0.234	0.220	0.232
	(9.4)	(8.3)	(10.6)
R^2	0.992	0.992	0.994
F-statistic for insignificance of all terms in BEST	10.31	10.11	1.81

Note: Each regression was based on a sample of 145 observations considered to have valid list prices; see the text for specific selection criteria. In addition to ln(MIPS) and ln(Memory), the explanatory variables for each regression included a constant, BEST, NEW, and fifth-order polynomials in Time and BEST*Time. The regressions reported in cols. 2 and 3 also included a fifth-order polynomial in the age variable shown.

Table 1.3 reports the same set of regression estimates as in table 1.2, with the dependent variable now equal to the secondhand market price. On the whole, the estimates are similar to those derived from list prices. There is no material change in the estimated coefficients on MIPS and memory size. Further, we continue to find evidence of multiple price regimes. The null hypothesis that the coefficients on BEST and $\Sigma(\text{BEST}^*t^j)$ are jointly zero is rejected at any reasonable significance level in columns 1 and 2 and at about the 10 percent level in column 3. Overall, the results in table 1.3 suggest that the finding of disequilibrium is not generated by the use of list prices.

1.4.3 A Further Look at Disequilibrium

In tables 1.2 and 1.3, multiple price regimes appeared to characterize equation (6). I now take a closer look at the prices for models with best technology (BEST = 1) relative to those with nonbest technology (BEST = 0). To isolate the effect of disequilibrium, the comparison should be between best and nonbest models that are otherwise identical. Imposing this requirement, equation (6) implies that

$$P_b/P_{nb} = \exp[\ln(P_b) - \ln(P_{nb})] = \exp\left(\alpha_2 + \sum_{j=1}^{5}\pi_j t^j\right),$$

where b and nb denote, respectively, best-technology models and nonbest models. Values of P_b/P_{nb} different than unity provide evidence of disequilibrium. This ratio will vary over time, and table 1.4 presents the average value of the ratios computed during each quarter of the period 1973:1–1981:4.[8]

The price ratio shown in the first row of column 1 was generated by the list-price regression without any age variables. That regression is essentially the one run by Dulberger to discern disequilibrium in her sample of mainframe processors. Consistent with her results, I find that models incorporating best technology have list prices 7.7 percent (1 − 0.923) below those for otherwise identical models with nonbest technology. Column 1 also shows that using secondhand market prices in place of IBM list prices does not materially change this result, as best-technology models sell for about 11 percent less than nonbest models. As shown in column 2, these results are largely unaffected by the inclusion of model age in the set of regressors. Best-technology models still appear to be at least 5 percent cheaper than nonbest models.[9] However, the results change markedly when the regression includes age terms based on technology class, as shown in column 3. The average ratio computed with list prices jumps to 1.167, indicating that best-technology models carry a sizable price *premium* over nonbest models. When secondhand market prices are used in the regression, the ratio is about unity.

The results in column 3 are at odds with Dulberger's characterization of disequilibrium and need to be examined more closely. As noted above, setting

8. Even though my full sample covers 1970–86, I computed the average price ratio only for 1973–81. The subsample of 145 valid list prices had no observations for nonbest models outside 1973–81, and I did not want to extrapolate the results out of sample.

9. Although table 1.4 does not present standard errors for the price ratios, it is unlikely that the ratios displayed in cols. 1 and 2 actually equal one. For these ratios to equal one at all times, α_2 and π_j ($j = 1, \ldots, 5$) must be jointly zero. However, the F-tests reported in tables 1.2 and 1.3 rejected this hypothesis at any reasonable confidence level for the sets of α_2 and π_j coefficients used to compute the ratios in the first two columns of table 1.4.

Table 1.4 **Price of Models with Best Technology Relative to Models with Nonbest Technology (average, 1973:1–1981:4)**

	Age Variable in Regression		
Price Measure	None (1)	Model (2)	Tech. Class (3)
IBM list	0.923	0.946	1.167
Secondhand market	0.889	0.903	1.020

Note: These ratios are based on the regressions reported in tables 1.2 and 1.3

$P_b/P_{nb} = \exp(\alpha_2 + \Sigma\ \pi_j t^j)$ forces all regressors apart from BEST to be equal across best and nonbest models. In column 3, that means we have forced the age of the technology class to be the same across these two groups. This constraint makes little sense in that, by definition, the best-technology models are those with new technology while the nonbest models are those with old technology. That is, the value of BEST and the age of the technology class jointly distinguish best-technology models from nonbest models. This reasoning suggests that the comparison in column 3 should allow for differences in both BEST and the age of the technology class. (Note that cols. 1 and 2 implicitly allow the age of the technology class to differ across best and nonbest models because that variable is excluded from the set of regressors.) With this broader approach,

$$P_b/P_{nb} = \exp\left[\alpha_2 + \sum_{j=1}^{5} \pi_j t^j + \sum_{j=1}^{5} \delta_j(\tau_b^j - \tau_{nb}^j)\right].$$

To calculate this adjusted measure of the price ratio, I used the estimates of δ_j from the regressions reported in the third column of tables 1.2 and 1.3. I also set τ_b and τ_{nb} to the average age of the technology class for best and nonbest models, respectively. The resulting value of P_b/P_{nb} is 0.852 when using IBM list prices and 0.745 when using secondhand market prices. Now, the results based on regressions that include the age of the technology class are qualitatively similar to the others in table 1.4. Best-technology models sell at a discount relative to nonbest models, supporting Dulberger's result. This discount does not appear to be an artifact of using IBM list prices. If anything, substituting prices in the secondhand market for IBM list prices slightly increases the amount of discount. Both sets of prices suggest that existing models of IBM mainframes are not repriced down immediately at the introduction of models embodying superior technology.[10]

10. Berndt and Griliches (1990) offer several possible explanations for the relatively high prices of older models. First, users may be willing to pay a premium for older models because of the large base of existing software and because they understand how to use these models; conversely, the prices of new models may be held down by uncertainty about their performance and by the limited amount of available software. Second, computer manufacturers may set the prices of new

1.4.4 Constant-Quality Price Change

Table 1.5 presents the rates of constant-quality price change implied by the regressions reported in tables 1.2 and 1.3. The main issue that I examine is whether the rate of price decline based on IBM list prices is different than that based on prices in the secondhand market for the same models. Each entry in table 1.5 represents the average annual rate of constant-quality price change over either 1973–81 or 1973–86, calculated as

$$\{[P(t_1)/P(t_0)]^{1/(t_1 - t_0)} - 1\} * 100, \tag{9}$$

where $t_0 = 1973$ and $t_1 = 1981$ or 1986.[11] These estimates of price change begin in 1973 because the subsample of valid list prices has no observations before that year. For models with nonbest technology, the price observations end in 1981, dictating the period 1973–81 shown in the table. For best-technology models, observations are available through 1986, and the table presents the average rate of constant-quality price change over both 1973–81 and 1973–86; the estimates for the latter period are shown in parentheses.

Virtually all the estimates in the table show constant-quality prices declining at average annual rates of around 20 percent. In particular, substituting secondhand market prices for IBM list prices has—with one exception—only a small effect on the estimated rate of price decline. The outlier in the table is the 8 percent decline shown at the bottom of column 3. This entry is heavily influenced by a single year, 1981, when prices are estimated to have more than doubled. There are few sample observations for nonbest models in that year. Excluding 1981, the average rate of price decline for this entry becomes 23.5 percent, similar to the other estimates in the table. Overall, the close match between the results based on list prices and those based on secondhand market prices suggests that the use of list prices in recent studies has not given a misleading impression of constant-quality price change for mainframe computers.

To complete this section, table 1.6 compares the constant-quality price

models relatively low to encourage purchases of an unfamiliar technology—i.e., to use low prices as a form of advertising. Third, the price premium for older models may simply reflect the higher quality of unobserved characteristics of models that have survived in the marketplace. The first two hypotheses imply a temporary premium for nonbest models, while the third hypothesis implies a long-term premium. Dulberger's finding that the premium for nonbest models was temporary argues against unobserved characteristics as the source of multiple prices for mainframe processors.

11. To see how the price ratio $P(t_1)/P(t_0)$ is calculated, note that eq. (6) can be written as

$$\ln P(t) = A + \sum_{j=1}^{5} (\gamma_j + \pi_j \text{BEST}) t^j,$$

where A represents all terms in the equation that are not explicit functions of time. Thus,

$$P(t_1)/P(t_0) = \exp[\ln P(t_1) - \ln P(t_0)] = \exp\left[\sum_{j=1}^{5} (\gamma_j + \pi_j \text{BEST})\,(t_1^j - t_0^j)\right].$$

Table 1.5 Average Annual Rate of Constant-Quality Price Change, 1973–81

	Age Variable in Regression		
	None (1)	Model (2)	Tech. Class (3)
Best-technology models:			
IBM list price	−19.9	−19.7	−23.9
	(−20.2)	(−19.8)	(−19.9)
Secondhand market price	−22.0	−21.8	−23.7
	(−22.2)	(−22.0)	(−22.0)
Nonbest models:			
IBM list price	−18.6	−18.8	−22.1
Secondhand market price	−22.0	−21.8	−8.0

Note: These ratios are based on the regressions reported in tables 1.2 and 1.3. Figures in parentheses refer to 1973–86.

Table 1.6 Alternative Measures of Constant-Quality Price Change Based on List Prices (percentage change in average price from previous year to year shown)

	Oliner				
Year	Best Tech. (1)	Nonbest Tech. (2)	Dulberger (3)	Cartwright (4)	Gordon (5)
1973	NA	NA	5.9	21.3	NA
1974	27.2	−2.9	−22.3	11.5	NA
1975	0.1	−0.6	−2.7	−30.1	NA
1976	−17.1	−5.5	−1.9	−8.8	NA
1977	−27.3	−14.4	−35.8	−31.6	NA
1978	−32.4	−23.8	−47.5	−28.3	−12.1
1979	−33.6	−31.0	−7.4	−35.7	−21.4
1980	−31.8	−33.7	−27.0	−12.5	−19.6
1981	−27.6	−29.3	−36.0	−19.3	−29.1
1982	−22.1	NA	−11.7	−15.1	−21.0
1983	−17.0	NA	−9.4	−16.0	−9.1
1984	−14.9	NA	−15.0	NA	−28.6
1985	−18.7	NA	NA	NA	NA
1986	−30.3	NA	NA	NA	NA
Averages:					
1973–83	−19.8	NA	−21.7	−19.6	NA
1973–81	−19.9	−18.6	−24.3	−20.6	NA
1977–84	−26.0	NA	−23.4	NA	−20.4

Sources: Columns 1 and 2: From regression estimates reported in table 1.2, col. 1 above. Column 3: Dulberger (1989, table 2.6, column labeled "Regression" index, p. 58). Column 4: Cartwright, from Triplett (1989, table 4.9, col. 3, p. 186). Column 5: Gordon (1989, table 3.7, col. 6, pp. 104–5).

Note: "NA" indicates not available.

indexes computed in this paper with those calculated by Dulberger (1989), Gordon (1989), and Cartwright (whose results, although unpublished, are cited in Triplett 1989, table 4.9). All the indexes in table 1.6 are similar in that they (1) are based on list prices for IBM mainframes or other "plug-compatible" makes and (2) are derived from the coefficients on time variables in hedonic regressions that omit measures of age. Moreover, in all cases, I calculated the rates of price change from equation (9). Despite these common features, the alternative indexes can differ because of variations in data sources, in the composition of the sample, and in the sample period used for estimation.

The bottom part of the table presents the average annual rate of price change for each index over several time periods. On the whole, the estimates are remarkably similar across columns. All the studies find that price declines averaged between 18.5 and 26 percent per year for the periods indicated. Moreover, as shown by the individual year entries in the table, all the indexes available back to the early 1970s indicate that the most rapid price declines were concentrated during the late 1970s and early 1980s. Even with the differences for particular years, the various studies all convey the same basic impression of constant-quality price changes for mainframe computers.

1.5 Depreciation and Retirement Patterns

This section shifts the focus away from price change over time to price change associated with age. As a mainframe model ages, its price will tend to fall because obsolescence draws ever closer. In addition, with advancing age, an increasing fraction of the installed units of that model will have been removed from service. Thus, to measure depreciation for a cohort of mainframes, one needs information on the rate of depreciation for units that remain in service and on the rate of retirement. Implicitly, the units no longer in service carry a zero price, and this zero price needs to be averaged with the prices observed in the secondhand market to obtain an uncensored estimate of depreciation (for further discussion, see Hulten and Wykoff 1981a). In equation form, the effect of age on price, corrected for censoring, can be written

$$\tilde{P}(\tau) = [1 - F(\tau)] * P(\tau) + F(\tau) * 0 = [1 - F(\tau)] * P(\tau) = S(\tau) * P(\tau),$$

where $P(\tau)$ is the price observed in the secondhand market at age τ, $F(\tau)$ is the probability that a given unit will have been retired by age τ, and $S(\tau) \equiv 1 - F(\tau)$ is the probability of survival to age τ. The correction for censoring scales the observed price by the survival probability for a unit at that age. Both $P(\tau)$ and $\tilde{P}(\tau)$ can be regarded as having been normalized to unity at age 0; thus, these series represent the percentage of initial value remaining at age τ.[12]

12. To express $\tilde{P}(\tau)$ as $S(\tau) * P(\tau)$, I have assumed that units removed from service have a market price of zero. This assumption will be violated if the assets retired by U.S. companies are

The first part of this section estimates $F(\tau)$ for IBM mainframe computers, the second part estimates $P(\tau)$, and the third part brings the two pieces together to estimate $\tilde{P}(\tau)$.

1.5.1 Estimates of the Retirement Distribution

I estimated the retirement distribution for mainframe computers using data on the installed stocks of various IBM models compiled by the International Data Corporation (IDC). My data from the IDC run from the end of 1970 to the end of 1986. For several IBM 360 models, I extended the series back to 1965 on the basis of IDC data shown in Phister (1974).[13] Retirement distributions were calculated for fourteen IBM mainframe models: models 20, 30, 40, and 65 in the 360 family; models 135, 138, 145, 148, 155, and 165 in the 370 family; and models 3031, 3032, 3033N, and 3033S in the 30XX family.[14]

The IDC data provide a time series of installed stocks for each model but no information on shipments from IBM or on retirements. My method for inferring the pattern of retirements can be illustrated with the following example:

	1975	1976	1977	1978	1979	1980	1981	1982	1983
Installed stock	0	100	400	500	450	400	250	100	0
Shipments (inferred)	0	100	300	100	0	0	0	0	0
Retirements (inferred)	0	0	0	0	50	50	150	150	100

In this example, the installed stock rises through 1978 and then declines through 1983. I assumed that shipments ceased in 1978, the peak year for the installed stock, and that retirements began the following year, when the stock began to decline. Starting in 1979, I take the change in the stock from the previous year to be the estimate of retirements. This method implies that 50 units were retired in 1979 and 1980, 150 units in 1981 and 1982, and 100

not scrapped but rather sold to U.S. consumers or for use abroad. To refine $\tilde{P}(\tau)$, it would be useful to have information on the value and destination of computing equipment exiting the U.S. business sector.

13. Over the years 1970–74, the IDC data on installed stocks shown in Phister (1974, 333) often differed from the IDC data I obtained in 1987, reflecting revisions to the data in the intervening years. To splice together the two IDC series for a given model, I level-adjusted the series in Phister for 1965–70 by the ratio of the 1970 value of my IDC series to the 1970 value of the Phister series.

14. The models in the 360 and 370 families were almost fully retired by the end of my IDC data in 1986; only 4 percent of the 360 units and 5 percent of the 370 units remained in service in that year. However, the retirement of the four 30XX models was less complete by 1986, with 30 percent of these units still in service. To fill in the tail of the 30XX distribution, I assumed that one-third of the remaining units of each model were retired in each year after 1986. These assumed retirements continued until only 5 percent of the total installed units for each model remained in the stock.

units in 1983. It seemed reasonable to assume that retirements do not begin until IBM stops shipping a model; to assume otherwise would mean that firms are scrapping units that could be sold in the secondhand market for a substantial fraction of IBM's list price.

The next task was to determine the age of the units retired in any year. As discussed earlier, age can be defined either for specific models or for an entire technology class. A retirement distribution can be constructed for each of these definitions of age. The distribution based on model age relates retirements to the time elapsed since the first unit of a model was shipped. In contrast, the distribution based on the age of a model's technology class relates retirements to the first shipment of any model from that technology class, thus providing information on the economic life of an embodied technology, rather than that of a model.

These two distributions correspond to the concepts of age used so far in the paper. However, neither distribution is appropriate for constructing capital stocks from data on investment outlays, as in the perpetual inventory method. In that method, the units purchased in a given year represent the inflow to the stock, and one must determine how long *these particular units* remain in service. Accordingly, I used the IDC data to construct a distribution of retirements based on the age of individual units, employing two alternative assumptions to identify their date of installation.[15]

One assumption is that the oldest units are the first retired, the analogue to first-in first-out (FIFO) accounting for inventories. This assumption would be appropriate if all firms tended to keep a computer for a fixed number of years, regardless of when the computer was acquired. Under this FIFO retirement pattern, all fifty units retired in 1979 in the above example are assumed to have been produced in 1976 and are thus three years old at retirement. The alternative assumption is that all vintages are represented proportionately among the units retired in each year. Returning again to the example, the fifty units retired in 1979 represent 10 percent of the peak stock. Under this alternative assumption, 10 percent of the units shipped in 1976, 1977, and 1978 are assumed to be retired in 1979, thus implying a mixture of one-, two-, and three-year-old units leaving the stock. This second assumption would be appropriate if firms tended to retire their computers whenever improved models become available, regardless of the number of years of service already obtained from the existing units.

Because it is not obvious which of these assumptions is more realistic a

15. As discussed earlier, the age of individual units has no bearing on prices in the secondhand market; model 360/30 units shipped by IBM in different years all sell at the same price at a given date. However, even if all firms scrapped their 360/30s at the same date (when their market price fell below scrap value), there would be a nondegenerate distribution of (unit) ages at retirement because the units were shipped by IBM at different times. In practice, the 360/30s were not all retired simultaneously, and a somewhat different—but again nondegenerate—distribution of unit ages at retirement would result.

priori, I calculated the retirement distribution for each of the fourteen models in both ways. I then produced an aggregate distribution for the 360 models, the 370 models, the 30XX models, and all fourteen models under both the FIFO method and the proportional method. These aggregates were constructed as a weighted average of the retirement distribution for each model in the aggregate, with the weights based on total shipments of each model in constant dollars.[16]

The results of this exercise are displayed in figures 1.1–1.4. The bars in figures 1.1 and 1.2 show the retirement distribution for the weighted aggregate of all fourteen models, with figure 1.1 displaying the FIFO retirement pattern and figure 1.2 the proportional retirement pattern. Both versions of the aggregate distribution have a mean retirement age of about 6.5 years and are strongly asymmetric, with a long right-hand tail. The proportional version in figure 1.2 is less tightly concentrated around the mean than the FIFO version; this spreading occurs because units of every vintage are assumed to be retired in each year.

The asymmetry that characterizes both versions of the distribution may have a simple economic interpretation. For mainframe computers, retirement occurs primarily because the model becomes obsolete, not because of wear and tear or accidental damage. As a result, few units will be retired until a superior model becomes available. When an improved model is introduced, firms that want cutting-edge technology will retire their existing units, producing the burst of retirements evident in figure 1.1 at five to six years of age. At the same time, other firms whose needs continue to be well served by older technology will retain their existing models until the cost advantage of replacement becomes apparent. These firms are responsible for the long tail in the retirement distributions. Thus, an asymmetric retirement pattern may be the rule for goods such as mainframe computers for which obsolescence rather than decay causes retirement.

For the purpose of comparison, the solid line in figures 1.1 and 1.2 shows the "Winfrey S-3" retirement distribution used by BEA for calculating stocks of office and computing equipment, while the dashed line represents the

16. My method of weighting involved the following steps. First, I inferred the number of units shipped annually for each model using the IDC data on installed stocks. Next, I determined the nominal value of these shipments by multiplying the units shipped by a measure of average price. For the models in the 370 and 30XX families, this price measure was the average of IBM's list price for units with maximum memory size and units with minimum memory size, as shown in Dulberger's (1989) data base. For the 360 models, I obtained the same information from Phister (1974, 342–47). Phister shows only one set of IBM prices for each model, which pertains to a period about two years after the first installation. I applied this single set of prices to each year of shipments. Finally, I converted the nominal shipments in each year to constant dollars by deflating with BEA's implicit price deflator for investment in office and computing equipment. The result was a vector of annual constant-dollar shipments for each model, which I summed to get total shipments for the model. The weight applied to each model's retirement distribution was this constant-dollar estimate of total shipments divided by the constant-dollar total summed across all models in the aggregate.

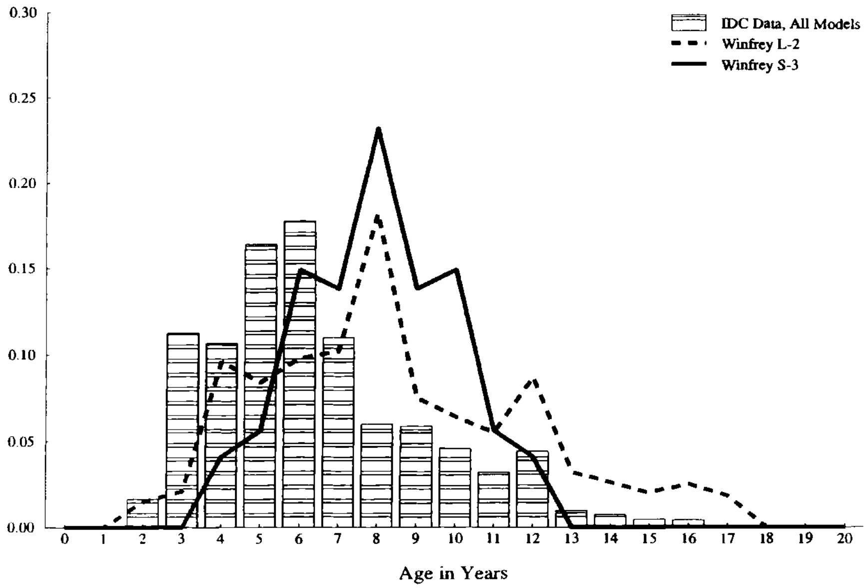

Fig. 1.1 Distribution of retirements of IBM mainframe computers by age based on FIFO retirement pattern

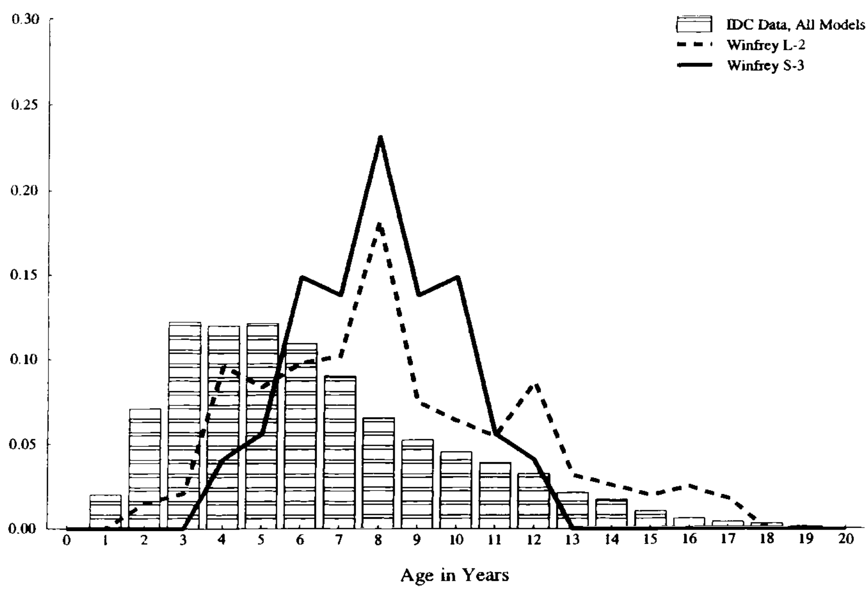

Fig. 1.2 Distribution of retirements of IBM mainframe computers by age based on proportional retirement pattern

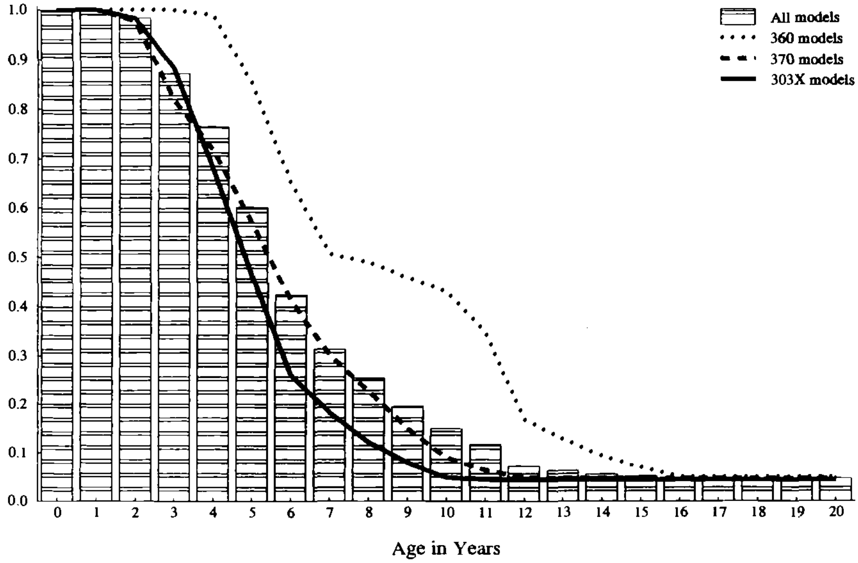

Fig. 1.3 Survival probability of IBM mainframe computers by age based on FIFO retirement pattern

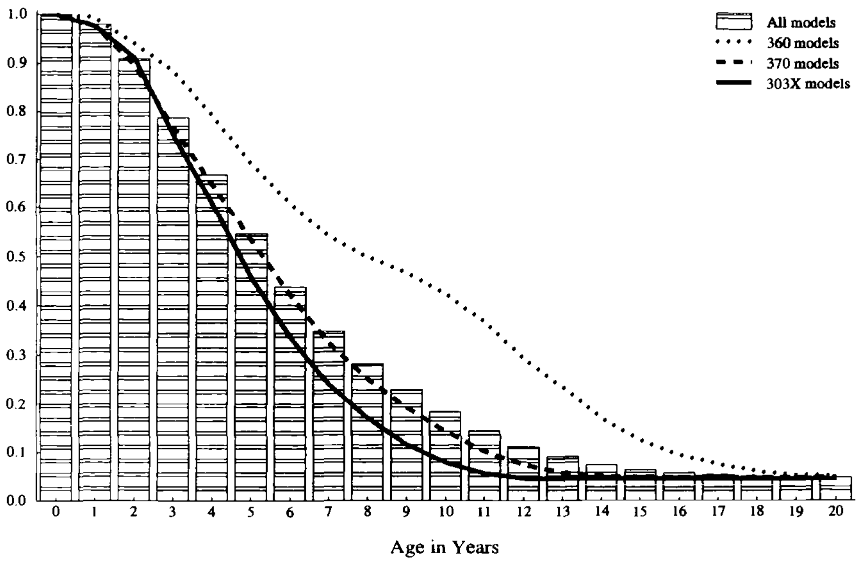

Fig. 1.4 Survival probability of IBM mainframe computers by age based on proportional retirement pattern

"Winfrey L-2" distribution, an asymmetric retirement distribution applied by BEA to consumer durable goods. Both Winfrey distributions are plotted with an average retirement age of eight years.[17] The symmetric Winfrey S-3 is clearly a poor approximation to either distribution calculated with the IDC data. The Winfrey L-2 provides a somewhat better fit by virtue of its long right-hand tail. Moreover, if asymmetry is a general trait of the retirement distributions of "high-technology" equipment, as suggested above, the Winfrey L-2 would dominate the S-3 for a broad set of assets.

Figures 1.3 and 1.4 explore the differences in retirement patterns across the 360, 370, and 30XX families. These figures plot the probability of survival $S(\tau)$, with the three lines pertaining to the separate families and the bars to the weighted aggregate of all fourteen models. The results in figure 1.3 are based on the FIFO retirement pattern, while those in figure 1.4 are based on the proportional pattern. As shown in both figures, the models in the 360 family had longer service lives, on average, than the 370 and 30XX models. Indeed, after ten years of use, more than 40 percent of the 360 units are estimated to have remained in service, compared with estimates of 5–15 percent for the 370 and 30XX families. Stated differently, the average service life for the 360 units was around eight and three-quarter years in both versions of the retirement distribution, well above the six-year average for the 370s and the five-and-a-half-year average for the 30XXs. Accordingly, it appears that average service lives for IBM mainframes have become shorter over time. This finding accords with a commonly expressed view of market participants, who note that increased competition in the industry, among other factors, has forced computer manufacturers to speed up the pace of product introductions (see, e.g., the *Computer Price Guide Readers Report*, April 1979, 1).

1.5.2 Estimates of Depreciation

As discussed in section 1.1 above, the age of a mainframe computer model can affect its price through several channels. Referring back to equation (1), these channels include age-related changes in the embodied characteristics **z**, age-related jumps across hedonic surfaces, and any residual effect of aging on price. Typically, empirical studies of depreciation—including the pioneering work of Hulten and Wykoff (1981a, 1981b)—measure depreciation as the combination of all these effects. This summary measure, which I label *full* depreciation, is the total derivative

$$\left.\frac{d\,\ln(P)}{d\tau}\right|_{t\text{ fixed}}.$$

17. Until recently, BEA had assumed an eight-year average lifetime for all cohorts of office and computing equipment. However, in the revision of the national income and product accounts released in December 1991, BEA shortened this mean life to seven years for all post-1977 cohorts while retaining the eight-year mean life for all earlier cohorts. This revision was due, in part, to evidence (discussed below) of a shift toward shorter service lives for mainframe computers.

A simple way to estimate this total derivative is to omit the characteristics **z** and the terms proxying for disequilibrium from the regression equation. By doing so, the coefficient on age picks up all age-related influences in price. I estimated such an equation by removing ln(MIPS), ln(Memory), and all terms in BEST from the set of regressors. Moreover, as a first step, I also imposed the restriction that depreciation be geometric, producing the following stripped-down version of equation (6):

$$(6') \qquad \ln P = \alpha_1 + \sum_{j=1}^{5} \gamma_j t^j + \delta^* \tau + \rho^* \text{NEW},$$

in which δ measures the geometric rate of depreciation.

Columns 1 and 4 of table 1.7 present the resulting OLS estimates of δ from the entire sample of 1,905 observations. As shown by the first entry in column 1, each additional *quarter* of model age is estimated to reduce price 8.7 percent. Thus, over a full year, an IBM mainframe model depreciates about 29.4 percent.[18] This rate is slightly faster than the 27.3 percent depreciation rate estimated by Hulten and Wykoff (1979) for Royal typewriters, which they applied to the entire class of office and computing equipment. The two figures, however, are not comparable because Hulten and Wykoff's estimate has been adjusted for retirement (i.e., it measures $\tilde{P}[\tau]$, not $P[\tau]$). If my depreciation estimate were adjusted for retirement, it would become more rapid, moving further away from Hulten and Wykoff's estimate.[19]

As shown in column 4, the full depreciation rate for a mainframe technology class is estimated to be 5.76 percent per quarter, about 20.6 percent for each year of age. This rate is considerably slower than that for individual models, implying that an embodied technology has a longer economic life than any single model in that technology class. IBM extends the economic life of a technology class by introducing new models from the class over the course of several years, with each model filling a particular market niche. As an example of this practice, IBM first shipped mainframes with 64KB memory chips in early 1979 (the model 4331–1); four years later, IBM introduced the model 4341–12, also built around the 64KB chip.

The depreciation rates shown in columns 1 and 4 capture, as noted above, all age-related effects on prices. This total effect can be decomposed into the

18. The 29.4 percent estimate is derived as

$$100 * \{[P(\tau + 1)/P(\tau)]^4 - 1\} = 100 * \{[\exp(\delta)]^4 - 1\}.$$

19. To see that adjusting $P(\tau)$ for retirement raises the rate of depreciation, recall that $\tilde{P}(\tau) = P(\tau)S(\tau)$. Then,

$$d[\ln \tilde{P}(\tau)]/d\tau = d[\ln P(\tau)]/d\tau + d[\ln S(\tau)]/d\tau,$$

so that the depreciation rate adjusted for retirement equals the unadjusted rate plus the percentage change in the probability of survival. Because the probability of survival falls with age, this percentage change is negative, which makes the adjusted depreciation rate more negative than the unadjusted rate.

Table 1.7 **OLS Estimates of Geometric Depreciation (*t*-statistics in parentheses)**

	Age of Model			Age of Technology Class		
Regressor	Full (1)	Partial (2)	Residual (3)	Full (4)	Partial (5)	Residual (6)
τ	−.0870	−.0439	−.0433	−.0576	−.0397	−.0395
	(37.2)	(36.6)	(32.9)	(22.3)	(39.7)	(34.9)
Inclusion of:						
ln(MIPS)	No	Yes	Yes	No	Yes	Yes
ln(Memory)	No	Yes	Yes	No	Yes	Yes
BEST	No	No	Yes	No	No	Yes
BEST*Time	No	No	Yes	No	No	Yes
R^2	.441	.882	.892	.234	.890	.897

Note: Each regression used the full sample of 1,905 observations. The dependent variable was the secondhand market price from the *Computer Price Guide*. Each regression included a constant, the NEW dummy variable, and a fifth-order polynomial in Time, in addition to the terms shown in each column. When included, BEST*Time entered as a fifth-order polynomial.

separate parts identified in equation (2). The remaining columns of table 1.7 present this decomposition for the geometric pattern of depreciation. Columns 2 and 5 add terms in ln(MIPS) and ln(Memory) to equation (6′), thus controlling for the effects of the characteristics **z** on depreciation. This partial depreciation rate is about 4.4 percent per quarter in column 2 and 4.0 percent per quarter in column 5, roughly 16 percent per year of aging. Thus, even controlling for differences in MIPS and memory size, IBM mainframe models and technology classes depreciate at a fairly rapid pace, reflecting the influence of all factors other than **z** that are correlated with age. Columns 3 and 6 add BEST and the fifth-order polynomial in BEST*Time to the set of regressors, which then controls for disequilibrium as well as the characteristics **z**. The estimates of δ in these two columns show the residual effect of aging on price, $\partial \ln(P)/\partial\tau$. The similarity of the depreciation estimates in columns 2 and 3 and in columns 5 and 6 indicates that disequilibrium has little effect on the estimated rate of geometric depreciation.

Thus far, the pattern of depreciation has been forced to be geometric. Table 1.8 reports depreciation estimates that remove this restriction by replacing the $\delta*\tau$ term in equation (6′) with

$$\sum_{j=1}^{5} \delta_j \tau^j + \Theta*\text{Time}*\tau.$$

The latter term allows the rate of depreciation to change over time, a generalization suggested by the finding that service lives for IBM mainframe models appear to have become shorter since the demise of the 360 family.

The structure of table 1.8 is the same as that of table 1.7, the only difference

Table 1.8 **OLS Estimates of General Depreciation (*t*-statistics in parentheses)**

	Age of Model			Age of Technology Class		
Regressor	Full (1)	Partial (2)	Residual (3)	Full (4)	Partial (5)	Residual (6)
τ	0.0288	0.0778	0.1033	−0.3441	−0.0837	−0.1680
	(.4)	(2.3)	(2.9)	(3.3)	(2.4)	(4.2)
τ^2	0.0015	−0.0013	−0.0041	0.0383	0.0228	0.0293
	(.2)	(.4)	(1.3)	(4.1)	(7.6)	(8.5)
τ^3	−1.1E-4	3.8E-5	1.6E-4	−0.0018	−0.0012	−0.0014
	(.4)	(.3)	(1.3)	(5.0)	(10.7)	(11.2)
τ^4	1.1E-6	−1.6E-6	−4.0E-6	3.3E-5	2.4E-5	2.6E-5
	(.2)	(.8)	(1.9)	(5.5)	(12.3)	(12.5)
τ^5	4.3E-9	2.1E-8	3.7E-8	−2.1E-7	−1.5E-7	−1.7E-7
	(.1)	(1.5)	(2.7)	(5.7)	(13.0)	(13.0)
Time*τ	−0.0021	−0.0022	−0.0020	2.3E-4	−0.0012	−0.0012
	(7.9)	(19.3)	(16.8)	(1.0)	(16.1)	(11.9)
Inclusion of:						
ln(MIPS)	No	Yes	Yes	No	Yes	Yes
ln(Memory)	No	Yes	Yes	No	Yes	Yes
BEST	No	No	Yes	No	No	Yes
BEST*Time	No	No	Yes	No	No	Yes
R^2	0.462	0.903	0.909	0.253	0.922	0.923
F-statistic for constant geometric depreciation	14.8	84.3	70.7	9.7	157.3	131.8

Note: Each regression used the full sample of 1,905 observations. The dependent variable was the second-hand market price from the *Computer Price Guide*. Each regression included a constant, the NEW dummy variable, and a fifth-order polynomial in Time, in addition to the terms shown in each column. When included, BEST*Time entered as a fifth-order polynomial.

being the expanded set of age coefficients reported for each regression. The results in table 1.8 indicate that depreciation for IBM mainframes has not occurred at a constant geometric rate. The F-statistic for the null hypothesis of constant geometric depreciation ($\delta_2 = \delta_3 = \delta_4 = \delta_5 = \Theta = 0$), shown at the bottom of the table, is significant in every column at the 1 percent level. For the regressions that measure depreciation based on model age, the chief violation of the null hypothesis is the significance of Θ, the coefficient on Time*τ. Thus, although the depreciation pattern may be close to geometric at any given time, the best-fitting geometric rate has become more rapid over time. For the regressions that measure depreciation of a technology class, the geometric form is not appropriate at any point in time, as indicated by the uniformly significant coefficients on the higher-order terms in τ. In addition, the estimated coefficient on Time*τ in columns 5 and 6 points to a speedup in the depreciation rate over time.

Figures 1.5 and 1.6 plot the depreciation patterns implied by the estimates in table 1.8; figure 1.5 portrays the patterns based on model age and figure 1.6 those based on the age of the technology class. Because these depreciation schedules vary over time, the figures show the schedules at the mean pricing date in the sample, 1979:2. In both figures, the solid line represents the full measure of depreciation, computed from the regressions that exclude MIPS, memory size, and the terms in BEST. The dotted line depicts the partial measure, which controls for the effects of MIPS and memory size on depreciation but not for the effect of disequilibrium. The dashed line shows the residual measure, which controls for the effects of MIPS, memory size, and disequilibrium. For comparison, the bars in each figure represent the geometric pattern of full depreciation estimated in table 1.7.

In both figures, the schedule of full depreciation shows a considerably faster loss of value than the partial and residual measures, as would be expected. Further, as seen in figure 1.5, increases in model age imply essentially monotonic declines in value, although the depreciation schedules are not sufficiently convex to be geometric. The depreciation schedules shown in figure 1.6, however, do not even decline monotonically, displaying a local maximum at age 4. This pattern can be explained as follows. When age is defined by technology class, the models introduced late in a product cycle have an age at inception of three or four years. Because these models are differentiated from their predecessors within the technology class and may be in short supply, they tend to sell initially at relatively high prices, producing the sharp deviation from the geometric form shown in figure 1.6. This premium, however, quickly erodes, as these models with aging technology are soon forced to compete with models that embody the next generation of technology.

As revealed by figures 1.5 and 1.6, the depreciation schedules based on model age are quite different from those based on the age of the technology class. Each set of schedules is useful in answering a particular question. The depreciation patterns in figure 1.6 provide information on age-related losses of value for each new wave of semiconductor technology, taking account of IBM's efforts to extract full value from the technology by embedding it in a large number of different models. In contrast, the depreciation patterns in figure 1.5 summarize the age-related loss of value for a single model from its date of introduction.

For the purpose of constructing stocks of computing equipment from data on investment flows, these latter estimates of depreciation are the more appropriate ones. In particular, IBM can sustain—and, for a while, increase—the value of a technology class by introducing differentiated models, even though the value of each model falls steadily with age. The rise in value for a technology class will not characterize the depreciation pattern for an investment cohort, which moves ever closer to obsolescence with each year of age. For this reason, I focus on the depreciation estimates based on model age for the rest of the paper.

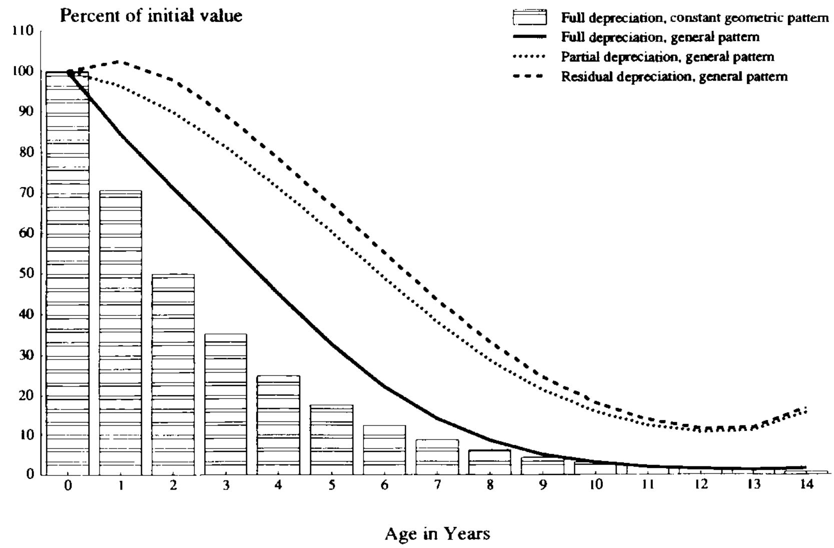

Fig. 1.5 Depreciation of IBM mainframe computers based on model age

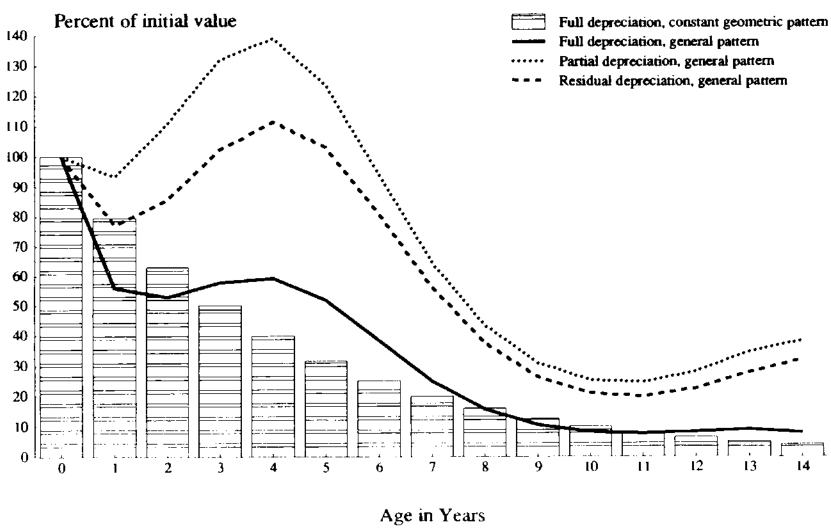

Fig. 1.6 Depreciation of IBM mainframe computers based on age of technology class

1.5.3 The Combined Effect of Depreciation and Retirement

Given an estimated retirement distribution from the IDC data and an estimated depreciation schedule from the *Guide* data, one can calculate depreciation for an entire cohort of IBM mainframes, $\tilde{P}(\tau)$. As outlined above, $\tilde{P}(\tau) = S(\tau)P(\tau)$, the proportion of units still in service at age τ multiplied by the percentage of initial value retained by these units at that age.

BEA also calculates an estimate of $\tilde{P}(\tau)$, although it applies to the broad aggregate of office and computing equipment, not just mainframe computers. BEA assumes that depreciation occurs in a straight-line pattern over an asset's service life. Thus, given a ten-year service life, an asset would retain 90 percent of its initial value one year after installation and 80 percent two years after installation. BEA's estimate of $\tilde{P}(\tau)$ takes account of the fact that retirements occur, not at a single age, but over a number of years, as characterized by the Winfrey distribution. As a result, BEA breaks each dollar of investment into the share with a one-year life, the share with a two-year life, and so on. Each cohort is depreciated by the straight-line method over its service life, and the results are then summed across cohorts to obtain the aggregate $\tilde{P}(\tau)$ for that asset.

Table 1.9 presents six alternative estimates of $\tilde{P}(\tau)$. Column 1 shows the $\tilde{P}(\tau)$ schedule currently applied by BEA to post-1977 cohorts of investment in office and computing equipment. Column 2 displays BEA's schedule for all earlier cohorts. The difference between the two columns is due solely to the use of a seven-year mean service life in column 1 and an eight-year mean life in column 2. Column 3 retains the eight-year mean life assumed in column 2 but substitutes the Winfrey L-2 retirement distribution for the Winfrey S-3. Columns 4–6 present my alternative estimates of cohort depreciation. Each of these columns uses the survival probability $S(\tau)$ based on the FIFO retirement pattern for the aggregate of all models (shown by the bars in fig. 1.3 above). However, the depreciation schedule $P(\tau)$ differs across the three columns; columns 4–6 reflect, in turn, the schedules of full, partial, and residual depreciation plotted by the lines in figure 1.5. All six columns in the table employ the so-called half-year convention used by BEA. Under this convention, new goods are assumed to suffer a half year of depreciation during the year in which they are installed. This convention explains why the age 0 entry in each column differs from 100.

All three BEA schedules imply rapid cohort depreciation. Three years after installation, roughly half the cohort's initial value has been lost; at age 5, only 20–30 percent of initial value remains. Naturally, the loss of value is most rapid in column 1, owing to the use of a shorter mean service life. Given a common mean life, the Winfrey S-3 and L-2 distributions (cols. 2 and 3) produce nearly identical results between ages 0 and 5. Because almost three-quarters of initial value has been depreciated by age 5, the two distributions produce similar estimates of net capital stocks, as seen in the next section. My alternative estimates of cohort depreciation span a wider range. The schedule

Table 1.9 **Cohort Depreciation Schedules (percentage of initial value of investment remaining at each age)**

	BEA			Oliner, by Measure of Depreciation		
	Winfrey S-3		Winfrey L-2			
Age in Years	7-Yr. Life (1)	8-Yr. Life (2)	8-Yr. Life (3)	Full (4)	Partial (5)	Residual (6)
0	92.4	93.3	92.8	91.4	99.2	104.3
1	77.2	79.9	78.4	77.5	95.1	105.5
2	62.0	66.6	64.3	64.1	86.9	98.4
3	46.9	53.2	51.0	46.1	69.5	79.0
4	32.8	40.3	39.2	31.1	53.2	60.9
5	20.5	28.5	29.5	17.5	35.1	40.6
6	11.1	18.6	21.4	8.3	20.0	23.4
7	5.0	10.8	14.9	3.9	11.5	13.6
8	1.7	5.5	10.2	1.9	7.0	8.4
9	0.4	2.4	7.1	0.9	3.9	4.7
10	0.1	0.8	4.8	0.4	2.3	2.7
11	0.0	0.2	3.0	0.2	1.4	1.6
12	0.0	0.0	1.8	0.1	0.8	0.9
13	0.0	0.0	1.1	0.1	0.7	0.8
14	0.0	0.0	0.6	0.1	0.9	1.0
15	0.0	0.0	0.2	0.0	0.0	0.0

Note: Columns 1–3 are from printouts provided by John Musgrave of BEA. Columns 4–6 are constructed from the FIFO retirement distribution aggregated over all models and the depreciation schedules shown by the solid, dotted, and dashed lines in fig. 1.5.

in column 4, based on full depreciation, virtually matches the BEA schedule in column 1. In contrast, the partial and residual measures of depreciation in columns 5 and 6 imply markedly slower losses of value than any of the BEA schedules.

On the basis of the different estimates of cohort depreciation in columns 4–6, one can argue that BEA depreciates investment in office and computing equipment at about the right rate or much too quickly. The next section resolves this ambiguity. There, I show that the estimate in column 5 is the most appropriate one for constructing net capital stocks from investment spending when both are expressed in constant dollars. This result suggests that BEA's constant-dollar net stock of office and computing equipment is constructed with a schedule of overly rapid depreciation.

1.6 Alternative Estimates of Capital Stock

Do my estimates of depreciation and retirement patterns imply substantial revisions to BEA's published stocks of office and computing equipment for the private nonresidential business sector? I consider this question first for

BEA's gross capital stock and then for its net capital stock. For an in-depth description of BEA's methodology, see U.S. Department of Commerce (1987).

1.6.1 Gross Capital Stock

BEA's gross capital stock represents the initial purchase value of all previous investment still in service. No adjustment is made for depreciation. In equation form, the gross capital stock can be written

$$\text{GS}(t) = \sum_{\tau=0}^{T} I(t - \tau)S(\tau), \tag{10}$$

where $I(t - \tau)$ is investment spending at time $t - \tau$, and $S(\tau)$ is the proportion of this investment expected to survive τ years after installation. T is the maximum lifetime of the capital good, assumed to be constant across vintages. For a "one-hoss shay" asset—which provides a fixed level of service until retirement—the gross stock can be regarded as an indicator of that service flow. Thus, the gross stock is useful in analyses of output and productivity involving one-hoss shay assets, such as IBM computing equipment.[20]

To assess potential biases in BEA's gross stock of office and computing equipment, I calculated equation (10) with four alternative survival patterns $S(\tau)$, denoted $S_1(\tau), \ldots, S_4(\tau)$. $S_1(\tau)$ is the survival pattern used by BEA before the revisions introduced in December 1991; this prerevision $S(\tau)$ comes from the Winfrey S-3 retirement distribution with an eight-year mean service life. $S_2(\tau)$, the survival pattern currently used by BEA, is the same as $S_1(\tau)$ for pre-1978 cohorts; however, for later cohorts, $S_2(\tau)$ uses the shorter seven-year mean life. $S_3(\tau)$ substitutes the Winfrey L-2 retirement distribution for the S-3 but retains BEA's current assumptions regarding mean service lives. Finally, $S_4(\tau)$ incorporates my estimates of the FIFO survival patterns for the IBM 360, 370, and 30XX families, which were shown in figure 1.3 above.[21] Specifically, $S_4(\tau)$ varies across investment cohorts as follows:

$$S_4(\tau) = \begin{cases} \text{360 survival pattern for pre-1970 cohorts;} \\ \text{370 survival pattern for 1970–79 cohorts;} \\ \text{30XX survival pattern for post-1979 cohorts.} \end{cases}$$

By applying the survival functions $S_1(\tau), \ldots, S_4(\tau)$ to BEA's constant-dollar series on investment in office and computing equipment, I obtained the gross capital stocks denoted $\text{GS}_1(t), \ldots, \text{GS}_4(t)$.

Table 1.10 displays the BEA gross stocks $\text{GS}_1(t)$ through $\text{GS}_3(t)$, each di-

20. Note that the one-hoss shay assumption is a very strong one. In addition to requiring that the flow of output from the good remain constant with age, it requires that there be no increase in maintenance and repair costs to achieve that constant output flow.

21. The survival patterns based on the proportional retirement distributions yield results similar to those reported in table 1.10 below and are omitted for brevity.

Table 1.10 **Constant-Dollar Gross Stock of Office and Computing Equipment (ratio of alternative BEA Stocks to GS_4)**

	BEA Gross Stock in Numerator of Ratio		
Year	Prerevision (GS_1)	Current (GS_2)	Winfrey L-2 (GS_3)
1965	0.908	0.908	0.931
1970	0.882	0.882	0.923
1975	1.003	1.003	1.019
1980	1.130	1.130	1.115
1985	1.119	1.090	1.076
1990	1.214	1.149	1.127

Note: See the text for definitions of GS_1 through GS_4.

vided by $GS_4(t)$. A value of 1.0 indicates that the particular BEA gross stock equals the gross stock based on my estimate of survivals. As shown in the first column, BEA's prerevision gross stock trended up from 90.8 percent of GS_4 in 1965 to 121.4 percent in 1990. This upward trend reflects BEA's use, before the recent revision, of a constant service life for office and computing equipment. Until 1970, GS_1/GS_4 was less than one because the eight-year mean service life assumed by BEA was shorter than the mean life that I found for the 360 models. By 1975, the difference between GS_1 and GS_4 had disappeared, as many of the 360 models had been retired and replaced by shorter-lived 370 models. However, with the continued substitution of the 370 and 30XX models for 360 models, BEA's prerevision stock moved substantially above my estimate of the gross stock. Thus, by failing to capture the shift toward shorter service lives, BEA had overstated considerably the growth of the constant-dollar gross stock of office and computing equipment.

BEA attempted to correct this bias by introducing a one-year reduction in the mean service life of post-1977 investment cohorts. The second column of table 1.10 indicates that this change was only partly successful. Given the lag between investment and the beginning of retirements, BEA's revision did not affect its estimate of the gross stock until after 1980. As a result, BEA's estimate of the gross stock of office and computing equipment continues to grow too rapidly until that year. Still, BEA's revision does appear to have eliminated the excessive growth in the gross stock during the 1980s.

As a final point, note that the ratios shown in the second and third columns are quite similar. This similarity implies that BEA's estimate of the gross stock would not change much if the Winfrey L-2 retirement distribution were substituted for the S-3, given a fixed mean service life. Thus, BEA's use of a symmetric distribution when a skewed distribution may be more appropriate does not, by itself, introduce much bias into the gross stock. The more serious problem is that BEA likely has not yet built a sufficient downward trend into its assumed mean service life of office and computing equipment. This conclusion is bolstered by the preliminary results in Oliner (1992), which showed a substantial reduction over time in the average service lives of computer peripheral equipment, another important class of assets within the aggregate of office and computing equipment.

1.6.2 Net Capital Stock

BEA's net capital stock represents the value of all previous investment outlays after subtracting depreciation. In equation form, the net capital stock can be written as

$$\text{NS}(t) = \sum_{\tau=0}^{T} I(t - \tau)\,\tilde{P}(\tau), \tag{11}$$

where, as above, $\tilde{P}(\tau)$ is the proportion of the initial value of an investment cohort still remaining τ years after installation.

Table 1.9 above reported three measures of $\tilde{P}(\tau)$ based on model age, each incorporating a different measure of depreciation. Which is the appropriate one for use in equation (11)? I now show that, when constructing a constant-dollar net stock from BEA's constant-dollar investment series, $\tilde{P}(\tau)$ should not be based on the full measure of depreciation.

To explore this issue, assume that the market for computing equipment is always in equilibrium and that the market price can be written as

$$P(t, \tau) = f(t)g[\mathbf{z}(t - \tau)]h(\tau), \tag{12}$$

where $f(t)$ represents the influence of time on price, holding age and characteristics fixed; $g[\mathbf{z}(t - \tau)]$ represents the influence of embodied characteristics on price; and $h(\tau)$ is the residual effect of age on price. Equation (12) restricts these three effects to be multiplicative. Now, the question at hand can be stated as follows: if the constant-dollar net stock is calculated as a weighted sum of past constant-dollar investment outlays (as in eq. [11]), how should the weights be constructed in terms of the functions on the right-hand side of equation (12)?

To begin, let $\text{IU}(t, \tau)$ represent the number of units of age τ computing equipment still in service at time t. Then, in current dollars, the net stock can be written

$$\text{NSCURR}(t) = \sum_{\tau=0}^{T} \text{IU}(t, \tau)P(t, \tau), \tag{13}$$

which is the number of units of each investment cohort still in service at time t multiplied by the period t price of each such unit, summed over cohorts. The constant-dollar counterpart to equation (13) simply deflates the current-dollar value to the prices of some base year. Denoting the deflator by $\text{PD}(t)$, the constant-dollar net stock is

$$\text{NS}(t) = \sum_{\tau=0}^{T} \text{IU}(t, \tau)P(t, \tau)/\text{PD}(t). \tag{14}$$

Now, $\text{IU}(t, \tau)$ can be written as $\phi(\tau)\text{IU}(t - \tau, 0)$, where $\text{IU}(t - \tau, 0)$ is the number of new units installed at time $t - \tau$, and $\phi(\tau)$ is the proportion of these units still in service at age τ. Further, $\text{IU}(t - \tau, 0)P(t - \tau, 0)$ equals $I(t - \tau)\text{PD}(t - \tau)$ because both represent current-dollar investment at time $t - \tau$. Thus

$$\text{IU}(t, \tau) = \phi(\tau)\text{IU}(t - \tau, 0) = \phi(\tau)I(t - \tau)\text{PD}(t - \tau)/P(t - \tau, 0).$$

Substituting this expression for $\text{IU}(t, \tau)$ into equation (14) yields

$$\begin{aligned} \text{NS}(t) = {} & \sum_{\tau=0}^{T} I(t - \tau) * \\ & \{\phi(\tau)[\text{PD}(t - \tau)/\text{PD}(t)][P(t, \tau)/P(t - \tau, 0)]\}. \end{aligned} \tag{15}$$

The term in braces is the expression for $\tilde{P}(\tau)$ that we are seeking.

To complete the derivation, we must relate this bracketed expression to the functions in equation (12). First, as constructed by BEA, the deflator for office and computing equipment is a constant-quality price measure; thus

$$\text{PD}(t - \tau)/\text{PD}(t) = f(t - \tau)/f(t).$$

Second, using equation (12),

$$\begin{aligned} P(t, \tau)/P(t - \tau, 0) &= \{f(t)g[\mathbf{z}(t - \tau)]h(\tau)\}/\{f(t - \tau)g[\mathbf{z}(t - \tau)]\, h(0)\} \\ &= [f(t)h(\tau)]/[f(t - \tau)h(0)]. \end{aligned}$$

Substituting these expressions for the price ratios into equation (15) and canceling terms yields

$$\tilde{P}(\tau) = \phi(\tau)[h(\tau)/h(0)] \tag{16}$$

as the weight on $I(t - \tau)$. This weight is simply the proportion of units surviving to age τ multiplied by the percentage of initial value remaining at age τ for these units. The crucial point is that $h(\tau)/h(0)$ represents the schedule of *partial* depreciation; it measures the effects of aging on price after controlling for the influence of $\mathbf{z}$. As indicated at the outset, $\tilde{P}(\tau)$ should not be based on an estimate of full depreciation, $P(t, \tau)/P(t, 0)$.

The intuition for the use of a partial depreciation measure is simple. The weight on $I(t - \tau)$ indicates that one constant dollar of vintage $t - \tau$ investment is worth $\phi(\tau)[h(\tau)/h(0)]$ constant dollars of vintage t investment. Because BEA deflates current-dollar outlays with constant-quality prices, one constant dollar of investment has the same embodied quality for all vintages. Thus, one constant dollar of vintage $t - \tau$ investment that remains in service will be worth less than a full constant dollar of vintage t investment only because of price differences due to factors other than the embodied characteristics. These price differences are captured in what I have called the partial measure of depreciation.

For assets subject to slower technological change than computers, the distinction between full and partial depreciation is less important. In the extreme case of no embodied improvement, $\mathbf{z}(t - \tau) = \mathbf{z}(t)$ for all τ and

$$\begin{aligned} P(t, \tau)/P(t, 0) &= \{f(t)g[\mathbf{z}(t - \tau)]h(\tau)\}/\{f(t)g[\mathbf{z}(t)]h(0)\} \\ &= h(\tau)/h(0), \end{aligned}$$

indicating that the full and partial measures coincide. However, for assets undergoing rapid technological change, such as computers, the distinction between the two measures is crucial for constructing constant-dollar net capital stocks.

The only theoretical point left to explore is the effect of disequilibrium on the weights in equation (11). To examine this question, the expression for $P(t, \tau)$ in equation (12) must be augmented to include a term for multiple price regimes:

$$P(t, \tau) = f(t)g[\mathbf{z}(t - \tau)]h(\tau)B(t - \tau, t).$$

As in section 1.1 above, $B(t - \tau, t)$ indexes the hedonic price regime for a vintage $t - \tau$ asset at time t, with $B(\cdot, \cdot) = 1$ for models embodying best technology and $B(\cdot, \cdot) > 1$ for nonbest models.

Now, the steps that led from equation (12) to equation (16) can be repeated to yield the new weight. The result, it turns out, hinges on the properties of PD(t), BEA's price deflator for computing equipment. On the basis of the discussion in Cartwright (1986), BEA's computer deflator incorporates prices for a broad set of models sold in each year, some proportion of which embody best technology. PD(t) therefore depends on $B(t - \tau, t)$ for all vintages $t - \tau$ in BEA's sample at year t. Letting $B'(t)$ denote the weighted average value of $B(t - \tau, t)$ across these vintages, the deflator PD(t) can be written as $f(t)B'(t)$. Then, the ratio of the deflator at times $t - \tau$ and t is

$$\mathrm{PD}(t - \tau)/\mathrm{PD}(t) = [f(t - \tau)B'(t - \tau)]/[f(t)B'(t)].$$

With this specification for $\mathrm{PD}(t - \tau)/\mathrm{PD}(t)$, it can be shown that

$$(17) \quad \tilde{P}(\tau) = \phi(\tau)\frac{h(\tau)}{h(0)}\,\frac{B(t - \tau, t)}{B(t - \tau, t - \tau)}\,\frac{B'(t - \tau)}{B'(t)} \equiv \phi(\tau)\,\frac{h(\tau)}{h(0)}\,\bar{B}.$$

$\tilde{P}(\tau)$ now depends on the product of ratios involving the indexes B and B'. To help interpret (17), assume that the deflator reflects only the prices of best-technology models and that all vintages embody best technology when new; given these assumptions, $B'(t) = B'(t - \tau) = B(t - \tau, t - \tau) = 1$, so that $\bar{B} = B(t - \tau, t)$. Then, $\tilde{P}(\tau)$ will be greater than $\phi(\tau)[h(\tau)/h(0)]$ whenever $B(t - \tau, t)$ exceeds unity—that is, whenever the vintage $t - \tau$ cohort moves to a higher price surface as it ages. When this happens, the vintage

$t - \tau$ cohort has, in effect, appreciated relative to the new cohort, and the weight on $I(t - \tau)$ should be raised accordingly.

As a practical matter, we know too little about the properties of BEA's computer deflator to specify $\bar{B}$. However, some headway can be made under the assumption that the period t deflator is constructed only from the prices of vintage t models (which may or may not embody best technology). In this case, $B'(t) = B(t, t), B'(t - \tau) = B(t - \tau, t - \tau)$, and (17) reduces to

$$\tilde{P}(\tau) = \phi(\tau)\frac{h(\tau)}{h(0)}\frac{B(t - \tau, t)}{B(t, t)}. \tag{17'}$$

The measure of depreciation in (17') is $[h(\tau)B(t - \tau, t)]/[h(0)B(t, t)]$. This ratio controls for differences in the characteristics $\mathbf{z}$ across vintages but includes any price differences stemming from disequilibrium. This measure of depreciation is what I have called the partial measure. Thus, in the presence of disequilibrium, the partial depreciation schedule—not the narrower residual schedule—is the theoretically appropriate one for use with BEA's constant-dollar investment series.

Using equation (11), I calculated the constant-dollar net stock for office and computing equipment for four specifications of the cohort depreciation schedule $\tilde{P}(\tau)$, denoted $\tilde{P}_1(\tau), \ldots, \tilde{P}_4(\tau)$. Parallel to the survival patterns defined in connection with table 1.10 above, $\tilde{P}_1(\tau)$ is the cohort depreciation schedule used by BEA prior to the December 1991 revision, $\tilde{P}_2(\tau)$ is the schedule currently used by BEA, $\tilde{P}_3(\tau)$ is the hypothetical schedule based on the Winfrey L-2 distribution, and $\tilde{P}_4(\tau)$ is the schedule calculated from my time-varying survival function $S_4(\tau)$ combined with the partial depreciation schedule shown by the dotted line in figure 1.5 above. These four cohort depreciation functions yield a set of net capital stocks denoted $NS_1(t), \ldots, NS_4(t)$.

Table 1.11 displays the ratios NS_1/NS_4, NS_2/NS_4, and NS_3/NS_4. All the ratios in the table are less than one, indicating that each version of BEA's net

Table 1.11 Constant-Dollar Net Stock of Office and Computing Equipment (ratio of alternative BEA Stocks to NS_4)

	BEA Net Stock in Numerator of Ratio		
Year	Prerevision (NS_1)	Current (NS_2)	Winfrey L-2 (NS_3)
1965	0.708	0.708	0.741
1970	0.716	0.716	0.747
1975	0.819	0.819	0.829
1980	0.860	0.841	0.842
1985	0.866	0.813	0.814
1990	0.866	0.791	0.796

Note: See the text for definitions of NS_1 through NS_4.

stock is smaller than the net stock implied by my estimate of $\tilde{P}(\tau)$. That is, BEA depreciates each cohort of office and computing equipment more rapidly than my estimates of retirement and *partial* depreciation suggest is appropriate. The key to this result is the use of partial rather than full depreciation. BEA effectively uses a full measure of depreciation by writing off the entire value of an asset prior to retirement. To eliminate the downward bias in the level of its net stock, BEA must shift to a partial depreciation schedule.

In addition to this bias concerning levels, BEA's prerevision estimate overstated the growth rate of the net stock by failing to account for the trend toward shorter service lives. As shown in the first column, BEA's prerevision net stock grew from 70.8 percent of my estimated net stock to 86.6 percent between 1965 and 1990. In addition, this comparison almost surely understates the excessive growth of BEA's prerevision net stock because NS_4 was based on a fixed schedule of partial depreciation rather than on one that becomes more rapid over time. In the 1991 revision, BEA partially corrected the upward bias to the growth rate of its published net stock, as can be seen by comparing the first and second columns. However, this revision did not fix the overstatement of the growth rate before the late 1970s. To do so would require adding some downward tilt to the mean service life prior to 1978.

1.7 Conclusion

This paper used data from the *Computer Price Guide*, an industry bluebook, to estimate the rate of constant-quality price decline for IBM mainframe computers and their rate of depreciation. The paper also estimated the retirement distribution for IBM mainframes from separate data on the installed stocks of various models. The estimates of depreciation and retirement patterns were then used to assess BEA's published capital stocks for office and computing equipment.

In previous studies, estimates of constant-quality prices for mainframe computers have been based on manufacturers' list prices, owing to the absence of actual transaction prices. This paper examined whether the use of list prices substantially biased the results of those studies. On the whole, the answer was no. Using price quotes in the secondhand market, I inferred IBM's actual transaction prices for a number of mainframe models and found little evidence of discounting from list price over the period 1970–86. Moreover, these secondhand prices yielded estimates of constant-quality price change similar to those obtained with IBM list prices. In particular, both sets of prices indicated that constant-quality price declines for IBM mainframes averaged about 20 percent at an annual rate between the early 1970s and the mid-1980s. My results also support Dulberger's (1989) finding of disequilibrium in the mainframe market, a result that had been open to question because it was based on list prices. Whether using list prices or secondhand market prices, I found that older models were not marked down immediately to compete with newer, best-technology models.

The retirement pattern for IBM mainframes was calculated from fourteen models representing the 360, 370, and 30XX families. The distribution for the full set of models had a mean retirement age of 6.5 years. Although most retirements were estimated to occur within six years of installation, the distribution had a long right-hand tail. A key feature of the distribution was that service lives appear to have become shorter over time, with the mean life for the 360 models at about eight and three-quarter years and that for the 370 and 30XX models at six years or less.

Several measures of depreciation were estimated in the paper. The broadest one captured all age-related effects on price, the usual measure estimated in studies of depreciation. According to this measure, IBM mainframe models lose value fairly rapidly after introduction; in the geometric approximation to this schedule, prices declined nearly 30 percent with each year of age. I also estimated a less inclusive measure of depreciation, called partial depreciation, that controls for differences in embodied characteristics across models. Although this is not the standard notion of depreciation, section 1.6 proved that this measure is the appropriate one for constructing net capital stocks from past investment outlays when both are expressed in constant dollars. The geometric approximation to this partial measure showed mainframe prices declining about 16 percent with each year of model age.

As a complement to the depreciation measures for individual mainframe models, one can measure depreciation of the underlying technology. All the models with the same level of technology—defined by the density of their main memory chip—form a technology class. The depreciation schedules for a technology class did not display steady declines in value; rather, price increased between the first and the fourth years of age. This pattern likely reflects IBM's practice of introducing models late in a product cycle to fill a market niche; these models sell at relatively high prices even though they embody old technology. IBM apparently has been able to preserve the value of a technology despite relentless depreciation of the individual models in which the technology is embodied.

Whether measuring depreciation of a model or of a technology class, statistical tests always rejected the hypothesis of a constant geometric depreciation schedule. The schedules based on model age were not sufficiently convex, while those based on age of the technology class did not even decline monotonically, as noted above. Moreover, virtually all the schedules indicated that depreciation has become more rapid over time, consistent with a trend toward shorter service lives.

My estimates of depreciation and retirement suggest certain biases in BEA's constant-dollar gross and net stocks of office and computing equipment. Before the revisions introduced in December 1991, BEA set the mean service life for office and computing equipment at a constant eight years. By failing to account for the apparent trend toward shorter service lives, BEA likely overstated the trend growth of both the gross and the net stocks. Although BEA's 1991 revision shortened the mean service life for all post-1977 cohorts of office and computing equipment to seven years, this change does not appear to have fully eliminated the overstatement of trend growth rates. A second problem afflicts BEA's constant-dollar net stock of office and computing equipment. This stock is computed using a cohort depreciation schedule that declines more rapidly than the theoretically appropriate schedule based on partial depreciation. As a result, BEA consistently has understated the level of the net stock. The 1991 revision did not address this problem.

Although this appraisal of BEA's capital stocks was based solely on results for IBM mainframe computers, Oliner's (1992) analysis of depreciation and retirement patterns for computer peripheral equipment generally backs up the results found here. In particular, the shift toward shorter service lives and the speedup in the pace of depreciation appear to characterize peripheral equipment as well as mainframes. One hopes that BEA will reexamine its published capital stocks for office and computing equipment in light of emerging research findings in this area.

Data Appendix

For each IBM mainframe model in my sample, table 1A.1 below lists the dates of initial and final shipment from IBM, the MIPS rating, and the technology class for the model, as well as the sources for this information. Table 1A.2 provides further information on each technology class, including the first date a model in my sample was shipped from the class and the period for which each class represented best technology.

Table 1A.1 Shipment Dates, MIPS Rating, and Technology Class

	First Shipment from IBM		Final Shipment from IBM		MIPS		Technology Class	
Model	Date	Source[a]	Date	Source[a]	Value	Source[a]	Value	Source[a]
360 family								
20	12/65	15	1970	16	0.038	20	1	17
30	6/65	14	1969	16	0.036	13	1	17
40	4/65	14	1970	16	0.07	13	1	17
50	8/65	14	≤1970	12	0.158	13	1	17
65	11/65	14	≤1970	12	0.568	13	1	17
370 family								
115	3/74	14	1976	4	0.055	13	5	2
115-2	4/76	14	1978	19	0.077	13	5	25
125	4/73	14	1976	4	0.08	13	4,5	2
125-2	2/76	14	1978	19	0.099	13	5	25
135	4/72	14	1974	4	0.161	13	2,3	3
138	11/76	14	1979	4	0.214	13	4	3
145	6/71	14	1974	4	0.3	13	2,3	3
145-2	6/71	24	1974	18	0.3	24	2,3	18
148	1/77	14	1978	4	0.425	13	4	3
155	1/71	14	1972	4	0.55	13	1	2
155-2	1/71	24	1972	18	0.55	24	1	18
158	4/73	14	1977	4	0.829	13	4,5	2
158-3	9/76	14	1978	19	0.9	13	5	25
165	4/71	14	1972	4	1.9	13	1	2
168	5/73	14	1977	4	2.3	13	4,5	2
168-3	6/76	14	1978	19	2.5	13	5	25
30XX family								
3031	3/78	14	1980	4	1.045	13	5	2
3032	3/78	14	1979	4	2.5	13	5	2
3033-N	1/80	14	1981	4	4.0	13	5	2
3033-S	1/81	11	1981	4	2.3	6	5	2
3033-U	3/78	14	1983	4	5.9	13	5	2
3081-D	Q3/81	5	1982	22	10.0	7	8	25
3081-G	Q3/82	5	1983	21	11.4	8	8	2
3081-GX	Q1/84	5	1985	22	12.5	9	8	2
3081-K	Q2/82	5	1983	21	15.4	2	8	2
3081-KX	Q1/84	5	1985	22	16.3	9	8	2
3083-B	Q4/82	5	1983	22	5.7	8	8	2
3083-BX	Q1/84	5	1985	22	6.0	9	8	2
3083-E	Q1/83	5	1983	22	3.1	8	8	2
3083-EX	Q1/84	5	1985	22	3.3	9	8	2
3083-J	Q4/82	8	1983	22	7.9	8	8	2
3083-JX	Q1/84	8	1985	22	8.4	9	8	25
3084-QX	Q2/84	8	1985	22	29.1	9	8	25
4300 family								
4331-1	3/79	14	1983	12	0.2	6	8	25
4331-2	8/80	14	1983	18	0.4	6	8	25
4341-1	11/79	14	1983	4	0.7	6	8	2

(*continued*)

Table 1A.1 (continued)

Model	First Shipment from IBM		Final Shipment from IBM		MIPS		Technology Class	
	Date	Source[a]	Date	Source[a]	Value	Source[a]	Value	Source[a]
4341-2	Q2/81	1	1983	4	1.2	6	8	2
4341-10	Q1/82	1	1983	4	0.58	9	8	2
4341-11	Q1/82	1	1983	4	0.88	9	8	2
4341-12	Q1/83	1	1983	4	1.2	9	8	2
4361-5	Q2/84	1	1987	21	1.14	9	9	25
4381-1	Q1/84	23	1986	22	2.1	9	9	25
4381-2	Q2/84	23	1986	22	2.7	9	9	25
4381-3	Q1/85	23	1986	22	4.8	10	9	25
4381-12	Q1/86	5	1988	21	2.7	5	10	25
4381-13	Q1/86	5	1988	21	3.7	5	10	25
4381-14	Q1/86	5	1988	21	6.5	5	10	25

[a]Key: 1 = Computer Information Resources, *Computer Price Watch* (January 1986). 2 = Printout of data base from Dulberger (1989). 3 = Printout of data base from Dulberger (1989), cross-checked with her table 2.2. 4 = Final year in sample from Dulberger (1989). 5 = Gartner Group, *IBM Large Computer Market* (Midyear 1986): 8. 6 = Tom Henkel, "Annual Hardware Roundup," *Computerworld,* 13 July 1981, 12. 7 = Tom Henkel, "Annual Hardware Roundup," *Computerworld,* 2 August 1982, 24. 8 = Tom Henkel, "Annual Hardware Roundup," *Computerworld,* 8 August 1983, 30. 9 = Tom Henkel, "Annual Hardware Roundup," *Computerworld,* 20 August 1984, 24. 10 = Tom Henkel, "Annual Hardware Roundup," *Computerworld,* 19 August 1985, 24. 11 = International Data Corp., *EDP Industry Report,* 30 September 1983, 19. 12 = International Data Corp., IBM PIC file, Installed Base—U.S. (final year in which number of installed units rises). 13 = Lias (1980). 14 = Padegs (1981). 15 = Phister (1974, 344). 16 = Phister (1974, 333) (final year in which number of installed units rises). 17 = Phister (1974, table II.2.11.1, line 69, pp. 343 and 345). 18 = Assumed same as model 1. 19 = Assumed two-year production period. 20 = Assumed equal to average of MIPS for 360/22 and 360/25, for which MIPS ratings found in Lias (1980). 21 = Lloyd Cohn (International Data Corp.), telephone conversation, 25 January 1990. 22 = Rosanne Cole, telephone conversation, 20 March 1990. 23 = Rosanne Cole, telephone conversation, 25 July 1990. 24 = Ellen Dulberger, telephone conversation, 29 April 1986. 25 = Ellen Dulberger, telephone conversation, 6 February 1990.

Table 1A.2 **Further Information on Technology Classes**

Class	Chip Density	First Shipment of IBM Model from the Class	Period as Best Technology
1	0.0025KB	4/65	4/65–5/71
2	0.125KB	6/71	6/71–3/73
3	1KB (Bipolar chip)	4/73	Never
4	1KB (FET chip)	4/73	4/73–2/74
5	2KB	3/74	3/74–2/79
8	64KB	3/79	3/79–12/83
9	288KB	1/84	1/84–12/85
10	1MB	1/86	1/86–

Note: KB = kilobits, MB = megabits. Models in classes 6 and 7, which have 4KB and 16KB memory chips, respectively, were not represented in my sample.

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