Volume Title: The Measurement of Durable Goods Prices

Volume Author/Editor: Robert J. Gordon

Volume Publisher: University of Chicago Press

Volume ISBN: 0-226-30455-8

Volume URL: http://www.nber.org/books/gord90-1

Conference Date: n/a

Publication Date: January 1990

Chapter Title: Computer Processors and Peripherals

Chapter Author: Robert J. Gordon

Chapter URL: http://www.nber.org/chapters/c8314

Chapter pages in book: (p. 188 - 240)

6 Computer Processors and Peripherals

Economics is a one or two digit science.[1]

If the auto industry had done what the computer industry has done in the last 30 years, a Rolls-Royce would cost $2.50 and get 2,000,000 miles to the gallon.[2]

6.1 Introduction

It is now thirty-nine years since the first delivery of the UNIVAC I electronic computer, and thirty-six years since the introduction of IBM's first electronic computer model. It is well known that the price of mainframe computers per unit of performance has fallen radically since those early days, by a factor of hundreds or even thousands, and that a modern personal computer costing a few thousand dollars has more memory and a faster speed than mainframes costing a million dollars or more as recently as the mid-1970s. Yet to this day, the BLS in its PPI includes no price index for computers (either mainframe or personal), despite its inclusion of many hundreds of commodity indexes for less important types of mechanical and electrical machinery. And only in its December 1985 benchmark revision did the BEA introduce a deflator for the computer component of PDE dating back to 1969, after more than two decades of publishing NIPAs based on the assumption that the prices of electronic computers remained fixed year after year.[3] The NIPAs still assume that computer prices remained fixed before 1969.

1. This was a remark of Norbert Weiner's, apparently quoted with approval by Oskar Morgenstern in his work on the accuracy of economic statistics (Phister 1979, 4).

2. *Forbes*, 22 December 1980, 24, attributed to *Computerworld* magazine.

3. The BEA's deflation procedures are described by Cartwright (1986) and are based on hedonic price indexes for computer processors and peripherals developed in Cole et al. (1986).

This chapter attempts to construct a single price deflator for electronic computers for the full period 1951–84, based on an application of the hedonic regression technique to two different data sets. The source of one of these data sets (Phister 1979) also forms the basis of a recent study by Flamm (1987), although this chapter is the first to estimate hedonic regression equations for the Phister data, which cover the period 1951–79.[4] The other data source, *Computerworld* magazine, covers 1977–84 and is studied here for the first time.[5] While the "final" price index developed in the chapter is based entirely on the Phister and *Computerworld* data sets, the equations are also reestimated for the new-model portion of two other data sets used previously by Chow (1967) and Dulberger (1989). This allows us to explore the sensitivity of the implied hedonic price indexes to alternative data sources, while holding constant other aspects of the methodology.

The coverage of the study includes mainframe computer processors for the full 1951–84 period, minis from 1965 to 1984, and personal computers for 1982–87. This is the first study of computers to cover such a long sample period and to provide separate treatment of mini and micro computers.[6] The final price index for mainframe and mini computer processors exhibits a 1951 index number, on a base 1984 = 100, of 133,666, implying an annual rate of change over the thirty-three years of −21.8 percent.[7]

The desire for complete time coverage of the postwar period is partly dictated by the need to maintain consistency with the time coverage adopted for the other chapters. But the inclusion of the full period is also important for substantive reasons, since one objective of this line of research is to understand the relation (if any) between the measurement of durable goods prices and the mysterious decline in productivity growth that began about 1970. If computers have been so productive, why has the cyclically adjusted rate of productivity growth in the U.S. economy outside manufacturing slowed in the 1980s to a rate close to zero? Any contribution of the possible mismeasurement of PDE deflators to the productivity slowdown puzzle requires not simply the identification of a price measurement bias, but rather depends on identifying either a *change* in the bias or a change in the weight attributed to the product exhibiting the bias. The share of computers in PDE expenditure was obviously much higher after 1970 than before, but it

4. Also, Flamm's index is based on the price-performance ratio of the installed stock of computers, not on the flow of newly produced models, as in this study.

5. The BEA also uses *Computerworld* data to update its computer price index for years after 1984.

6. The only other hedonic price index that covers both the 1950s and the late 1970s is the Knight (1983) index, as quoted by Alexander and Mitchell (1984, table 9, p. 48). Triplett's (1989) survey paper summarizes results of other studies over our period but does not present new research results.

7. Some might prefer to omit the 1951–54 interval, which is based on a single 1951 observation. The 1954 index number on a 1984 base is 33,293, for an annual rate of change over thirty years of −19.4 percent. These indexes are presented in table 6.7 below.

remains to be seen whether the net impact of changing weights and the absence of a BEA price index for computers before 1969 implies a significant change in the extent of mismeasurement of the PDE deflator.

The chapter begins with three sections providing background material. Section 6.2 provides a brief overview of the postwar development of the computer industry and exhibits data on value and numbers of computers sold by major type (the same data are subsequently used to supply weights for the separate mainframe and minicomputer price indexes). Section 6.3 examines aspects of the hedonic regression methodology that are relevant to this study, including data availability and definitions, specification, functional forms, structural stability, and make effects.

Section 6.4 provides an introduction to the data sets, while section 6.5 discusses the hedonic regression estimates and section 6.6 the issues involved in choosing one equation in preference to another, including equations covering the same time interval yielded by alternative data sets. Section 6.7 discusses two weighting issues involved in converting a price index for computer processors into an index for computer systems, where a system is defined as the processor and its associated peripherals. Using the computer system index, the chapter then computes an index for the overall ''office, computing, and accounting machinery'' (OCAM) category of PDE. Traditional index number problems that are of only minor importance in most aspects of deflation assume major importance in combining computer price indexes into deflators for aggregates like OCAM. Two main problems are discussed. First, results are sensitive to the choice of base year for any price index (whether an implicit deflator or fixed-weight index) in which calculations require the source of a single base year. In the case of the implicit deflator method, the use by the BEA of the base year 1982, when computers were relatively cheap, tends to yield a low weight on computers in earlier years and understate the importance of price decreases that occurred prior to the mid-1970s. Correspondingly, the contribution of computers to real investment is understated before 1982 and overstated after 1982.

The second problem is that with the implicit deflator method, regardless of the base year chosen, the weight of computers is zero for any year prior to the introduction of computers, assumed to be 1958 in the NIPAs. Thus, in a comparison between 1957 (or any earlier year) and the base year, in this case 1982, the rapid price decline of computers has no effect at all on the growth rate of real investment or real GNP. This result, which may seem surprising, in fact reflects well-known properties of the Paasche implicit deflator methodology rather than any mistake made by the BEA. This chapter deals with both weighting problems by using the Törnqvist approximation to an ideal index number, in which the weights on computers shift every year to reflect their share of nominal expenditures within OCAM.

There are a number of studies that have created price indexes that may be compared to this one, including Knight (1983), Chow (1967) as extended by Miller (1980), Archibald and Reece (1979), Cole et al. (1986), and Dulberger (1989). Other hedonic regression studies of computer prices have not attempted to develop price indexes, but rather have been within the industrial organization literature concerned with whether IBM overprices or underprices its computers over relatively short time periods (Kelejian and Nicoletti 1974; Ratchford and Ford 1976; Stoneman 1978; Brock 1979; Michaels 1979; Fisher, McGowan, and Greenwood 1983). Other studies of technological change (Alexander and Mitchell 1984; Bresnahan 1986) and of functional form (Horsley and Swann 1983) have used the previous hedonic studies by Chow and/or Knight rather than producing their own. To limit its scope, this chapter provides only new research results and does not present any comparison of its results with the previous literature. Such comparisons are amply provided in the recent survey paper by Jack Triplett (1989).

6.2 The Postwar Development of the Computer Industry

This study develops price indexes for computer processors displaying enormous changes over time; a price index that shrinks from 100,000 to 100 over a span of thirty-three years is probably unprecedented in economic history (although changes in the opposite direction, from 100 to 100,000, over shorter periods have occurred in hyperinflations). A bit of intuition to support these startling numbers is provided by a few details on the first electronic computer, the ENIAC, which was developed during World War II. The ENIAC had a trifling computational capacity in comparison with today's PCs, yet was gigantic in size, measuring 100 feet long, ten feet high, and three feet wide, and containing about 18,000 vacuum tubes. This machine was programmed by setting thousands of switches, all of which had to be reset by hand in order to run a different program. It is reported to have broken down "only" about once per day.[8]

The first major successor to the ENIAC was the UNIVAC I, originally built on contract with the U.S. government for use in the 1950 census. All the UNIVACs built through 1953 were purchased by the government, and an initial commercial purchase occurred in 1954. Unlike the ENIAC, the UNIVAC operated with stored programs rather than hand-set switches, and is the first machine in my hedonic regression sample from the Phister (1979) data source.[9]

8. This section is based on Cole et al. (1986), the conference draft of Dulberger (1989), Einstein and Franklin (1986), and Fisher, McKie, and Mancke (1983).

9. The vintages associated with each observation in the Phister sample are those listed in the source. Thus, the UNIVAC I is attributed to the 1951 vintage, the year that the first unit was delivered to the Census Bureau. Those that may be interested in extending my price index

The development of computer technology is often described with a terminology of technical "generations." Early first-generation machines through the late 1950s operated with vacuum tubes, followed by the second-generation machines based on transistors, starting with the IBM 7000 series introduced in 1959. The first IBM third-generation machines with integrated circuits were the series 360 models, first installed in 1965. Since the introduction of semiconductor chips, continuous improvements have been achieved by packaging increased numbers of circuits closer together, both lowering the marginal cost of additional memory and reducing instruction execution time.

The evolution of the computer industry is quantified in table 6.1, which displays domestic purchases (i.e., including imports and excluding exports) for mainframes, mini computers, and micros (mainly PCs in the 1980s). Both numbers of units and the value of shipments are exhibited for each group.[10] Unit values are not shown to save space but can be calculated. These range for mainframes from $420,000 in 1955 to $968,000 in 1984; for minis from $110,000 in 1965 to $58,000 in 1984; and for micros from $15,000 in 1975 to $3,690 in 1984. Prior to 1965, virtually all computers were mainframes, and unit sales grew at a 50 percent annual rate, while the value of shipments grew at a 44 percent rate (1955–64). In subsequent decades, the annual growth rate of mainframe units tapered off to 4 percent (1964–74) and 2 percent (1974–84), while the value of shipments grew at annual rates of 14 and 5 percent in these two decades, respectively. For these two decades, growth rates were much faster for minis (48 and 23 percent for units versus 40 and 22 percent for values for 1965–74 and 1974–84, respectively). The annual growth rate for micro units during 1975–84 was 95 percent and for value was 67 percent.

In assessing the data in table 6.1, note the shift from mainframes to minis and micros; the value share of mainframes declined from 97 percent in 1969 to 46 percent in 1984. Since this is the period covered by the new BEA deflator for computers, which excludes both minis and micros, that deflator becomes less representative of the total computer industry as the years go on.

further back in time should note that the price/performance ratio of the ENIAC to UNIVAC I is 10.9, according to Knight's commercial index (1966, 45). This would imply a 1946 price index on a 1984 base of roughly 1.5 million.

10. The source for table 6.1 defines the breakpoint between micros and minis at $20,000 per units and between minis and mainframes at $250,000. The $250,000 figure corresponds precisely with Phister (1979, fig. 1.21.5, p. 13), which shows that $250,000 remains a consistent borderline between mainframes and mini computers over the 1955–74 period. Correspondingly, all machines in the Phister data set with prices below $250,000 are classified as "minis." When the minimum, mean, and maximum memory configurations of a model straddle the $250,000 boundary, the classification is decided by whether the mean configuration lies below or above $250,000.

Table 6.1 **U.S. Domestic Purchases of Electronic Computers, 1955–84 (value in millions of dollars)**

	Mainframes		Minis		Micros		Total	
Year	Units	Value	Units	Value	Units	Value	Units	Value
1955	150	63	...	...	...	...	150	63
1956	500	152	...	...	...	...	500	152
1957	660	235	...	...	...	...	660	235
1958	970	381	...	...	...	...	970	381
1959	1,150	475	...	...	...	...	1,150	475
1960	1,790	590	...	...	...	...	1,790	590
1961	2,700	880	...	...	...	...	2,700	880
1962	3,470	1,090	...	...	...	...	3,470	1,090
1963	4,200	1,300	...	...	...	...	4,200	1,300
1964	5,600	1,670	...	...	...	...	5,600	1,670
1965	5,350	1,770	250	29	...	...	5,610	1,799
1966	7,250	2,640	385	40	...	...	7,635	2,680
1967	11,200	3,900	720	69	...	...	11,920	3,968
1968	9,100	4,800	1,080	100	...	...	10,180	4,900
1969	6,000	4,150	1,770	152	...	...	7,770	4,302
1970	5,700	3,600	2,620	210	...	...	8,320	3,810
1971	7,600	3,900	2,800	218	...	...	10,400	4,118
1972	10,700	5,000	3,610	271	...	...	14,310	5,271
1973	14,000	5,400	5,270	369	...	...	19,270	5,769
1974	8,600	6,200	8,880	577	...	...	17,480	6,777
1975	6,700	5,410	11,670	642	5,100	77	23,470	6,128
1976	6,750	5,580	17,000	816	25,800	374	49,550	6,770
1977	8,900	6,600	24,550	1,203	58,500	761	91,950	8,563
1978	7,500	7,590	29,550	1,596	115,600	1,098	152,650	10,284
1979	7,200	7,330	35,130	2,038	160,000	1,488	202,330	10,856
1980	9,900	8,840	41,450	2,487	250,500	2,104	301,850	13,431
1981	10,700	9,540	44,100	2,699	385,100	2,503	439,900	14,842
1982	10,600	10,300	47,820	2,821	735,000	4,190	793,420	17,311
1983	9,985	10,480	45,420	3,330	1,260,000	5,300	1,315,405	19,110
1984	10,700	10,360	72,130	4,185	2,100,000	7,750	2,182,005	22,295

Source: 1960–84: Einstein and Franklin (1986, table 1); 1955–59: Phister (1979, table II.1.21).

6.3 Implementation of the Hedonic Regression Methodology

6.3.1 "Matched Model" versus Hedonic Regression Indexes

Triplett (1986) has provided a concise introduction to the interpretation of hedonic price indexes. These indexes can be distinguished from the "conventional method" used by the BLS to construct the CPI and the PPI. In the recent literature on computer price indexes, the conventional method has been called the "matched model" method, since it involves comparing prices only for models that are identical in quality from one year to the next.

The most important potential defect in a matched model index is the omission of price changes implicit in the introduction of new or "unmatched" models. A matched model index assumes that the price change implicit in the introduction of new models is identical to the price change of the matched models over the same time interval. While this might be a valid assumption for some products, it is clearly invalid for electronic computers, as has been demonstrated recently by Cole et al. (1986) in their comparison of matched model and hedonic price indexes for the same sample of computers. The effect of the introduction of new technology that reduces the price of quality characteristics (e.g., computer speed and memory) is to cause the price of old models to be bid down. The prices of old models included in the matched model price indexes may fail to duplicate the price reductions on new models either because firms may sell old models at a discounted price but report list prices to the compiler of the price index or because firms may fail to reduce the transaction price of old models, thus causing their sales to disappear at a speed that depends on lags in information, lags in consumer reaction (due perhaps to employee training costs for switching to new models), and supply bottlenecks or backlogs on new models.

6.3.2 The Hedonic and Imputation Methods

The hedonic regression approach can be viewed as one of several methods to estimate the slope of the function relating the cost of a product to its quantity of characteristics. A common approach to the estimation of quality-adjusted price change is to include time dummy variables (D_t) in cross-sectional regressions explaining price (p_{it}) for two or more years:

$$\text{(6.1)} \qquad \log p_{it} = \beta_0 + \sum_{t=1}^{N} \delta_t D_t + \sum_{j=1}^{m} \beta_j \log y_{ijt} + u_{it}\,, \qquad i = 1, \ldots, n;\ t = 0, \ldots, N.$$

Here y is the quality characteristic. Equation (6.1) uses a log-linear (or "double log") specification, following the majority of hedonic regression studies of computers. An alternative would be a semilog specification, with the log of price of the left and the unlogged values of the y variables on the right. Whatever the functional form, as long as the log of price is related to linear time dummy variables like the D_t in (6.1), a hedonic price index with a base of unit y in year $t = 0$ can be calculated from the antilogs of the δ_t coefficients. This has been the most common procedure in hedonic regression studies and is what Triplett (1989) calls the dummy variable method.

The leading alternative is the imputation method, in which an imputed base-year price for each model is calculated as the fitted value of (6.1), with the time coefficient for year t (δ_t) replaced by the time coefficient for the base year ($\delta_0 = 0$). If, for instance, the regression equation covers 1954–65 and 1954 is the base year, the imputed 1954 price of a 1965 model can be calculated as the fitted value with the time coefficient set to zero. Since computer prices fell rapidly from 1954 to 1965, the imputed 1954 price of a 1965 model will be much higher than the actual price charged in 1965. Triplett (1989) compares the dummy variable and imputation methods and on balance prefers the latter. In this chapter, I compute price indexes using both methods. To his list of advantages of the imputation technique we can add the extremely useful role of imputed prices in providing a straightforward measure of base-year quality that can be used to edit a data set. If the ratio of the actual to the imputed price for a given model is much higher than the average of all models for a given year, that model is "overpriced," that is, its actual price in year t is much higher relative to base-year quality than the average model. Below, I adopt this criterion to omit selected models from the Phister data set, following the precedent set by Knight (1966).[11]

Returning to equation (6.1), there remains the problem of determining the optimal sample period for the regression. At one extreme, we can obtain an aggregate index of price change from the series of δ_t coefficients obtained in a single regression for an entire data set, and at the other extreme an index can be calculated by linking together a string of δ_t coefficients obtained from a series of "adjacent year" regressions on data for successive pairs of years. To the extent that the prices of quality characteristics are changing through time, the adjacent-year technique allows the regression coefficients on the y_{ijt} to change every year. The disadvantage of the adjacent-year technique is that sample sizes are sometimes too small to yield efficient estimates, and estimated coefficients on the quality characteristics jump erratically from year to year and may even change sign.

Clearly, there is no reason to choose either the extreme of running a single regression or N separate adjacent-year regressions. Instead, we can begin with numerous equations estimated for overlapping short periods and successively pool the data into longer periods, checking for structural change with the conventional "Chow test" for aggregation. This chapter tests for aggregation not only over time but also across different types of computer models.

6.3.3 Interpreting Residuals in Hedonic Regression Equations

No hedonic regression equation will fit the data perfectly. The estimated residuals (u_{it}) represent the effects of excluded attributes, incorrect specification of functional form, marketing practices unrelated to production costs, demand discontinuities, and time lags due to the fact that a new model

11. This discussion omits the third type of price index described by Triplett (1989), the "characteristics price index," since this technique is not used here.

may have a lower price than an older model containing the same quantity of characteristics. Some variables are omitted because they are highly correlated with other variables that are included. The coefficients on an included variable thus represent not just its own effect on price, but also that of the omitted variables. Thus, the estimated coefficients cannot necessarily be interpreted as representing the value that users place on a particular attribute.

Omitted attributes afflict all hedonic regression studies but may be particularly important in research on computer prices, since no study, including this one, has been able to quantify software maintenance, engineering support, or manufacturer's reputation. If these omitted variables differ systematically across manufacturers, then their effect on prices can be captured by manufacturer dummy variables or "make effects." Since my major emphasis is on changes in computer price indexes over time, my investigation of make effects is limited to the inclusion of IBM make-effect dummy variables in all those regression equations that include IBM models.

Related to make effects is the question of commodity boundaries. In a sense, this study does not extend back far enough in time, since the first electronic computer may have represented a decline in the price-performance ratio of the previous "computer," some mixture of a punched card sorting machine and a clerk with a calculator.[12] The same issue arises in a cross section, since one can ask whether mainframe, mini, and micro computers are all the same product. Below, we find that pooling tests reject the aggregation of minis and mainframes into a single equation.

6.4 The Data

The results in this study are based on two overlapping data sources. For the years 1951–79, we have the compilation of Phister (1979), which provides for roughly 100 mainframe models a long list of quality characteristics, as well as a variety of sales prices and rental rates. For many but not all of the models, the Phister tables list ninety-five separate quality characteristics, including a wide variety of different performance measures (e.g., included memory, several dimensions of speed, and the Knight commercial and scientific indexes) as well as a number of attributes of more dubious importance (e.g., floor space, weight, and price per pound of both central processor and memory), and twenty lines of information on prices and rental rates.

For the period 1977–84, the data source is *Computerworld* magazine, published by the International Data Corporation (IDC), which also publishes the bimonthly *EDP Industry Report,* the source of data in several earlier

12. Fisher, McKie, and Mancke (1983, 3) report that the first electronic computer, the ENIAC, carried out calculations between 100 and 500 times faster than punched card machines with electromagnetic relays.

studies. The *Computerworld* annual hardware issue makes available all the required information in a single place for each year of the sample period. Unfortunately, the annual hardware issue began only in 1981, making an issue-by-issue search necessary for earlier years. It was possible to search back only to 1977 within the span of time available for this study.

Two other data sources are used to check the sensitivity of these results to data sources. Gregory Chow provided the data used in his original 1967 article, and the BEA provided the data used by Ellen Dulberger (1989) and Cole et al. (1986) for computer processors. In the following sections, the Phister and *Computerworld* data are described in some detail, since these are used here for the first time, and the Chow and Dulberger data in less detail, since these are described by those authors.

6.4.1 The Phister Data

Phister's data on speed and memory mainly come from *Auerbach Computer Technology Reports*, a comprehensive guide published since the early 1960s by Auerbach Information, Inc. His sources for system prices include General Service Administration catalogs, price lists published by various manufacturers, and Auerbach. Phister dates his prices as pertaining to roughly two years after a model was introduced, where the introduction dates come from IDC.[13]

The Phister data include, for most computer models, two types of prices. First, there is a system price accompanied by information on the amount of memory included in that price. Second, there is information on the price of incremental memory. A pitfall in working with the Phister data is that the prices of several machines are listed with zero memory included. For most but not all machines, information is given on the incremental price of memory, and for each such machine three observations were created, corresponding to the price and characteristics of models configured with minimum, maximum, and mean memory sizes. This procedure is identical to that carried out by Dulberger in creating her sample, except that she creates two observations corresponding to minimum and maximum memory. In short, in the Phister data set, each model is entered three times if data on the price of incremental memory are provided, but only once if only a single price at a fixed memory configuration is provided without any supplemental information on the price of incremental memory.[14]

Seven indexes of speed are provided by Phister, including memory cycle time and several different measures of addition and multiplication speed.

13. This two-year-lag criterion is not consistently applied, however, since Phister presents prices for the IBM 4331 and 4341 models, which were introduced in 1979, the same year as his book was published.

14. Eighty-nine models are entered as triplets and eight as single observations, for a total of 287 total observations. Dulberger's data set includes sixty-six new models (twenty-seven IBM and thirty-nine plug-compatible), for a total of 132 observations on new models.

Initially, I included memory cycle time and multiplication speed, as did Chow (1967), but soon found that they are highly collinear in the Phister sample. Multiplication speed is omitted from the results presented in section 6.5 of this chapter, which include only memory and memory cycle time for the regressions estimated for the Phister data.

Also available from Phister are the Knight commercial and scientific performance indexes, which use a formula to weight together memory, processor time, and input-output time factors, and these are calculated from more basic specifications of each computer. Because the Knight indexes are composite blends of memory and speed based on "the opinions of 43 senior computer engineers and programmers" (Phister 1979, 358) in the early 1960s, the weighting factors may be obsolete, and so the weights on memory and speed are freely estimated and do not include the Knight indexes as explanatory variables. In the last part of the chapter, the Knight indexes are used as part of a comparison of the quality of particular IBM models over time. It is interesting that, as an example of the extent of reduction in the price-performance ratio in the industry, the Knight commercial index increases from 119 for the 1954 IBM model 650 to 564,000 for the 1979 IBM model 4331, yet the nominal price of the 4331 was less than half that of the 650.[15]

6.4.2 The Computerworld Data

The *Computerworld* data set for 1977–84 includes several quality attributes not available from Phister, including minimum and maximum number of input-output channels, cache buffer size, and, most important, millions of instructions per second (MIPS) beginning in 1981. Additional input-output channels allow a computer to use its central processor and memory more efficiently by loading instructions and data from several devices at the same time, and a cache buffer memory allows a powerful processor to use a low-cost, relatively slow integrated circuit memory (Phister 1979, 524). Triplett (1989) discusses the advantages of MIPS over machine cycle time as a quality attribute, and for the 1981–84 period equations are estimated that contain both MIPS and cycle time. Because these additional variables are available in the *Computerworld* sample but not in the Phister sample, separate equations are estimated for each sample and are not pooled.

6.4.3 Other Data Sources

The new data from Phister and *Computerworld* are supplemented by two other data sets, the original Chow (1967) data set covering 1954–65, and the

15. This implies an annual rate of change of the performance/price ratio of 36.9 percent, when we use the price of the 4331 with the mean memory configuration. Price and performance data come from Phister (1979, 339, 359, 631).

Dulberger (1989) data set covering IBM and compatible machines for 1972–84. The Chow data set is considerably larger than the Phister sample for the years of overlap but yields similar results. The main defect of the Chow data set, as discussed in section 6.6, is its underrepresentation of IBM mainframes and overrepresentation of mini computers. The Dulberger data set includes information on the technological class of computers not available in either the Phister or the *Computerworld* samples.[16] The main limitation of the Dulberger data set is its relatively small size, particularly when it is limited to new models only. During 1972–79, the Dulberger data set includes just nineteen new models (all IBM except for four plug-compatibles), as contrasted to forty-one new models in the Phister data set. In the 1981–84 period, the Dulberger data set includes forty-two new models (eleven IBM and thirty-one plug compatible), in contrast to the 266 new models in the *Computerworld* data set (thirty-four IBM and 232 others, including sixty-eight minis and superminis).[17]

There are several differences among these data sets that we need to keep in mind. Chow (with a few exceptions) and Phister include only computers in their first year of production (new models), while Dulberger and *Computerworld* cover all models in production. Dulberger's data cover a narrower range of manufacturers (IBM and three plug-compatible manufacturers) but are the most carefully developed for the consistency of price and quality characteristics. I deal with the first aspect of noncomparability by editing the Chow, Dulberger, and *Computerworld* data sets to include only new models. The importance of the data consistency issue is assessed by comparing the estimate of performance improvements on specific IBM models implied by the estimated coefficients from the Phister, Dulberger, and *Computerworld* data sets.

6.4.4 Data Issues

New Models versus All Models

Numerous pitfalls in applying the hedonic regression technique have surfaced in the literature, but one seems to apply with particular force in the computer industry. The Rosen (1974) equilibrium interpretation of a hedonic surface may not apply in the computer case, because the computer market has "never been close to long-run equilibrium in its entire existence" (Fisher, McGowan, and Greenwood 1983, 149). Old inferior models do not just

16. The Dulberger data set includes a technological class variable for each mainframe processor (those produced by IBM and three other "plug-compatible" manufacturers), including two classes of "bipolar" semiconductors and five classes of field effect transistor (FET) semiconductors, which gradually increased from one to sixty-four kilobits per chip.

17. Each of these comparisons refers to separately numbered models. In the Dulberger data set, each model appears twice, priced at minimum and maximum memory. In the Phister data set, most but not all models appear three times, priced at minimum, mean, and maximum memory. The *Computerworld* data set is unduplicated.

disappear when a new superior model is introduced, nor are they repriced at a lower price/performance ratio equal to that of the new model. This suggests that new and old models may lie on different hedonic surfaces.

When new models are introduced, they tend to offer a lower ratio of price to performance than existing models. Instead of falling until price/performance ratios are equalized across machines, older models that remain in production tend to be overpriced. This phenomenon suggests two possible arguments for excluding old models in hedonic regressions. First, mixing old and new models having different price-to-performance ratios together in the same hedonic regression equation may lead to biased estimates of the rate of price change. Second, the rate of price change will be sensitive to the changing fraction of the same, consisting of old models in a given year. For these reasons, Fisher, McGowan, and Greenwood (1983) argue forcefully that a hedonic regression study should include only new models.

By including only new models, the hedonic price index traces out the technological "frontier" as successively more powerful new models are introduced. The main limitation of such a price index is that the total production of computers includes both new and old models, and so for deflation of current-dollar computer sales the price index should take into account existing models as well as new models. Thus, a case can be made for producing two hedonic price indexes, both including and excluding old models. To be consistent over time, a hedonic price index should be of one form or another, rather than mixing forms. If a data source included both old and new models, there would be no problem, since separate indexes could be developed based on all and only new models. Unfortunately, the Phister data source used in this chapter contains only new models, and thus to be consistent the resulting Phister-data price index should be compared to price indexes for the other data sets based on only new models. To maintain consistency, the basic results for the *Computerworld* data set include new models only. The results for both the Chow and the Dulberger data sets estimate hedonic indexes only for the subset of new models in those data sources; hence the hedonic price indexes for the Chow and Dulberger data do not constitute a replication of those authors' results and would not be expected to be identical to the results published by those authors.[18]

Weighting by Market Shares

Ideally it would be desirable to weight each observation by market share in each year. However, the requisite market share data are not available from the data sources. Phister presents an inventory of the installed number of computers for some but not all models, and *Computerworld* does not provide numbers produced or installed. The regression equations weight each

18. Readers can find price indexes based on the full Chow and Dulberger samples in the original papers by those authors and in Triplett (1989).

observation equally, which results in an underweighting of IBM machines, which had a share ranging from 60 to 75 percent in the total revenue of the data-processing industry, but represent only about half the observations in the Phister sample and only about 18 percent of the observations in the *Computerworld* sample. To deal with the weighting issue, separate price indexes for mainframe and mini computer processors are estimated over 1965–79, and the separate rates of price change are weighted by market shares in each year. Yearly market share weights are also applied to separate indexes over 1979–84 and IBM and plug-compatible mainframes, other mainframes, and minis and superminis. I also present a linked imputed price index over the entire sample period for major IBM mainframe models, in order to assess the plausibility of the final price index for those models that had the dominant market share.

Rental Rates versus Purchase Prices

The dependent variable in all the regressions is the log of purchase price. How different would the results be if the log of the rental rate were instead taken as the dependent variable? Phister provides data for all models on the rental rate, purchase price, and price/rental ratios. A scan of this ratio of purchase price to monthly rental indicates that it falls within the range of forty to sixty for almost all models in the Phister sample, with no evident time trend. The variance of this ratio over time is trivial compared to the variance of the price/performance ratio over time, suggesting that alternative regressions using the rental rate would yield similar results to those exhibited in section 6.5. Further evidence that this distinction is not important comes from the similarity of the price indexes yielded by the Phister and Chow data sets over 1954–65 (see table 6.3 below), where the Phister results are based on prices and the Chow results are based on rental rates.

Peripherals

While price/performance ratios for peripheral equipment (tape and disc drives, printers, etc.) fell over time by substantial amounts, the available evidence, especially that presented by Cole et al. (1986) and Flamm (1987), suggests that the rate of price decline was less than that for mainframe processing systems. Below, the Flamm series for peripherals is linked to that of Cole et al., so that the final price index properly weights together the price experience of computer processors and peripherals.

Software

The regressions cover only hardware prices, not the full operating cost of performing "computations," which would also include costs of software, maintenance, electricity, and rent on floorspace. However, the hardware prices include the basic system software that a manufacturer supplies with each machine. This has increased manyfold in quality and quantity, along with the increase in system performance. For instance, in 1954, IBM supplied only about 6,000 lines of code as programming support for the model 650 computer. The company provided an assembler and a few basic utility routines, but that was all. But as new models were introduced, the software provided grew exponentially. By the late 1960s, the operating system for the IBM 360 series, designed to improve system performance and to provide a wide variety of useful operating features, included over 5 million lines of code. From 1965 to 1975, software was a constant share (roughly 35 percent) of the total developmental cost of computer manufacturers (Phister 1979, 26–27).

Then, in 1969, IBM announced its "unbundling" decision, that separate charges would be made for systems engineering services and education and for new program products, "as distinct from system control programming." IBM also reduced its prices by 3 percent, an amount that represented its estimate of the value of the excluded services. No adjustment is made in this study for unbundling, partly on the ground that 3 percent is a small number, and partly because software developments had led to increasingly sophisticated operating systems that have relieved customer programmers of various complex tasks and made them more self-sufficient of the manufacturers' systems engineering personnel (Fisher, McKie, and Mancke 1983, 173–79). This would lead us to overstate the rate of decline of computer processor prices, particularly because unbundling progressed further during the 1970s, with IBM separately pricing more and more operational software until, by the end of the 1970s, all software was separately priced. Set against this bias are other omissions that work in the opposite direction, including the reduced energy and space requirements of computer processors.

6.5 Regression Results

6.5.1 Phister Data: General Procedures

All regressions estimated for the Phister data include two basic quality characteristics, memory and speed ("memory cycle time"). In addition, two types of dummy variables were included. First, an intercept dummy, equal to unity for an IBM machine and zero for a non-IBM machine, was included to test for an "IBM effect." Second, the data source listed the type of memory, allowing tests for the effect of memory types other than the standard core or integrated circuit types.

Perhaps the most important difference in memory type occurred in the early years of the sample period, when "drum" memory was supplanted by "core" memory. Although it would have been preferable to include a dummy for drum memory, this was precluded by the unfortunate fact that all the 1954 observations but *none* of the 1955 observations have drum memory.

Hence, the drum memory coefficient is collinear with the 1954–55 price change and prevents the estimation of plausible price coefficients in 1954–55. However, in the 1969–72 period, several isolated machines with unusual memory types ("wire" memory and "rod" memory) were identified. Because only a few machines had these memory types, inclusion of a memory-type dummy in this period did not preclude estimating the time coefficients. The form of the memory-type dummy was left to the computer, which selected an interactive memory type and memory slope dummy in preference to a shift in the intercept or in the speed coefficient.[19]

Lacking a priori evidence whether coefficients on quality characteristics could be assumed to remain constant over long periods, our estimation procedure began with short periods. Equations were first estimated for overlapping "triplets" of years, extending from 1951, 1954, and 1955 through 1977, 1978, and 1979.[20] Subsequently, groups of triplets were joined together and subjected to aggregation (or "pooling") tests to determine whether coefficients were stable across three-year periods. In the tables below, the triplet results are not presented, and the estimates shown are for the longer sample periods that accept aggregation over time.

For each of these longer sample periods, the ratio of the actual price to imputed base-year price was then inspected for "overpriced" models (see the discussion of the imputation method above following eq. [6.1]. Models selected for exclusion were those that had a log ratio of actual price to imputed price greater than 1.5 times the standard error of the estimated regression equation (in most equations, this criterion translates into the statement that the excluded models had an actual price double or greater the imputed price). Then the equations were reestimated with the overpriced models excluded. A precedent for excluding observations is Knight (1966, 49), who excluded overpriced models lying more than half a standard error above an initially fitted regression line.[21] It should be noted that less than 10 percent of the observations in this study are excluded by this procedure,

19. Thus, the "other memory" dummy is equal to the value of memory for those machines with wire or rod memory and zero otherwise. The estimated coefficient on this dummy in table 6.4 below is positive, indicating that extra memory raises price more for these other memory types than for standard memory types. I also tested for a difference between integrated circuit and core memory, but did not obtain any significant coefficients.

20. In some previous versions of this chapter, regressions for pairs of adjacent years were presented. Since sample sizes in some of those regressions were so small, in this version the first estimates were for triplets of years.

21. This sentence translates Knight's actual procedure into the language of this paper. As shown by Triplett (1989, eqq. [9] and [10]), Knight's procedure amounts to a regression of performance on price, rather than the usual regression of price on performance, and a price index can be calculated from the antilogs of the negatives of the estimated time dummy coefficients. Hence, when Knight states that he eliminates observations lying more than half a standard deviation below the regression line, he means that he eliminated overpriced observations, i.e., those that had a low ratio of performance to price. I was guided to this precedent for omitting observations by Triplett (1989, sec. II.B.3).

Table 6.2 **Hedonic Regressions, Phister Sample, 1951–69**

	1951–60 (1)	1960–69 (2)	1951–69 (3)
Memory	0.64**	0.65**	0.70**
Memory cycle time	−0.17**	−0.55**	−0.22**
IBM dummy	−0.25	0.11	0.08
Other memory[a]	...	0.16*	0.20**
1951	1.32*	...	1.46**
1954	base	...	base
1955	−0.01	...	−0.45
1956	no data	...	no data
1957	excluded	...	excluded
1958	−0.29	...	−0.42
1959	−0.62	...	−0.88*
1960	−0.72	base	−1.02**
1961	...	−0.40**	−1.30**
1962	...	−0.49**	−1.33**
1963	...	−0.54**	−1.26**
1964	...	−1.04**	−1.67**
1965	...	−1.81**	−2.33**
1966	...	−2.06**	−2.64**
1967	...	−2.28**	−2.58**
1968	...	excluded	excluded
1969	...	−3.07**	−3.52**
$\bar{R}^2$	0.808	0.894	0.872
S.E.E.	0.427	0.431	0.451
Observations	39	110	133

[a]"Other memory" is a dummy that allows for a shift in the coefficient on memory for models having wire or rod memory.

*Indicates significance at the 5 percent level.

**Indicates significance at the 1 percent level.

in contrast to Knight, who appears to have discarded about half his observations.[22]

6.5.2 The Phister Sample: Regression Results

The regression results are presented beginning in table 6.2 for the 1951–69 period. The specification is double log, as in equation (6.1) above, with asterisks used to designate the significance levels of the coefficients so as to avoid an excessive clutter of numbers in the tables. The base year for each equation is indicated by the word *base*. The implied price index in each other year can be calculated by taking the antilog of the coefficient shown opposite each year.

22. This procedure led to the exclusion of nine of the ninety-seven models in the Phister data set (twenty-one observations of 287). The list of overpriced models and their ratios of actual to imputed prices is presented in the Appendix. Knight (1966) does not report how many observations were omitted, but the number must have been substantial, since he began with 225 observations (45–46) but reports that "over 120 observations were used [in the final regressions]" (49).

Successive aggregation tests suggested that pooling was accepted over the entire decade 1960–69, but not beyond. There is a decisive break in 1969 revealed by the failure of 1960–69 to pool with 1969–72, 1969–75, and 1969–79. The break in 1960 is less decisive. One can test for such a break in two ways, by asking (1) whether the addition of, say, 1951–59 to 1960–69 passes an aggregation test, but also (2) whether the addition of 1960–69 to 1951–59 passes an aggregation test. These are two separate questions, and there is no statistical reason why the answer to them should be the same. Aggregation test 1 is accepted at the 5 percent level, but 2 is rejected at the 1 percent level. In light of this mixed finding, the final price index for 1951–65 is based on the average of the price changes shown in columns 1 and 2 and those shown in column 3. For the years after 1965, there are sufficient data to split the sample into two separate segments for minis and mainframes, as shown below in table 6.5.

In table 6.2, the coefficients on memory and speed ("memory cycle time") are highly significant. That on memory is stable across the 1960 break, as shown in a comparison of columns 1 and 2, while that on speed increases in absolute value after 1960. The "other memory" dummy variable is significant in both columns 2 and 3; the IBM dummy is not significant but is included to remain consistent with results displayed below that extend after 1969. The other point of interest in table 6.2 is that the time coefficients imply a relatively smooth rate of price decline. There are no price increases registered in any year in columns 1 and 2, while in column 3 there are small increases of 7 and 6 percent, respectively, in 1963 and 1967.

Data source effects are explored in table 6.3, which compares results for the Phister and Chow data sources. The sample period ends in 1965, which is the last year in the Chow data set. The "other memory" dummy is excluded, since it is not defined over 1951–65, and the IBM dummy is excluded in light of its insignficance in table 6.2. The only difference in the specification of the Chow equations is in the differing speed variables included in the data, "access time" and "multiplication time," as contrasted with the single Phister speed variable, "memory cycle time."

The Chow data used in table 6.3 refer only to new models, not to both new and old models, as in the original Chow (1967) article. Editing the Chow data in this way is necessary to achieve consistency with the Phister data set. While the overall rate of price decline over 1954–65 is not affected by excluding old models, one aspect of Chow's original research is altered. When all models are included, an aggregation test to add 1954–59 to 1960–65 is rejected at the 5 percent level, but this is not true for new models only. The new-only data set easily passes an aggregation test over 1954–65 by either method 1 or 2 listed above.

Thus, the basic Chow result is that presented in column 6. Because of the ambiguous results in aggregating the Phister data over 1954–65, we can compare the Chow estimates in column 6 with either columns 1 plus 2, or 3

Table 6.3 **Comparison of Hedonic Regressions, Phister versus Chow (new models only), 1951–65**

	Phister			Chow (new models only)		
	1951–60 (1)	1960–65 (2)	1951–65 (3)	1954–60 (4)	1960–65 (5)	1954–65 (6)
Memory	0.67**	0.66**	0.71**	0.38**	0.58**	0.54**
Memory cycle time	−0.21**	−0.57**	−0.21**	. . .	. . .	. . .
Access time	. . .	. . .	. . .	−0.16**	−0.14**	−0.15**
Multiplication time	. . .	. . .	. . .	−0.13**	−0.06**	−0.07**
1951	1.59**	. . .	1.43**	. . .	. . .	. . .
1954	base	. . .	base	base	. . .	base
1955	0.03	. . .	−0.42	−0.02	. . .	−0.03
1956	no data	. . .	no data	−0.17	. . .	−0.33
1957	excluded	. . .	excluded	−0.18	. . .	−0.22
1958	−0.11	. . .	−0.45	−0.60**	. . .	−0.56**
1959	−0.40	. . .	−0.92*	−0.63**	. . .	−0.74**
1960	−0.54	base	−1.01*	−1.20**	base	−1.14**
1961	. . .	−0.42**	−1.31**	. . .	0.13	−1.24**
1962	. . .	−0.56**	−1.37**	. . .	−0.47**	−1.62**
1963	. . .	−0.56**	−1.24**	. . .	−0.58**	−1.72**
1964	. . .	−1.15**	−1.73**	. . .	−0.91**	−2.03**
1965	. . .	1.86**	−2.33**	. . .	−1.15**	−2.29**
$\bar{R}^2$	0.801	0.887	0.856	0.932	0.896	0.902
S.E.E.	0.435	0.433	0.456	0.340	0.387	0.380
Observations	39	86	109	43	81	115

*Indicates significance at the 5 percent level.

**Indicates significance at the 1 percent level.

alone. The most interesting similarity is in the overall rate of price decline: on a base 1965 = 100, the implied Chow index number for 1954 is 987, while the implied Phister index number for 1954 in column 3 is 1,028 (cols. 1 and 2 together imply 1,102). A further similarity between columns 3 and 6 is the roughly similar rate of price decline over the 1954–60 and 1960–65 subperiods; columns 1 and 2 differ in this regard in exhibiting a much slower price decline over 1954–60 and a much faster price decline over 1960–65. The other notable differences in table 6.3 are in the pattern of coefficients: both sets of results indicate a shift in coefficients after 1960, but for the Phister data in columns 1 and 2 this takes the form of a jump in the absolute value of the speed coefficient, whereas for the Chow data in columns 4 and 5 the jump is in the coefficient on memory.

Table 6.4 displays the Phister results covering the remainder of the sample period through 1979. The sample periods shown are 1960–69, 1969–79, and 1960–79. These periods emerged as the outcome of a set of aggregation tests. The period 1960–65 could be extended to 1960–69 but not beyond 1969, and 1969–72 could be pooled with 1973–79. But pooling any period

Table 6.4 **Hedonic Regressions, Phister Sample, 1960–79**

	1960–69 (1)	1969–79 (2)	1960–79 (3)
Memory	0.65**	0.73**	0.71**
Memory cycle time	−0.55**	−0.43**	−0.51**
IBM dummy	0.11	1.25**	0.70**
Other memory[a]	0.16*	0.20	0.19
1960	base	. . .	base
1961	−0.40**	. . .	−0.34
1962	−0.49*	. . .	−0.23
1963	−0.54**	. . .	−0.57
1964	−1.04**	. . .	−0.70*
1965	−1.81**	. . .	−1.82**
1966	−2.06**	. . .	−2.05**
1967	−2.28**	. . .	−1.83**
1968	excluded	excluded	excluded
1969	−3.07**	base	−2.84**
1970	. . .	−0.19	−3.07**
1974	. . .	−0.60	excluded
1972	. . .	−0.81	−3.43**
1973	. . .	−0.80	−3.41**
1974	. . .	−1.37**	−3.96**
1975	. . .	−1.28**	−3.95**
1976	. . .	−2.12**	−4.54**
1977	. . .	−1.52**	−4.05**
1978	. . .	−2.04**	−4.44**
1979	. . .	−3.04**	−5.32**
$\bar{R}^2$	0.894	0.896	0.885
S.E.E.	0.431	0.626	0.604
Observations	110	139	243

[a] "Other memory" is a dummy that allows for a shift in the coefficient on memory for models having wire or rod memory.

*Indicates significance at the 5 percent level.

**Indicates significance at the 1 percent level.

before 1969 with any period after 1969 is rejected, usually at the 1 percent level.

It is evident from a comparison of columns 1 and 2 in table 6.4 that the large coefficient shifts are not in memory and speed, but in the dummy variables for IBM. The IBM dummy has an enormous coefficient of 1.25 during 1969–79, which implies that IBM charged more than triple the price per unit of quality during this interval as other manufacturers. It seems puzzling that IBM would pursue such an extreme price policy during the decade of the famous antitrust case. However, as we shall see in the next table, this finding results from an aggregation error, the inclusion of mini and mainframe computers in the same equation.

We have already examined the coefficients on the time dummies for the 1960–69 equation in table 6.2. The time dummies for 1969–79 in column 2 of table 6.4 exhibit more of a tendency to zigzag around a declining trend. We should view these results as more useful for indicating the magnitude of price changes for periods of several years than for annual changes between successive pairs of years.

It is important to note that this tendency to zigzag can occur in any data set consisting of new models. Note in table 6.3 that the Chow data display a price increase of 10 percent in 1957. Columns 3 and 4 in table 6.5 indicate that the Dulberger data for new-only models display price increases of 10 percent in 1973, 21 percent in 1974, and 23 percent in 1976 (this occurs when her technological class variables are omitted; price increases still remain in 1974 and 1976 when those variables are included).

Aggregation tests were also carried out for minis and mainframes. This test is carried out for 1965–79, since this is the first year when we have substantial data on minis, and for various subperiods. In each period, the test rejects the aggregation of minis and mainframes at a 1 percent significance level or better, confirming a similar result reported below for the *Computerworld* data. However, a combined test of time and type aggregation indicates that both mini and mainframe equations accept aggregation over the full 1965–79 period.

These results are shown in the first two columns of table 6.5. Note that minis tend to have a higher coefficient on memory and that mainframes have a higher speed coefficient. This suggests one source of the aggregation problem. The pooled equation for 1969–79 (table 6.4, col. 2) has a coefficient of 0.73 on memory, higher than for either minis or mainframes separately in table 6.5. This implies that the marginal price of memory is greater when a purchaser shifts from a mini to a mainframe than when a purchaser shifts to a larger machine within each category. A sensible interpretation is that minis and mainframes are different products, and mainframes provide extra services, for example, more channels and input-output ports, that justify their high relative prices.

Another interesting result is that the IBM dummy, which was implausibly high in the 1969–79 regression in table 6.4, declines substantially in table 6.5. The mainframe IBM coefficient of 0.30 seems consistent with the range of 0.24–0.34 in the results for IBM and plug-compatible mainframes for 1977–84 in the *Computerworld* data set (table 6.6). The coefficient of 0.75 for minis still seems high; an inspection of imputed prices traces this mainly to two particular 1970 models (S3/6 and S3/10).

Time dummy coefficients are missing for some years where we are missing an observation on minis, mainframes, or both. Hence, price indexes cannot be constructed for every year. Also, partly because of smaller sample sizes, the separate mini and mainframe time coefficients display more of a tendency to "jump" than the pooled results in table 6.4. For minis, there are three periods when the overall price decline is interrupted, 1966–67 and by lesser amounts in 1973 and 1977. These jumps clearly result from the small

Table 6.5 **Hedonic Regressions for Mini and Mainframe Models, Phister Sample, 1965–79, and for New-Only Portion of Dulberger Sample, 1972–84**

	Phister Data		Dulberger Data, Technology Variables	
	Minis (1)	Mainframes (2)	Excluded (3)	Included (4)
Memory	0.59**	0.47**	0.19**	0.24**
Memory cycle time	−0.31**	−0.45**	. . .	. . .
IBM dummy	0.75**	0.30**	−0.01	0.02
Other memory[a]	. . .	0.06	. . .	. . .
MIPS	. . .	. . .	0.84**	0.80**
Core 72	. . .	. . .	. . .	−0.60**
FET1K77	. . .	. . .	. . .	0.33
FET4K77	. . .	. . .	. . .	0.59**
FET24K80	. . .	. . .	. . .	0.40**
FET2K81	. . .	. . .	. . .	0.33
F16K81	. . .	. . .	. . .	0.36**
F16K82	. . .	. . .	. . .	0.40*
1965	1.17**	0.95**	. . .	. . .
1966	1.48**	−0.13	. . .	. . .
1967	1.44**	0.77*	. . .	. . .
1968	excluded	no data	. . .	. . .
1969	no data	−0.07	. . .	. . .
1970	0.37	no data	. . .	. . .
1971	no data	no data	. . .	. . .
1972	base	base	base	base
1973	0.07	−0.52	0.11	0.29
1974	−0.16	no data	0.41	−0.01
1975	−0.40	−0.05	−0.49	−0.84**
1976	−1.13**	−0.52	−0.23	−0.65**
1977	−1.01**	−0.48	−0.57	−1.07**
1978	no data	−0.83*	−1.03**	−1.44**
1979	−1.41**	−2.08**	−1.66**	−2.36**
1980	. . .	. . .	−1.65**	−2.33**
1981	. . .	. . .	−1.65**	−2.28**
1982	. . .	. . .	−1.94**	−2.40**
1983	. . .	. . .	−2.12**	−2.52**
1984	. . .	. . .	−2.35**	−2.76**
$\bar{R}^2$	0.599	0.953	0.951	0.965
S.E.E.	0.637	0.220	0.256	0.217
Observations	111	68	133	133

Note: Because only new models are excluded, there are too few observations to permit the following technology variables from the original Dulberger specification to be entered: BP1K73, BP1K74, FET2K75, FET2K76, FET2K77, FET1K78, FET1K79, FET2K79.

[a]"Other memory" is a dummy that allows for a shift in the coefficient on memory for models having wire or rod memory.

*Indicates significance at the 5 percent level.

**Indicates significance at the 1 percent level.

Table 6.6 **Hedonic Regressions by Type of Machines, *Computerworld* Sample, 1977–84 and 1981–84**

	IBM and Plug-Compatible Machines			Other Mainframes			Minis (including superminis)		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Memory	0.43**	0.43**	0.31**	0.21**	0.20*	0.18**	0.44**	0.43**	0.44**
Machine cycle time	−0.23**	−0.16	−0.08	−0.93**	−0.93**	−0.20*	−0.31	−0.05	−0.09
MIPS	. . .	. . .	0.43**	. . .	. . .	0.79**	. . .	. . .	−0.06
Minimum number of channels	0.58**	0.28*	0.20*	0.36*	0.36*	0.10	. . .	−0.04	−0.02
Maximum number of channels	0.16**	0.50**	0.27*	0.16	0.17	−0.05	. . .	0.27**	0.26*
Cache buffer size[a]	0.003**	0.003**	0.001	0.002	0.002	0.000	. . .	0.005	0.005*
IBM dummy	0.24**	0.34**	0.28**	. . .	. . .	. . .	. . .	. . .	. . .
1977	1.43**	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
1978	1.30**	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
1979	1.06**	. . .	. . .	1.94**	. . .	. . .	1.33**	. . .	. . .
1980	0.84**	. . .	. . .	no data	. . .	. . .	0.84**	. . .	. . .
1981	0.50**	0.55**	0.67**	0.53	0.52	0.99**	0.62**	0.81**	0.83**
1982	0.32**	0.44**	0.43**	0.43	0.43	0.54**	0.42	−0.05	−0.09
1983	0.17	0.26	0.34**	0.75**	0.74**	0.85**	0.06	0.17	0.15
1984	base	base	base	base	base	base	base	base	base
$\bar{R}^2$	0.866	0.890	0.928	0.776	0.780	0.920	0.398	0.508	0.502
S.E.E.	0.472	0.470	0.380	0.759	0.761	0.457	0.660	0.664	0.669
Observations	191	110	112	94	92	92	111	68	68

[a]This variable is not in log levels because it often takes a zero value.

*Indicates significance at the 5 percent level.

**Indicates significance at the 1 percent level.

sample size, just two mini models in 1966, two in 1967, one in 1973, and one in 1977. For mainframes, there are substantial jumps in 1967 (one model) and 1975 (two models). Below, in constructing the final price index, the estimated time dummy coefficients for mainframes are smoothed over the 1966–76 period, but this does not prove to be necessary for minis.

Columns 3 and 4 of table 6.5 display equations for the new model component of the Dulberger data set (which includes only mainframes, not minis) over the 1972–84 period. These results do not correspond to the equations estimated in Dulberger (1989), which covers both new and old models (132 new models and 164 old models). Column 3 omits Dulberger's technology-type variables for purposes of comparison with the Phister results, and column 4 reestimates the equation with the technology variables included. While the standard errors are not comparable, since the sample periods are different, they are of the same order of magnitude in the mainframe results (col. 2) and the two Dulberger equations. On a base 1972 = 100, the implied price index for 1979 in columns 2–4 is 12.6, 19.0, and 10.6, respectively.

6.5.3 The *Computerworld* Sample: Regression Results

The *Computerworld* sample is very large in comparison to the other data sets studied in this chapter. The number of new model observations is fifty per year, as contrasted with 9.6 for Chow, 5.1 for Dulberger, and 3.8 for Phister (all these calculations refer to individual models, not observations created by doubling and tripling, as in the Dulberger and Phister data sets). Compared to the Dulberger data set that overlaps its 1977–84 time period, it not only covers minis, superminis, and mainframes of noncompatible manufacturers, which are excluded from Dulberger's data set, but also it provides a much greater coverage of IBM and plug-compatible mainframes (191 new models over 1977–84 as contrasted with fifty-five for Dulberger), hereafter abbreviated I/PC. It also makes available additional variables (minimum and maximum channels and cache buffer size). Its main limitation, in addition to lacking the Dulberger technology variables, is that coverage of non-I/PC mainframes begins only in 1981 (plus two 1979 models), mini and supermini coverage begins only in 1979, and the MIPS measure of quality is available beginning only in 1981.

In table 6.6, the results are presented in three groups: I/PC mainframes, other mainframes, and minis. A pooled regression equation is not presented for the entire *Computerworld* data set, since aggregation tests indicate that these three subsets cannot be merged. Because the MIPS variable is not available before 1981, for each group results are displayed for an equation that omits MIPS from 1977–84, then one that omits MIPS for 1981–84, and finally an equation that includes MIPS from 1981–84. In every case, the third equation that includes MIPS indicates a more rapid rate of price decline between 1981 and 1984 than either equation omitting MIPS. The third equation also indicates a faster 1981–84 rate of price decline for other mainframes and minis for I/PC mainframes. The other main difference in the three groups is that the price decline for I/PC mainframes is smooth, while the other mainframes have a price jump in 1983. Columns 8 and 9 also display a smaller and statistically insignificant price jump for minis in 1983.

There are several interesting features of the estimated coefficients for the various quality characteristics. For I/PC mainframes, almost all the estimated coefficients are significant. The inclusion of MIPS in column 3 greatly improves the fit and reduces the coefficient on memory but still leaves room for a significant contribution of the minimum and maximum channels variables. Cache buffer size is significant when MIPS is omitted but insignificant in conjunction with MIPS. The IBM dummy is quite stable in the range of 0.24–0.34 and highly significant. The elasticity on MIPS is considerably lower than in the Dulberger data set results (table 6.5, cols. 3 and 4), probably because those results do not include any variables for the number of channels.

For other mainframes, the results including MIPS (col. 6) yield memory and MIPS coefficients very similar to the Dulberger data set results, and it is interesting that the inclusion of MIPS still leaves a significant role for cycle time. Interestingly, MIPS is not significant for minis. In light of the high standard error in this equation, it would appear that mini prices are largely explained by variables omitted from the data set.

6.6 The New Processor Price Index and Its Interpretation

6.6.1 Linking the Component Indexes

With the hedonic regression equations now estimated, there are only a few decisions required to develop a final index of computer processors. This section presents the basic results for indexes constructed from tables 6.2, 6.5, and 6.6 using the dummy variable technique. Indexes for the same equations are also developed using the imputation technique. Because the year-to-year changes are extremely similar when the two different methods are used, only the dummy variable indexes are presented in annual detail, while subsequently growth rates over multiyear intervals are presented for the imputation indexes.

The final processor price index and its ingredients are displayed in table 6.7. The first eight columns of table 6.7 exhibit the components. Because the aggregation test yielded an ambiguous conclusion regarding the feasibility of pooling the 1951–60 and 1960–69 regressions on the Phister data set, both the separate 1951–60 and 1960–69 results are included in columns 1–2 with the pooled 1951–69 results in column 3. Since aggregation tests reject the pooling of minis and mainframes in the post-1965 period, separate indexes are shown for these two components over 1965–79. This

Table 6.7 **The Final Price Index for Computer Processors, 1951–84 (1984 = 100; all indexes shown are based on the dummy variable method)**

	Phister Data Set (1965 = 100)					*Computerworld* (1984 = 100)			
	All Models			1965–79					
	1951–60 (1)	1960–69 (2)	1951–69 (3)	Minis (4)	Mainframes (5)	I/PC Mainframes (6)	Other Mainframes (7)	Minis (including supermini) (8)	Final Price Index (9)
1951	4,699	. . .	4,426	. . .	. . .	. . .	. . .	. . .	133,666
1954	1,255	. . .	1,028	. . .	. . .	. . .	. . .	. . .	33,293
1955	1,243	. . .	655	. . .	. . .	. . .	. . .	. . .	26,452
1956	no data	. . .	no data	. . .	. . .	. . .	. . .	. . .	25,373
1957	excluded	. . .	excluded	. . .	. . .	. . .	. . .	. . .	24,337
1958	939	. . .	675	. . .	. . .	. . .	. . .	. . .	23,344
1959	675	. . .	426	. . .	. . .	. . .	. . .	. . .	15,726
1960	611	611	371	. . .	. . .	. . .	. . .	. . .	13,948
1961	. . .	410	280	. . .	. . .	. . .	. . .	. . .	9,928
1962	. . .	374	272	. . .	. . .	. . .	. . .	. . .	9,349
1963	. . .	356	292	. . .	. . .	. . .	. . .	. . .	9,444
1964	. . .	246	193	. . .	. . .	. . .	. . .	. . .	5,992
1965	. . .	100	100	100	100	. . .	. . .	. . .	2,931
1966	. . .	57	73	136	34	. . .	. . .	. . .	1,583
1967	. . .	90	78	131	84	. . .	. . .	. . .	1,582
1968	. . .	excluded	excluded	excluded	no data	. . .	. . .	. . .	1,296
1969	. . .	28	30	no data	36	. . .	. . .	. . .	1,058
1970	. . .	. . .	. . .	45	no data	. . .	. . .	. . .	1,065

(continued)

Table 6.7 (continued)

	Phister Data Set (1965 = 100)					*Computerworld* (1984 = 100)			
	All Models			1965–79					
	1951–60 (1)	1960–69 (2)	1951–69 (3)	Minis (4)	Mainframes (5)	I/PC Mainframes (6)	Other Mainframes (7)	Minis (including supermini) (8)	Final Price Index (9)
1971	. . .	. . .	. . .	excluded	no data	. . .	. . .	. . .	1,084
1972	. . .	. . .	. . .	31	39	. . .	. . .	. . .	1,099
1973	. . .	. . .	. . .	33	23	. . .	. . .	. . .	846
1974	. . .	. . .	. . .	26	no data	. . .	. . .	. . .	831
1975	. . .	. . .	. . .	21	37	. . .	. . .	. . .	813
1976	. . .	. . .	. . .	10	23	. . .	. . .	. . .	606
1977	. . .	. . .	. . .	11	24	495	. . .	. . .	638
1978	. . .	. . .	. . .	no data	17	435	. . .	. . .	554
1979	. . .	. . .	. . .	7.6	4.8	342	1,102	466	439
1980	. . .	. . .	. . .	. . .	. . .	275	no data	286	307
1981	. . .	. . .	. . .	. . .	. . .	195	269	229	211
1982	. . .	. . .	. . .	. . .	. . .	154	58	91	138
1983	. . .	. . .	. . .	. . .	. . .	140	234	116	145

Sources by column: **(1–3)** Table 6.2, cols. 1–3. **(4–5)** Table 6.5., cols. 1–2. **(6–8)** Table 6.6, cols. 1, 4, and 7, linked in 1981 to cols. 3, 6, and 9. **(9)** 1977–84: Törnqvist index of cols. 6–8. 1965–77: Törnqvist index of cols. 4–5, with the mainframe index smoothed by taking an average of 1966–67 as the value for both years; an average of 1972–73 as the value for both years; and by omitting 1975. 1951–65: A geometric average of Törnqvist indexes of col. 1 linked to col. 2, and of col. 3.

Geometric interpolation is used to span any year where an index value is missing because of no data or excluded observations.

Source of weights for value share of mainframes and minis, table 6.1. Source of weights for value share of I/PC mainframes and other mainframes, *Computerworld*, various issues.

aggregation test result leads me to make no use at all of the equation estimated for the full Phister data set over 1969–79, as displayed in table 6.4. Columns 6–8 exhibit the *Computerworld* results. In each case, the indexes displayed for 1981–84 use the results with the significant MIPS variable included, and these are linked at 1981 to the 1977–84 equations that omit the MIPS variable.

The separate components are aggregated using the Törnqvist approximation to an ideal index number. This simply weights the logarithmic changes between year t and $t + 1$ of each component index by the average in t and $t + 1$ of the value shares of the components being combined. Then the string of weighted changes is cumulated starting with zero in the base year and converted into a price index by taking antilogs. In table 6.7 the final processor price index is presented with a base of 1984 = 100. For instance, with hypothetical 1983 index values for components A and B of ninety-eight and 150, and a value share for A in 1983 of .40 and in 1984 of .48, the weighted change would be

$$(0.44)[\log(100/98)] + (0.56)(\log[100/150)] = -0.218,$$

and the resulting 1983 index value would be 100[exp(0.218)] = 124.4.

Working backward from 1984, for 1979–84 the index combines the *Computerworld* indexes from columns 6–8 with value shares for I/PC mainframes, other mainframes, and minis (see source notes to table 6.7). For 1977–79, only the *Computerworld* I/PC mainframe index (col. 6) is used. An alternative would have been to weight this index with the Phister index for minis (col. 4), interpolated through the missing year 1978. By coincidence, the 1977/1979 ratio for these two indexes is identical (1.45), indicating that the alternative would have made no difference. More important is the fact that the choice of the *Computerworld* indexes after 1977 implies that no use is made of the Phister mainframe index for 1977–79, which has a drastically different 1977/1979 ratio of 5.0. This large discrepancy implies that the decision to omit the 1977–79 decline in the Phister mainframe index has an important effect on the final results. A close examination of actual and imputed prices for individual models has convinced me that the *Computerworld* results are more reliable because of their larger sample size and lesser dependence on particular unusual models. The excessive reliance of both the Phister and the Dulberger samples on a particular atypical model in 1979 causes both resulting indexes to overstate the rate of price decline during 1977–79 and to understate it during 1979–84.

The aggregation test results suggest that the separate Phister mini and mainframe indexes should be used as far back as possible, that is, from 1977 back to 1965. Note that the choice of the component indexes makes no use of the 1960–69 or 1951–69 results for all Phister models during the years

1966–69. Over the period 1951–65, the ambiguity of the aggregation test results suggests the use of an unweighted geometric average of separate Törnqvist indexes of the 1951–60 linked to the 1960–69 equation (cols. 1 and 2) and the pooled 1951–69 equation (col. 3).

6.6.2 The Price and Performance History of IBM Mainframes

The next section exhibits the annual percentage growth rates of the final processor price index over several basic multiyear intervals (e.g., 1954–60, 1960–65, etc.). While the overall growth rate of the final processor price index is in the same general range as other research, −19.4 percent per year, the pace of its decline is irregular, with rates of −22.1 percent in 1954–65, −12.7 percent in 1965–77, and −26.5 percent in 1977–84. The relatively slow rate of price decline observed between 1965 and 1977 conflicts with some other research, including some of that surveyed by Triplett (1989).

What would seem a hopeless task of reconciling conflicting results becomes a bit more feasible when one considers the dominant market share of IBM.[23] By comparing major IBM models of succeeding computer "generations," we can determine whether the evolution of the price-performance history of IBM models is consistent with the behavior of the final processor price index. This history is displayed in table 6.8. For each of thirty-seven different IBM models, plus the early ENIAC and UNIVAC I machines, data are shown on the memory, speed, the Knight "commercial index" of computation power, MIPS (since 1972), the actual system price with the memory configuration shown, and the imputed system price in the 1965 base year. The latter is calculated separately for each of the regression equations that serves as a component of the final index, and, if 1965 is not part of the sample period of that equation, the resulting imputed price is linked to 1965 at some common overlap period (see notes to table 6.8). The ratio of the actual to the imputed 1965 price is shown in column 8 as an index number (1965 = 100) and again in column 9 on the basis 1984 = 100.

6.6.3 Using the IBM History to Evaluate Index Discrepancies

We need to examine table 6.8 in conjunction with table 6.9, which converts all the relevant price indexes discussed thus far into annual percentage growth rates over key intervals divided in 1960, 1965, 1972, 1977, 1979, and 1981. The year 1960 was a dividing point within Chow's study; 1965 marks the end of Chow's study; 1972 the beginning of Dulberger's data; 1977 the beginning of the *Computerworld* data; and 1981 the year when the MIPS variable becomes available in the *Computerworld*

23. IBM's 360 line accounted for about 70 percent of mainframe revenue in the last half of the 1960s; IBM's overall share of world mainframe revenues in 1987 was 76 percent. See *Business Week*, 30 November 1987, 121.

Table 6.8 **The History of Price and Performance for Selected IBM Computer Processors**

Year	IBM Model (1)	Memory (kbytes) (2)	Memory Cycle Time (milliseconds) (3)	Knight Commercial Index (4)	MIPS (5)	Actual System Price ($000) (6)	Imputed 1965 Price ($000) (7)	Actual/Imputed (1965 = 100) (8)	Actual/Imputed (1984 = 100) (9)	Regression (10)
1946	[ENIAC]	. . .	. . .	0.04	. . .	. . .	. . .	47,753	1,095,252	A
1951	[UNIVAC I]	8	220	0.29	. . .	750	17	4,406	101,055	B,D
1954	650	10	2,400	0.27	. . .	174	19	998	22,890	B,D
1955	704	108	12	3.79	. . .	1,054	153	588	13,486	B,D
	705	30	17	2.09	. . .	608	62	864	19,817	B,D
1958	709	108	12	10.23	. . .	1,108	149	642	14,725	B,D
1959	7090	197	2.2	45.47	. . .	1,652	282	465	10,615	B,D
1960	7070	37	6.0	5.14	. . .	488	81	506	11,606	C,D
1961	1410	45	4.5	4.7	. . .	424	91	380	8,716	C,D
	7074	88	4.0	31.7	. . .	1,012	196	473	10,849	C,D
	7080	100	2.2	30.9	. . .	1,366	244	508	11,651	C,D
1962	7094	197	2.0	95.9	. . .	1,274	435	278	6,376	C,D
1963	7010	70	2.4	11.5	. . .	578	201	272	6,238	C,D
	7044	122	2.0	23.4	. . .	963	318	290	6,651	C,D
1965	360–20	10	3.6	4.5	. . .	41	49	81	1,858	E,D
	360–30	36	1.5	17.1	. . .	132	138	90	2,064	E,D
	360–40	136	2.5	50.1	. . .	340	500	82	1,881	F,D
	360–50	288	2.0	149	. . .	721	784	103	2,362	F,D
	360–65	1,088	0.75	810	. . .	2,458	2,255	115	2,638	F,D
1966	360–44	144	1.0	858	. . .	252	813	33	757	F
1972	370–135	304	0.94	172	0.16	472	1,123	42	963	F
	370–145	1,184	0.61	446	0.30	798	2,574	31	711	F
	370–155	1,152	0.12	1,203	0.55	1,553	5,355	29	665	F
	370–165	1,792	0.08	3,515	1.90	2,647	7,785	34	780	F

(continued)

Table 6.8 (continued)

Year	IBM Model (1)	Memory (kbytes) (2)	Memory Cycle Time (milliseconds) (3)	Knight Commercial Index (4)	MIPS (5)	Actual System Price ($000) (6)	Imputed 1965 Price ($000) (7)	Actual/Imputed (1965 = 100) (8)	Actual/Imputed (1984 = 100) (9)	Regression (10)
1973	370–125	176	0.48	70	0.08	266	1,209	22	505	F
1974	370–115	165	0.48	39	0.05	147	474	31	711	E
1975	370–158–3	3,328	0.12	2,423	0.83	2,593	8,643	30	688	F
1976	370–138	768	0.94	496	0.21	395	1,717	23	528	F
1977	370–148	1,000	0.23	1,014	0.42	687	3,440	20	459	G
1978	3031	2,000	0.12	2,317	1.05	831	6,812	12	280	G
	3032	2,000	0.08	6,921	2.50	1,905	13,004	15	336	G
	3033	6,000	0.06	19,019	5.90	3,613	15,757	23	526	G
1979	4341	2,000	0.12	1,863	0.72	247	3,555	6.9	160	G
1980	3081	16,000	0.03	. . .	10.40	3,723	56,927	6.5	150	G
1981	8140	1,000	0.80	. . .	0.36	81	780	9.2	211	G
	3033-M	16,000	0.06	. . .	9.10	2,678	2,880	4.1	93	G
1982	4321	1,000	0.90	. . .	0.19	85	1,284	6.7	153	G
1984	4361–5	2,000	0.10	. . .	1.14	201	4,518	4.4	102	G
	4381–2	4,000	0.07	. . .	2.70	499	11,560	4.4	99	G

Sources by column: **(2, 3, 6)** Phister data set 1951–76, *Computerworld* data set 1977–84. Cycle time linked by dividing *Computerworld* machine cycle time by 1,000; by this method, cycle times coincide exactly on five models that overlap the Phister and *Computerworld* data sets in 1977–79. **(4)** Phister data set. **(5)** Dulberger data set 1972–80, *Computerworld* data set 1981–84.(7) Obtained from predicted value of regression indicated in col. 10. Regressions C, D, and E all have 1965 base year. B is linked at 1960, F by the average of the five overlapping observations in 1977–79. **(8)** 100 times col. 6 divided by col. 7, except for 1954–65, for which is reported the average of imputed indexes from the regressions indicated in col. 10. **(9)** Col. 8 divided by 0.0436, which is the 1984 index number of a 1965 base implied by the average of the five overlapping observations in regressions E and F. **(10)** A: ENIAC linked to UNIVAC I with Knight's performance/price ratio (1966, table 6.1, col. 4 divided by col. 5). B: Phister 1951–60, table 6.2, col. 1. C: Phister 1960–69, table 6.2, col. 2. D: Phister 1951–69, table 6.2, col. 3. E: Phister minis 1965–79, table 6.5, col. 1. F: Phister mainframes 1965–79, table 6.5, col. 2. G: *Computerworld* IBM and plug compatibles, 1977–84, table 6.6, col. 1.

Table 6.9 **Comparison of Alternative Indexes for Computer Processors, Annual Percentage Growth Rates, Various Intervals, 1954–84**

	1954–60 (1)	1960–65 (2)	1965–72 (3)	1972–77 (4)	1977–79 (5)	1979–81 (6)	1981–84 (7)	1954–65 (8)	1972–84 (9)	1977–84 (10)	1954–84 (11)
Mainframes:											
1. Phister (51–60) (imputed)	−12.0 −7.2	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
2. Phister (60–69) (imputed)	. . .	−36.2 −32.6	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
3. Phister (51–69) (imputed)	−17.0 −15.1	−26.2 −26.8	. . .	. . .	. . .	. . .	. . .	−21.2 −20.4	. . .	. . .	. . .
4. Chow new-only (54–65) (imputed)	−19.0 −18.8	−23.0 −22.7	. . .	. . .	. . .	. . .	. . .	−20.8 −20.6	. . .	. . .	. . .
5. Phister mainframe (imputed)	. . .	. . .	−13.6 −13.5	−9.2 −9.7	−80.5 −81.1	. . .	. . .	. . .	. . .	. . .	. . .
6. Dulberger N-O (A) (imputed)	. . .	. . .	. . .	−11.4 −12.7	−54.5 −54.2	+0.5 +0.4	−23.3 −23.1	. . .	−19.6 −20.0	−25.4 −25.3	. . .
7. Dulberger N-O (B) (imputed)	. . .	. . .	. . .	−21.4 −22.1	−64.5 −64.7	+4.0 +4.9	−16.0 −15.5	. . .	−24.1 −23.7	−23.0 −23.1	. . .
8. *Computerworld* I/PC (imputed)	. . .	. . .	. . .	. . .	−18.5 −12.9	−28.0 −27.1	−22.3 −22.8	. . .	. . .	−22.9 −20.3	. . .
9. Linked mainframe (imputed)	−14.5 −11.2	−31.2 −29.7	−13.6 −13.5	−9.2 −9.7	−18.5 −12.9	−28.0 −27.1	−22.3 −22.8	−22.1 −19.6	−17.2 −15.9	−22.9 −20.3	−18.2 −16.7
10. IBM imputed mainframe	−11.3	−33.6	−13.8	−10.6	−53.2	−2.6	−14.0	−21.4	−17.2	−21.9	−17.9
Minis:											
11. Combined Phister and *Computerworld*	. . .	. . .	−16.7	−20.2	−20.0	−35.5	−27.6	. . .	−24.5	−27.7	. . .
Mainframes and minis:											
12. Final price index	−14.5	−31.2	−14.0	−10.9	−18.7	−36.6	−24.9	−22.1	−20.0	−26.5	−19.4

Sources by row: **(1–3)** Table 6.2, cols. 1–3. **(4)** Table 6.3, col. 6. **(5)** Table 6.5, col. 2. **(6–7)** Table 6.5, cols. 3–4. **(8)** Table 6.7, col. 6. **(9)** 1954–77 this table rows 1–3 and 5. 1977–84 this table row 8. **(10)** Table 6.8. **(11)** Table 6.5, col. 1, and table 6.7, col. 8.**(12)** Table 6.7, col. 9.

data. Also included is 1979, since this is the introduction date of the IBM 4300 series, which plays such an important role in explaining the divergent behavior of alternative indexes in the 1977–81 period.

The IBM price index in column 8 or 9 can be interpreted as an imputation index for a subset of the available data. In order to isolate the effects of the selection of particular IBM models as opposed to the effect of using the imputation technique itself, most of the indexes in table 6.9 are displayed as pairs; the index constructed by the dummy variable technique is shown as the top member of the pair, with the corresponding imputation index directly below. Comparing the growth rates of the IBM index in row 10 of table 6.9 with the mainframe component of the final processor price index in row 9 and with the results for the Chow and Dulberger new-only ("N-O") samples in rows 4, 6, and 7, we can isolate four main discrepancies that warrant discussion. These are the differing growth rates for the Chow and Phister samples within the 1954–65 period; the slow price decline of the final index during 1965–72, which differs from some of the results surveyed by Triplett; the slow price decline of the final index during 1972–77; and the differing time path of the price decline of the final index from the Dulberger results during 1977–84.

1954–65: Chow versus Phister

All the indexes for 1954–65 summarized in column 8 agree on a rate of price decline in the range of 20–22 percent per annum. Particularly remarkable is the close agreement over 1954–65 of the pooled Phister equation with the new-only component of the Chow sample (rows 3 and 4). A greater discrepancy occurs in the timing of price changes before and after 1960. The Phister sample registers a smaller price decrease before 1960 and a faster price decrease between 1960 and 1965. This is particularly pronounced in 1963–65, and more so for the separate regressions split at 1960 (rows 1 and 2) than the pooled regression (row 3).

The IBM history provides a clue as to the source of this phenomenon; for the IBM subset, the imputed price index shows a tendency to decline slowly during 1954–60 and more rapidly during 1960–65. Some intuition about this is provided by the Knight commercial index, which is not used in the regressions. Taking pairs of machines with roughly equivalent Knight indexes, we get an annual rate of decline of the price/performance ratio from 1955 (model 704) to 1961 (model 1410) of 19 percent, from 1959 (model 7090) to 1965 (model 360–40) of 28 percent, and from 1961 (model 1410) to 1965 (model 360–20) of 57 percent. The differing pattern for the Phister and Chow samples is largely due to the greater IBM share of the observations in the Phister sample (49 percent) than in the Chow sample (21 percent). Another indication that the Chow sample is less representative comes from its higher proportion of mini computers, which, as is evident in table 6.1, had negligible sales before 1965.[24] Particularly worth noting is the much higher representation in the Phister sample of the third-generation IBM 360 series in 1965 (fifteen of twenty-four observations) than in the Chow sample (five of sixteen observations, of which twelve are minis). This helps explain why the Phister indexes drop so fast between 1963 and 1965. Although the agreement between the two samples over 1954–65 is reassuring, an index weighted by market shares would show more similarity to the slow-fast pattern over the 1954–60 and 1960–65 subperiods evident in the Phister data than the more evenly paced tempo of Chow's price decline.

1965–72: Comparing the 360 and 370 Series

Timing of new-model introductions is uniform across data sets: the same five 360-series IBM models are introduced in the Chow and Phister data in 1965, and the same four 370-series models in the Dulberger and Phister data in 1972. Given the dominant market share of IBM and the miniscule value share of minis during this period, the price history of 1965–72 boils down to a single question. How much did the quality-corrected price of 370s decline relative to 360s? The imputed base-year prices (1965 = 100) for the 1972 370s in table 6.8 indicate an average 1972 price index of 34 percent. This is a far more modest price decline than in the evidence for 1965–72 surveyed by Triplett, which leads him to a 1972 index number of 15 (1989, table 6-A).

It seems inconceivable that anyone could compare the 1972 370 models and the 1965 360 models and conclude that a quality-corrected price index had declined from 100 to fifteen. In fact, it is hard to justify an index of thirty-four. Note, for instance, that the average Knight performance index for the 370–145 and 370–155 is 825, close to the 360–65 value of 810. Yet the ratio of the average 1972 price of the two 370 models to the 360–65 price in 1965 is 0.48. To use the information contained in the Knight index more systematically, an additional regression equation is estimated only for the thirty-six Phister model 360 and model 370 observations over 1965–74 with the speed variable replaced by the Knight index.[25] Because we are comparing like with like, the standard error is just 0.139, far lower than in any other equation estimated in this chapter. Both the memory and the

24. Chow's data provides monthly rentals and Phister's provides both monthly rental and purchase prices. As noted above, price tends to equal forty to sixty times monthly rental. Corresponding to the $250,000 dividing line between minis and mainframes would be about a $10,000 monthly rental. Fifty-seven percent of Chow's new-only observations are minis by this definition, vs. 36 percent of the Phister sample.

25. This use of the Knight index in preference to speed is an afterthought. If I were beginning this research again, I would have tested each equation to learn if the Knight index was superior to speed as an explanatory variable, or whether it and speed should enter together along with memory.

Knight index variables are highly significant, with respective coefficients of 0.44 and 0.40, and the price indexes (1965 = 100) are as follows:

	1966	1972	1973	1974
Dummy variable method	23	52	60	47
Imputation method	23	48	61	44

Thus, the use of the Knight index yields an even slower rate of price decline over 1965–72 than the basic Phister index for mainframes. The underpricing of the single 1966 model (360–44) stands out as well.[26] These results suggest that, far from understating the rate of price decline over 1965–72, the indexes in column 3 of table 6.9 may have overstated it.

1972–77: The Second-Generation 370s

The next discrepancy in table 6.9 occurs during 1972–77. The Phister mainframe index in row 5 agrees fairly well with price index (A) from the Dulberger new-only sample, registering a 9.2 percent annual rate of decline, compared to 11.4. But both indexes decline far more slowly than the 21.4 percent rate registered for price index (B), which is based on the same sample but adds the Dulberger technology variables. On the basis 1972 = 100, in 1977 the Phister price index is at sixty-one, the Dulberger (A) at fifty-seven, and the Dulberger (B) at thirty-four. Which rate of change is more plausible? Once again, turning to the IBM data in table 6.8, we note that the only new 1977 model is the model 370–148. This is the only new IBM model introduced in 1977 in either the Dulberger or the Phister sample.

To assess the rate of price change over 1972–77, we can compare the price-performance characteristics of the 370–148 with the similar-sized 370–155 in 1972. The Phister 1977/1972 ratio of actual prices for these two models is 0.48; the equivalent Dulberger ratio is an identical 0.48. The imputed quality ratio is 0.58 for Phister, 0.69 for Dulberger (A), and 2.56 for Dulberger (B).[27] The implied imputed price index, expressed as the actual ratio over the imputed quality ratio, is eighty-three for Phister, seventy for Dulberger (A), and nineteen for Dulberger (B). The Dulberger (B) result seems implausible. By every measure of quality listed in table 6.8, the 1977

26. Further support for the view that the IBM 360-44 was underpriced, and should not be given undue weight in the final processor price index, is provided in a letter from Franklin M. Fisher. According to Fisher, "the 360/44 was deliberately stripped-down to be a 'lean' machine. . . . Any study that didn't show the 360/44 as underpriced wouldn't be doing its job. Perhaps more important for your purposes, since we know that this was done off the pricing surface, it may be a mistake to use 360/44 observations in your sample. This is particularly true because the machine didn't sell very well."

27. Using the substitute equation that employs the Knight commercial index instead of speed, the Phister quality ratio is 0.87.

vintage 370–148 is inferior to the 1972 vintage 370–155: it has 87 percent of the memory, operates at half the speed, has 84 percent of the Knight performance index, and has 76 percent of the MIPS performance measure. The only reason the B result attributes such high quality to the 370–148 is the contribution of the technology variables—these alone imply that the 370–148 has 255 percent of the quality of the 370–155 simply because of the different materials used in the memories of the two machines (magnetic core vs. semiconductor). However useful the technology variables may be in explaining price differences of particular machines within a given year, they seem misleading in evaluating quality across a span of years.[28] Viewed from the standpoint of the user, who neither knows nor cares about chip technology but values quality characteristics like memory, cycle time, and MIPS, it seems implausible to argue that the 370–148 had a higher quality than the 370–155, much less 2.5 times the quality. Fully two-thirds of the contribution of the Dulberger technology variables to the implausible imputation of the 1972–77 price increase comes from the 1972 coefficient, which rates the 370–165 as having seven times the quality of the 370–135, as contrasted to twelve times the quality when the technology variable is omitted. Rather than concluding that the 370–165 and 370–155 were of low "quality" relative to their content of memory and MIPS, I prefer the alternative conclusion that the price-to-MIPS gradient was unusually flat in 1972, and that the Dulberger variable is standing as a proxy for an equally plausible MIPS-slope dummy in that year.[29] As is evident from the growth rates displayed in table 6.9, the implausible discrepancy between the A and the B results for the Dulberger sample applies only to 1972–77, and for 1977–84 both the A and the B indexes decline at about the same rate as the *Computerworld* index for mainframes.

1977–84: The Influence of the IBM 4341

Recall that the final processor price index is based on the *Computerworld* results from 1977 to 1984 and ignores the rapid rate of price decline exhibited by the Phister mainframe results in the overlapping years 1977–79. Overall, from 1977 to 1984, there is no conflict between the rate of change of the *Computerworld* and Dulberger price indexes, both A and B. The big difference is in timing within that interval: the Dulberger indexes fall at a fifty-five to sixty-five annual rate in 1977–79 and then rise in 1979–81

28. On this discussion, Franklin M. Fisher cautions that the 370/148 was a virtual memory machine, while the 370/155 was not.

29. The same evaluation applies to Dulberger's own results (1989), which differ from those here by including both old and new models. However, the Dulberger (1989) sample consists entirely of new models in 1972, and her estimate of the 1972 technology dummy of −0.55 is close to the estimate of −0.66 shown in table 6.5 above. It should be noted that the Dulberger sample for 1972, in addition to the four 370 models shown in table 6.8, also includes a model 2022. However, as a minicomputer priced at just $46,000 with maximum memory, the Phister results suggest that it should not be pooled with the much larger mainframes in her sample.

before resuming their decline. In complete contrast, the *Computerworld* mainframe index declines at a relatively constant rate over 1977–84, with if anything an acceleration after 1979.

This discrepancy is explained entirely by the small sample size of the Dulberger data set for new models, which contains only two new models in 1979. One of these is the IBM 4341, which is famous in the history of the computer industry for its low price in relation to performance, which suggested at the time to observers that IBM was adopting a newly aggressive marketing strategy.[30] The other model is a plug-compatible; both it and the IBM 4341 have an actual-to-imputed price ratio on a 1984 = 100 base of about 150, quite similar to the imputed ratio for the IBM 4341 in the *Computerworld* regression of 160. Quite simply, these two models introduced the price level of 1982–83 about three years early. But an index based only on these two models is misleading if other new models sold in 1979 were not similarly underpriced. The *Computerworld* sample contains not two but forty-two observations on new IBM and plug-compatible models introduced in 1979, having actual-to-imputed ratios on a 1984 base ranging from 111 to 644. The IBM models alone range from 160 to 474. Since the model 4341 was a relatively small mainframe, it is likely that other larger new machines with much less favorable prices had a substantial market share in 1979, suggesting that the *Computerworld* index is more reliable than the Dulberger A and B indexes. Gradually in the years after 1979, lower-priced machines are introduced into the *Computerworld* sample, so that over the entire period 1977–84 its rate of price decline is roughly the same as in the Dulberger sample. The heavy reliance of the Dulberger sample on the two unusual 1979 models explains the starkly different timing of price decline evident in table 6.9.

6.7 Peripherals and Weighting Issues

Table 6.7 has shown how the different indexes developed in this study are integrated to form the final index for computer processors displayed in its column 8. A computer processor is a "box" containing the central processor and its internal memory. The index of table 6.7 needs to be augmented by price indexes for the various peripherals that are essential to make a computer processor accessible to its users. Such a price index for computer systems would then be comparable to the index published by the BEA. Further, this index for computer systems could then be weighted together with the BEA price deflator for other products in the OCAM category of PDE. Thus, we construct a new deflator for OCAM machinery comparable in coverage to the one published in the NIPA. As in developing the index for processors, the method of weighting together the successive layers of indexes, from the computer box to OCAM, is the Törnqvist index formula.

30. See "IBM's New Models Jolt the Industry," *Business Week*, 12 February 1979, 42.

As suggested in the introduction to this chapter, differences among the alternative price indexes for computer processors that might be used in such an exercise are trivial compared to the major impact of alternative methods of weighting. A Törnqvist index has the triple advantage of maintaining year-to-year comparability, of being immune to distortions in weighting due to the choice of the base year, and of reflecting the continual shift in the importance of its components by using moving weights.

This chapter does not create new price indexes for peripherals similar to the one constructed for computer processors. To maintain consistency with the hedonic index for computer processors, I rely on the hedonic regression coefficients of the study by Cole et al. (1986, table 7). Their hedonic price indexes are available for three types of computer peripherals—disk drives, printers, and displays—but only over the 1972–84 interval. The source for the earlier years is the study by Flamm (1987, table A-3, p. 218), which covers four types of computer peripherals—moving-head disk files, line printers, card readers and punchers, and magnetic tape units. Flamm also displays weights for these four types of peripherals and for processors covering the period 1955–78. These weights are used throughout, with the 1955 weights extrapolated prior to 1955 and the 1978 weights after that year. Flamm's four series are linked to Cole's three series in 1972; to ascribe Flamm's four sets of weights to these three products priced by Cole, card readers and punchers were matched with displays, line printers with printers, and the weights of magnetic tape units and moving-head disk files were merged and applied to disk drives. Also, in order to match the time coverage of the peripherals index with the processor index, a price index for peripherals is created over the 1951–57 interval by backcasting, using the annual average growth rate of this index over 1957–65. The effect of this arbitrary choice on the final results is minimal, since Flamm's weight on peripherals in 1957 is only 11 percent (see table 6.10).

Results are displayed in table 6.10 and figure 6.1. The following summarizes the quantitative evidence of table 6.10 over selected intervals:

	Annual Percentage Rate of Change		
Alternative Deflators	1957–65	1965–72	1972–84
Computer processors	−26.5	−14.0	−20.0
Peripherals	−23.4	−17.5	−16.5
Difference: processor-peripherals	−3.1	3.5	−3.5
Computer systems	−24.3	−14.9	−18.5

Since the index for peripherals does not decelerate as much over 1965–72 as the processor index, inclusion of peripherals makes the final index for systems decline at a slightly slower rate than for processors over 1957–65 and 1972–84, but at a slightly faster rate over 1965–72.

Table 6.10 Components of and Final Index for Computer Systems, 1982 = 100

Year	Weight of Computers (1)	Index for Computers (2)	Weight of Peripherals (3)	Index for Peripherals (4)	Final Index for Computer Systems (5)
1951	89.11	96,859.42	10.89	21,863.93	56,208.97
1952	89.11	60,942.35	10.89	17,299.33	36,259.53
1953	89.11	38,343.92	10.89	13,687.69	23,390.46
1954	89.11	24,125.36	10.89	10,830.07	15,088.82
1955	84.08	19,168.12	15.92	8,569.04	11,982.96
1956	75.50	18,386.23	24.50	6,780.05	11,147.21
1957	69.00	17,635.51	31.00	5,364.56	10,199.54
1958	63.68	16,915.94	36.32	4,323.94	9,269.68
1959	58.71	11,395.65	41.29	3,649.38	6,777.39
1960	56.00	10,107.25	44.00	3,013.42	5,836.24
1961	56.44	7,194.20	43.56	2,152.32	4,160.46
1962	56.16	6,774.64	43.84	1,308.30	3,237.64
1963	52.50	6,843.48	47.50	961.47	2,844.75
1964	48.74	4,342.03	51.26	891.32	2,161.14
1965	45.23	2,123.91	54.77	824.03	1,464.99
1966	45.73	1,147.10	54.27	779.62	1,075.62
1967	50.75	1,146.38	49.25	694.86	1,010.20
1968	53.96	939.13	46.04	570.46	828.44
1969	55.94	766.67	44.06	482.57	687.48
1970	55.94	771.74	44.06	412.11	643.67
1971	54.23	785.51	45.77	313.32	576.12
1972	51.74	796.38	48.26	242.70	516.40
1973	51.24	613.04	48.76	243.52	451.75
1974	54.00	602.17	46.00	219.75	425.76
1975	58.00	589.13	42.00	194.99	398.25
1976	61.50	439.13	38.50	178.81	323.84
1977	64.00	462.32	36.00	135.63	300.51
1978	65.00	401.45	35.00	137.57	275.96
1979	65.00	318.12	35.00	108.56	218.35
1980	65.00	222.46	35.00	100.05	168.19
1981	65.00	152.90	35.00	98.07	130.89
1982	65.00	100.00	35.00	100.00	100.00
1983	65.00	105.07	35.00	41.52	75.92
1984	65.00	72.46	35.00	33.69	55.43

Sources by column: (1) Flamm (1987, p. 220), assumed to be constant after 1978. (2) Table 6.7, col. 9. (3) 1.0 minus col. 1. (4) 1951–72 Flamm (1987, table A-3, p. 218) linked to 1972–84 Cole et al. (1986, table 7). (5) Törnqvist index of cols. 1–4.

Figure 6.2 compares the new index for computer processors with Triplett's "best practice index" (1989, tables 13-A and 14). Except after 1976, there is a broad agreement in their time paths. As discussed earlier, Triplett's index behaves differently at this point partly because of two "outlier" models that were underpriced in 1979. Figure 6.3 compares the new index for computer systems with the BEA and Triplett indexes. The BEA index is based on actual information only in 1969 and assumes computer prices to be constant before that date; thus, comparisons are meaningful only beginning in 1969. Note that all three indexes exhibit

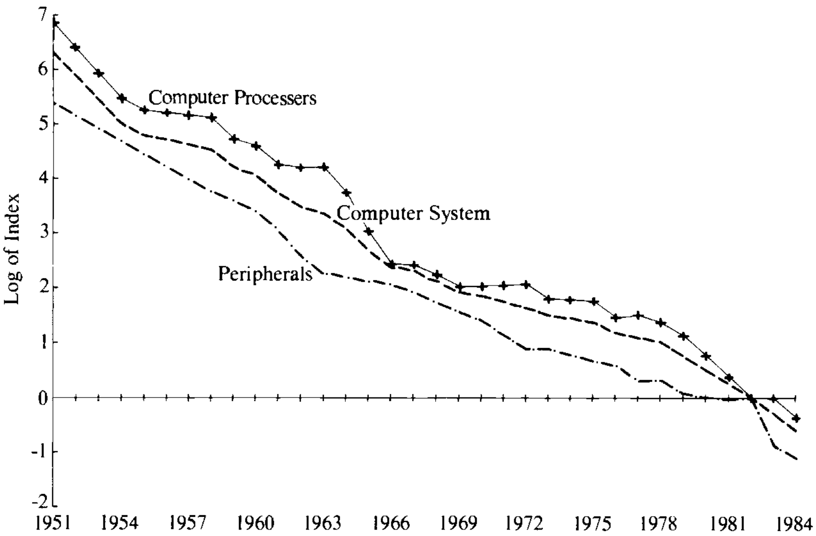

Fig. 6.1 Components of index for computer systems, 1982 = 100

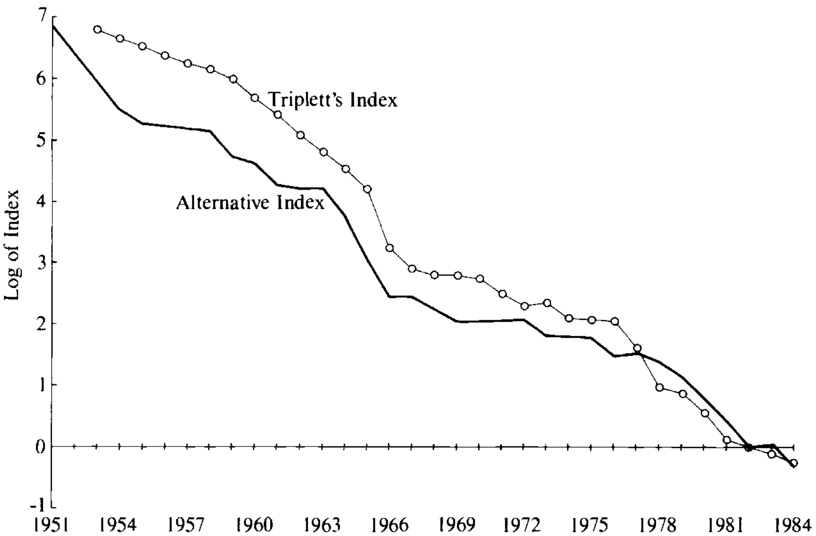

Fig. 6.2 Comparison of indexes for boxes

roughly the same rate of price decline during 1969–82, with the BEA and Triplett indexes sharing the feature of relatively more rapid decline until 1979 and the new index a relatively more rapid decline after 1979.

As shown above, the inclusion of peripherals makes the price index for systems decline somewhat more slowly than the price index for processors.

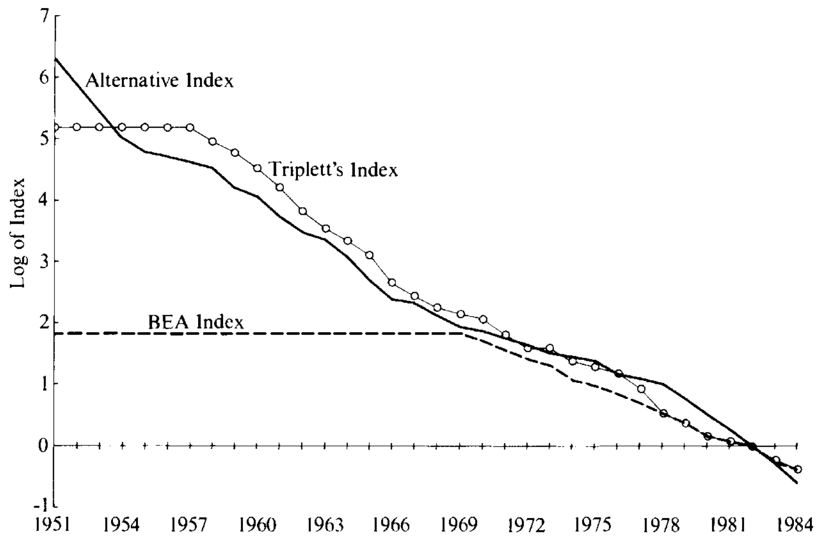

Fig. 6.3 Comparison of indexes for systems

But there are numerous dimensions of quality improvement that have been omitted and have the effect of making both the processor and the systems indexes understate the true rate of price decline (some of these factors may apply to peripherals as well). First, no allowance at all is made for the value of reduced repair, energy, and maintenance costs on computers. Chapter 7 finds for television sets that an allowance for the value of such cost savings increases the rate of price decline over the 1947–84 period from −4.4 to −6.9 percent per annum. I would be surprised if savings of a similar magnitude, say 2 percentage points per year, were not achieved on computer equipment. Any casual or anecdotal comparison of the energy, space, and maintenance requirements of the vacuum-tube processors of the 1950s with today's desktop PCs would reinforce this point.

Second, to the extent that price reductions were more rapid on mini and micro (i.e., PC-type) computers than on mainframes, a "true" price index for computer processors would decline more rapidly than the processor index developed here, which has no coverage of micro computers at all or of mini computers before 1977. As shown in section 6.8 below, a price index for personal computer (i.e., micro) processors has declined more rapidly over the 1981–87 period than the 1972–84 rate of decline of the IBM mainframe processor price index obtained by imputation in table 6.9.

Third, note from Table 6.1 above that the combined value of mini and micro sales had exceeded the value of mainframe sales by 1984. After 1966, the growth in the number of mainframe units purchased was very slow relative to the growth in the number of mini and micro units purchased.

Clearly, many computer users have found that the growing power of minis and micros allowed them to perform certain tasks at a lower cost than by continuing to rely on mainframes (any economist who in the past five years has shifted from mainframes to PCs will share this reaction). The price reduction implicit in this shift in mix is not taken into account in any of the indexes for computer processors developed in this chapter or in other studies.[31] A simple example dramatizes the importance of this point. In October 1987, one could buy for $5,718 a Compaq Deskpro 386 (20 MHz model) with a processing speed of 4.6 MIPS, a 1 MB memory, and a 130 MB disk drive.[32] This machine can be compared with the 1972 mean of Dulberger's sample: 0.59 MIPS, 0.79 MB memory, no disk drive, and a price of $1,143,640. The Compaq is superior in speed, memory, and disk drive, but lacks the multiple input-output channels and some of the multi-tasking capability that are the main distinguishing features of mainframe computers. If we call it a draw, we can calculate the annual rate of change of the price between the 1972 Dulberger mean and the 1987 Compaq price, −36.7 percent, as an indication of the enormous understatement of the decline in computer prices inherent in any index that ignores the shift from mainframes to minis, and from minis to micros.

The above three factors all were concerned with computer hardware. The presumption that processor price indexes understate the true rate of price decline is offset to some degree (although only over the 1969–79 decade) by the "unbundling" of computer operating software, discussed above. However, even if the cost of "free" operating software before 1969 amounted to 10 percent of the value of the typical processor, which seems improbable, the unbundling issue could only create an overstatement of the rate of price decline of 1 percent per annum over the decade of the 1970s. The magnitude of the three sources of bias in the opposite direction is doubtless much greater than that.

6.7.1 Aggregating the Computer Index into a Deflator for OCAM

Table 6.11, column 5, displays the implicit BEA deflator for OCAM, calculated with the following formula:

$$P_t^{BEA} = (V_t^C + V_t^O)/(W_t^C + W_t^O), \tag{6.2}$$

where

$$W_t^C = V_t^C/P_t^C,\ W_t^O = V_t^O/P_t^O\ ,$$

31. Up to this point, this chapter contains results identical to those reported in Gordon (1989). From this point on, the rest of the chapter is new.

32. Price quote for Compaq 386–20 from ad for Computer Discount Software, *PC* magazine, 27 June 1989. MIPS for Compaq 386–20 taken from ad for Everex Computer Systems, *PC* magazine, 27 June 1989.

Table 6.11 Calculation of BEA Deflator for OCAM, 1982 = 100

Year	Weight of Computers (1)	Deflator for Computers (2)	Weight of Other OCAM (3)	Deflator for Other OCAM (4)	Implicit Deflator for OCAM (5)	Fixed Weight Deflator for OCAM (6)
1947	0.00	617.30	100.00	59.55	59.55	. . .
1948	0.00	617.30	100.00	54.14	54.14	. . .
1949	0.00	617.30	100.00	66.17	66.17	. . .
1950	0.00	617.30	100.00	59.55	59.55	. . .
1951	0.00	617.30	100.00	63.16	63.16	. . .
1952	0.00	617.30	100.00	63.16	63.16	. . .
1953	0.00	617.30	100.00	66.17	66.17	. . .
1954	0.00	617.30	100.00	66.17	66.17	. . .
1955	0.00	617.30	100.00	68.71	68.71	. . .
1956	0.00	617.30	100.00	72.78	72.78	. . .
1957	0.00	617.30	100.00	73.13	73.13	. . .
1958	0.06	617.30	99.94	72.81	73.13	. . .
1959	0.17	617.30	99.83	70.73	71.68	627.90
1960	1.74	617.30	98.26	73.23	82.71	627.90
1961	2.88	617.30	97.12	77.07	92.63	627.90
1962	3.93	617.30	96.07	70.70	92.16	627.80
1963	7.45	617.30	92.55	70.94	111.66	628.00
1964	9.47	617.30	90.53	72.49	124.06	628.00
1965	10.82	617.30	89.18	69.13	128.44	628.10
1966	11.94	617.30	88.06	68.21	133.77	628.20
1967	13.61	617.30	86.39	69.85	144.36	628.60
1968	14.22	617.30	85.78	65.97	144.36	628.70
1969	15.87	617.30	84.13	72.30	158.80	628.70
1970	21.50	552.10	78.50	74.50	177.20	552.90
1971	27.61	473.80	72.39	79.29	188.20	487.50
1972	32.51	408.10	67.49	77.98	185.30	430.40
1973	27.00	369.30	73.00	78.19	156.80	431.30
1974	28.26	291.10	71.74	80.34	139.90	382.30
1975	32.40	265.10	67.60	86.85	144.60	347.70
1976	36.50	231.10	63.50	86.37	139.20	323.30
1977	39.68	199.70	60.32	88.30	132.50	247.30
1978	48.88	169.30	51.12	90.66	129.10	159.80
1979	57.09	146.20	42.91	92.37	123.10	140.30
1980	64.34	117.50	35.66	94.79	109.40	115.80
1981	71.24	107.40	28.76	95.93	104.10	105.10
1982	72.20	100.00	27.80	100.00	100.00	100.00
1983	78.05	77.10	21.95	103.98	83.00	88.80
1984	80.70	68.50	19.30	98.03	74.20	78.60

Sources by column: (1) Provided by David Cartwright of BEA. (2) Cartwright (1986, table 1, col. 1). (3) 1.0 minus col. 1. (4) Solved out as residual, given values in cols. 1–3 and 5. (5) NIPA, row 4 in table 5.6 divided by row 4 in table 5.7. (6) NIPA, table 7.13, row 4.

and where each variable refers to the current time period (t), and the price indexes P are expressed with 1982 as base year. In (6.2), W is the real value of shipments in 1982 prices, V is the value of shipments in current dollars, the superscript BEA stands for the BEA's OCAM deflator, the superscript C stands for computers, and the superscript O stands for other products within OCAM. Implicit in this formula are "weights" of the form

$W_t^C/(W_t^C + W_t^O)$. These are the implicit weights of an implicit deflator calculation.

The components of this calculation are shown in table 6.11. The first column displays the implicit weights for computers. The fact that they are computed in 1982 prices means that the current value shipments of computers, V, are divided by larger and larger P^c prices as one proceeds back into the 1970s and 1960s. The BEA's own current-value weight for computer systems within OCAM is 26.3 percent for 1962, but the implicit weight is a mere 4 percent for that year, as reported in table 6.11. This illustrates the distortion in weighting that the implicit deflator conveys.

Another problem of any implicit deflator is that its methodology precludes making year-to-year price comparisons, since measures of price change are valid only between each year separately and the base year, but not between one year and another nonbase year. The implicit deflator in column 5 represents the level of the OCAM deflator, which is in fact calculated relative to 1982 separately for each year. This implies that, since the computer weight is zero for 1957, the change of the OCAM deflator from 1957 to 1982 is identical to that for other OCAM products, for example, typewriters. This is evident by comparing columns 4 and 5. Consequently, the price decline of computers between 1957 and 1982 has absolutely no impact on the recorded change of the OCAM deflator over that interval. For a year like 1968, when computers have a 14 percent implicit weight, the computer deflator of 617 is averaged together with the "other" deflator of sixty-six, to yield an OCAM deflator of 144. One hundred forty-four is two times higher than the deflator for 1957, although the index for "other" declines over the 1957–68 period, while the index for computers remains constant. Figure 6.4 displays this phenomenon vividly and illustrates how the implicit deflator is pulled up by the level of the computer processor index as the weight of processors increases in systems. The implicit deflator distorts the information contained in its subcomponents, because it fails to cumulate them in a meaningful way, by cumulating the levels instead of the growth rates.

Because the implicit deflator methodology treats separately each year relative to 1982, year-to-year changes of the OCAM implicit deflator have no interpretation. This characteristic of the implicit deflator methodology is allegedly well known, and yet the only data for real OCAM investment produced by the BEA are based on the same OCAM implicit deflator, in the sense that the ratio of nominal OCAM expenditures to real OCAM expenditures equals by definition the OCAM implicit deflator.[33] It should be

33. The "well known" claim comes in correspondence with Jack Triplett. In my younger days, the implicit deflator was the only GNP concept of inflation, and we were aware that its quarter-to-quarter rate of change could be distorted by mix effects, but according to Triplett neither the BEA nor the press should ever have published quarter-to-quarter changes of the implicit deflator. Yet, to this day, the quarterly GNP report published in the *New York Times* contains the most recent quarterly change in both the fixed-weight and implicit deflators.

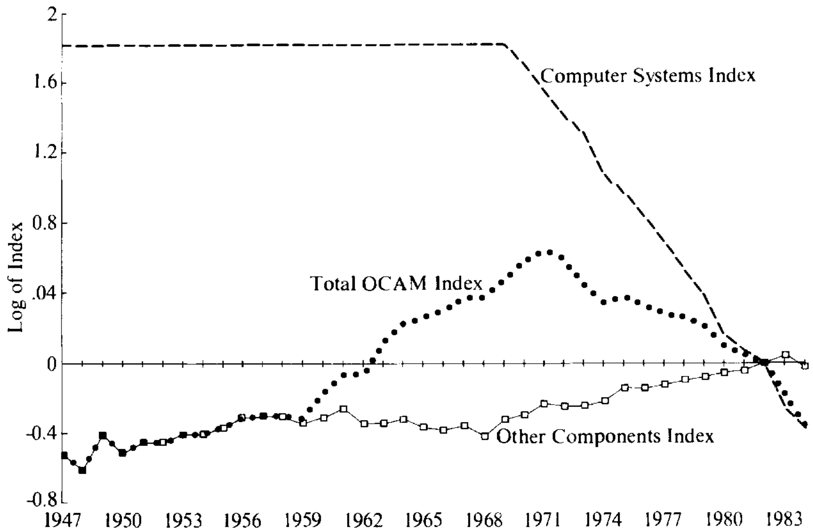

Fig. 6.4 BEA components for OCAM index

emphasized that the implicit deflator is only one of two price indexes for OCAM published by the BEA. Table 7.13 of the NIPA publishes a fixed-weight index for OCAM that, as shown in the right-hand column of table 6.11, and again in figure 6.5, displays a monotonic decline between 1969 and 1984, in contrast to the hump-shaped pattern of the implicit deflator. I emphasize the pitfalls of the implicit deflator methodology in this section for two reasons. First, the implicit deflator for OCAM was the only deflator displayed by Cartwright (1986, table 1, col. 2, p. 8) and is referred to by him as "the" BEA deflator. Second, and more important, the implicit deflator by definition is used to convert nominal investment expenditures into real investment expenditures. The BEA produces no alternative series of real OCAM investment based on a fixed-weight or moving-weight (e.g., Törnqvist) deflator.[34]

The results of the alternative Törnqvist method of weighting are illustrated in table 6.12, column 5.[35] The formula, using the same notation as in equation (6.2) but expressing logarithmic growth rates with lower-case letters, is

34. The BEA has calculated PDE and other major components of GNP for the period 1982–88 in 1987 prices as an alternative to 1982 prices (see Young 1989a). However, 1987-base measures of real GNP are even less accurate for the period before 1982 than 1982-base measures.

35. The name *Törnqvist* for a moving-weight average of percentage growth rates is suggested by Ruist (1968). The spelling is suggested by his reference to the original article by Törnqvist (1937). Diewert (1976) shows that the Törnqvist index is a so-called superlative index number.

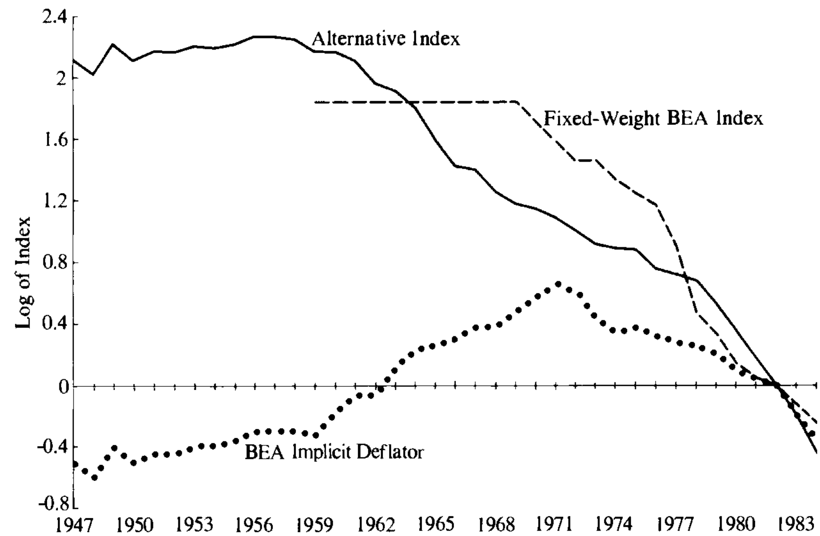

Fig. 6.5 Comparison of price indexes for OCAM

$$P_t^T = P_{t-1}^T \exp(p_t), \tag{6.3}$$

where

$$p_t = \sum_i [(V_t^i + V_{t-1}^i)/2] (\ln P_t^i - \ln P_{t-1}^i). \tag{6.4}$$

In words, this states that the Törnqvist index is a cumulative exponential index of growth rates, each of which aggregates the underlying subcomponent growth rates by a weighted average of the expenditure (or value of shipment) shares (V^i) in the two periods used to compute the growth rate between t and $t - 1$.

The value of shipments used to compute the V^i weights is the same as used by the BEA in equation (6.2) back to 1965 but differs before that date.[36] The resulting OCAM index falls relative to the BEA index, as shown in the comparison of the implicit BEA deflator in table 6.11 with the right-hand column of table 6.12. Two graphs are provided to summarize these results. Figure 6.4 displays the BEA indexes. It extracts from table 6.11 the BEA computer systems deflator (including peripherals), the BEA "other OCAM" deflator, and the BEA OCAM deflator that results using the implicit deflator weighting methodology as in equation (6.2). Note that the implicit OCAM

36. The BEA current-value weights are used from 1966 to 1984 (shown in their Törnqvist form in table 21). For 1951–65, I have created my own weights by taking the ratio of the value of U.S. computer shipments from Phister (1979) to total current-dollar OCAM, and linking that ratio to the BEA weight in 1966. This procedure results in a higher current-value weight on computers in the 1950s and early 1960s. For instance, my current-dollar weight for computers in OCAM in 1958 is 15 percent, as compared to the BEA's implausibly small value of 0.5 percent.

Table 6.12 New OCAM Index Combining Computer System Index from This Study with BEA Deflator for Other OCAM Weighted by Törnqvist Method, 1982 = 100

Year	Weight of Computers (1)	Index for Computers (2)	Weight of Other OCAM (3)	Deflator for Other OCAM (4)	Deflator for Total OCAM (5)
1947	0.00	56,208.97	100.00	59.55	827.88
1948	0.00	56,208.97	100.00	54.14	752.67
1949	0.00	56,208.97	100.00	66.17	919.92
1950	0.57	56,208.97	99.44	59.55	827.88
1951	1.41	56,208.97	98.59	63.16	877.78
1952	2.11	36,259.53	97.89	63.16	872.37
1953	2.95	23,390.46	97.05	66.17	904.64
1954	3.78	15,088.82	96.23	66.17	893.02
1955	5.80	11,982.96	94.20	68.71	917.96
1956	8.35	11,147.21	91.65	72.78	965.04
1957	12.07	10,199.54	87.94	73.13	962.13
1958	17.84	9,269.68	82.16	72.81	947.43
1959	21.32	6,777.39	78.69	70.73	874.88
1960	27.61	5,836.24	72.39	73.23	870.92
1961	39.21	4,160.46	60.79	77.07	823.12
1962	42.00	3,237.64	58.01	70.70	707.92
1963	42.46	2,844.75	57.54	70.94	671.81
1964	47.80	2,161.14	52.20	72.49	605.29
1965	52.38	1,464.99	47.62	69.13	490.34
1966	56.65	1,075.62	43.35	68.21	414.44
1967	59.50	1,010.20	40.50	69.85	404.10
1968	61.25	828.44	38.75	65.97	350.90
1969	64.35	687.48	35.65	72.30	324.33
1970	68.25	643.67	31.75	74.50	314.21
1971	70.55	576.12	29.45	79.29	297.14
1972	67.60	516.40	32.40	77.98	273.71
1973	61.20	451.75	38.80	78.19	250.27
1974	59.10	425.76	40.90	80.34	243.91
1975	60.00	398.25	40.00	86.85	242.06
1976	60.20	323.84	39.80	86.37	213.34
1977	61.95	300.51	38.05	88.30	205.75
1978	65.95	275.96	34.05	90.66	197.13
1979	68.45	218.35	31.55	92.37	170.01
1980	71.30	168.19	28.70	94.79	143.36
1981	72.85	130.89	27.15	95.93	120.30
1982	72.35	100.00	27.65	100.00	100.00
1983	73.50	75.92	26.50	103.98	82.82
1984	73.50	55.43	26.50	98.03	64.70

Sources by column: (1) BEA weights are used for 1966–84. For 1951–65, weights are calculated by taking the ratio of the value of U.S. computer shipments from Phister (1979) to current-dollar OCAM, and linking that ratio to the BEA weight in 1966. (2) Table 6.10, col. 5. (3) 1.0 minus col. 1. (4) Table 6.11, col. 4. (5) Törnqvist index of cols. 1–4.

deflator rises relative to either of its components between 1958 and 1968. Figure 6.5 contrasts this implicit deflator from table 6.11 and figure 6.4 with the alternative Törnqvist index from table 6.10. Figure 6.5 also reports the NIPA fixed-weight index for OCAM. The following is a summary of the growth rates of the two alternative OCAM deflators over selected intervals:

	Annual Percentage Rate of Change		
Alternative Deflators	1947–57	1957–72	1972–84
BEA OCAM implicit (table 6.11)	2.08	6.39	−7.34
BEA OCAM fixed weight (table 6.11)	. . .	−2.49	−13.20
This study OCAM (table 6.10)	1.50	−8.38	−12.02
Difference: This study OCAM minus BEA implicit OCAM	−0.58	−14.77	−4.68

Thus, the difference between the new index for OCAM and the corresponding BEA index is negligible before 1957, and is much larger between 1957 and 1972 than after 1972. While it may be illegitimate to compare changes in the BEA implicit deflators for OCAM for intervals like 1957–72 that do not include the 1982 base year, there is no denying the fact that the features of the table listed above carry over to the only published NIPA measures of real investment in OCAM. For instance, shifting from the BEA implicit deflator to the Törnqvist deflator raises the annual growth rate of OCAM investment for 1957–72 from the BEA figure of 2.3 percent to the new figure of 16.8 percent; for 1972–84 the BEA figure of 24.2 percent is raised to 28.1 percent. Figure 6.6 compares the time patterns of these two series. Much of the discrepancy between the two paths occurs before 1971. The divergence is particularly striking and reflects less the choice of the index used for deflating nominal investment than the method used to construct this index. Figure 6.6 is therefore just an echo of figure 6.5.

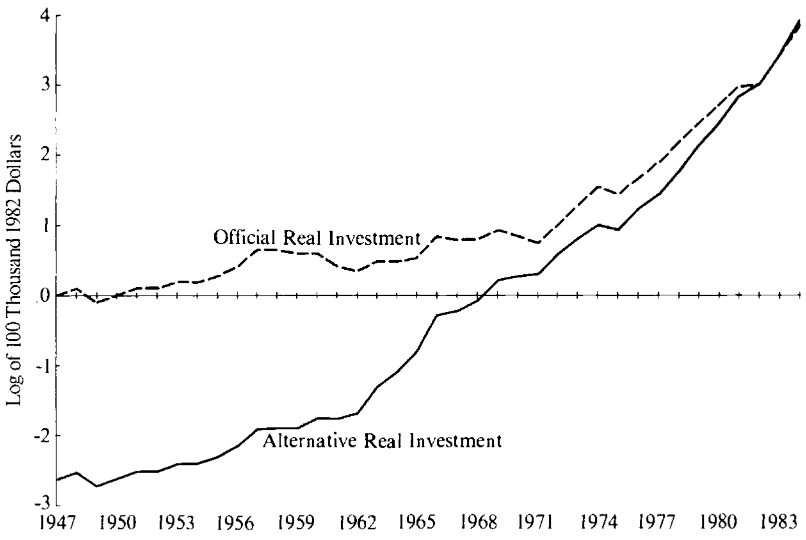

Fig. 6.6 Comparison of OCAM real PDE

6.8 Price Indexes for Personal Computers: A Pilot Study

There are few people in the academic profession who have not observed the rapid descent in the prices of personal computers and peripherals in the 1980s. It would be very difficult to compile the data required for a hedonic price index of PC processors and peripherals, because the number of relevant quality characteristics is very large, and so a large sample would be necessary to obtain sensible coefficient estimates. However, a matched model index can be created from a much smaller sample of observations, and the results of such a "pilot study" are shown in table 6.13.

For 1981–84, the only information shown in the table is the price decline for an IBM PC equipped with a standard and fixed configuration. For price changes covering 1984–85, 1985–86, and 1986–87, I have access to issues of *PC* magazine for the fall period in each of the three years. As explained in the notes to table 6.13, price changes for 1984–87 were calculated from advertisements of mail-order firms for several of the most popular models of IBM and IBM-compatible processors and peripherals. Each change that is labeled "matched model" (MM) compares identical models and configurations. The "matched characteristics" (MC) comparisons allow the purchaser to switch from brand-name equipment to "clones" in the first year that such a choice is available. Obviously, the MC comparisons make no allowance for possible quality differences in brand names and clones in warranties, quality of instruction manuals, or other dimensions, and presumably the "true" price decrease as perceived by a purchaser lies somewhere in between the MM and MC indexes.

For processors, the resulting price decreases appear to be substantially more rapid than my computer processor index in table 6.7, with annual rates of price change between 1981 and 1987 of −26.4 percent for the MM index and −30.0 percent for the MC index, as compared with −21.3 percent for the table 6.7 processor index over the 1972–84 interval. An unweighted average of the MM indexes for printers (including the MC hard drive index) exhibits an annual rate of price change for 1984–87 of −26.1 percent, and this increases to −34.9 percent when the MC index for other peripherals is substituted for the MM index. In light of the issues discussed above about the conversion of processor indexes into indexes for processors plus peripherals, it is interesting to note the result that the rate of price decline for peripherals is of roughly the same order of magnitude as for processors. The next research task should be an attempt to collect analogous MM and MC measures of price change for years before 1984–85. For the period 1982–87, an alternative price index for IBM PCs developed at the BEA declines at an annual rate of 19.6 percent, somewhat slower than our evidence in table 6.13 (see Cartwright and Smith 1988, table 1).

Table 6.13 Price Changes for Personal Computers and Peripherals, 1982–87 (numbers of models indicated in parentheses)

	1982 (1)	1983 (2)	1984 (3)	1985 (4)	1986 (5)	1987 (6)
Processors:						
1. Matched model	−22.8(1)	−26.3(1)	−25.8(1)	−32.6(2)	−26.4 (6)	−24.4 (7)
2. Matched characteristics	. . .	. . .	. . .	. . .	−36.0 (6)	−36.7 (7)
Peripherals:						
3. Printers—matched model	. . .	. . .	. . .	−26.2(7)	−21.0(19)	−13.0 (16)
4. Hard drives—matched characteristics	. . .	. . .	. . .	−78.7(2)	−21.6 (6)	−30.6 (11)
5. Other—matched model	. . .	. . .	. . .	−11.0(5)	−12.3 (7)	−20.4 (7)
6. Other—matched characteristics	. . .	. . .	. . .	−45.1(5)	−23.2 (7)	−54.6 (6)

Sources by row: ("1985" refers to comparison of 1984 with 1985, etc. *Code: PC Magazine,* 1 September 1984, 26 November 1985, 28 October 1986, and 10 November 1987; ACP: ads for Arlington Computer Products; PCN: ads for PC Network; PCL: ads for PC's Limited; LS: ads for Logic Soft, all from the same issues.) (1) *1981–84: Business Week,* 25 March 1985, 29. Refers to IBM PC with 256K, 1 floppy drive, DOS, and monochrome monitor. *1985:* PCN: IBM basic unit with 256K and 2 floppy drives but no monitor, IBM-XT with 256K and no monitor. *1986:* PCN: IBM basic, IBM-XT, Compaq portable 20MB, Compaq Deskpro 20MB hard drive, IBM AT basic unit; ACP: IBM AT (512K, 20MB, monochrome). *1987:* PCL: Turbo with 20MB hard drive, 286–8 with 20MB hard drive, 268-12 with 40MB hard drive, all equipped with standard B&W monitor and graphics card; PCN: Compaq Deskpro 640K with 20MB hard drive; ACP: IBM AT with 30MB hard drive and monochrome with 1986 price comparison for same unit from LS, Compaq basic portable with 20MB hard drive, and Compaq 286 portable with 640K and 20MB hard drive. (2) *1986:* Replaces IBM basic and IBM-XT with PC Network Turbo, without and with 10MB hard drive. *1987:* Replaces Compaq Deskpro with PCL Turbo, and IBM AT with PCL 286–8. (3) *1985:* PCN: Epson FX-80 (FX-85 in 1985), LQ-1500, NEC 3530, 3550, Qume Spring, Texas Instruments 855, Toshiba P1351 (P351 in 1985). *1986:* PCN: Citizen MSP-10, MSP-15, MSP-25, NEC 2050, 3550, 8850, and Toshiba P351; LS: Citizen MSP-10, MSP-15, MSP-20, MSP-25, Juki 6100, 6300, Epson LQ-1500 (LQ-1000 in 1986), Okidata 182P, 192P, 193P, 2410P, and Toshiba P351. *1987:* ACP: Epson LQ-800, LQ-1000, IBM Proprinter, Proprinter XL; LS: HP Laserjet (500+ in 1986, 500+ series 2 in 1987), Epson LQ-800, LQ-1000, Okidata 182P, 2410P, Toshiba P351, Citizen MSP-10, MSP-15, Premier 35; PCN: Epson LQ-1000, Citizen MSP-10, Premier 35. (4) *1985:* PCN: Teac half height drive (pair), Cogito 10MB internal hard drive ("THE" clone in 1986). *1986:* PCN: Iomega Bournoulli Box, Clone 10MB internal, 20MB internal, 10MB tape, Maynard 20MB drive with 20MB tape (clone 20 + 20 in 1986), clone half height drive. *1987:* PCN: Clone 20MB internal and 20MB card; LS: Mountain 20MB and 30MB cards, Plus 20MB card, Seagate 20MB half and full height, 30MB half and full height, 40MB and 80MB full height. (5) *1985:* PCN: Hayes Smartmodem 1200B, AST 6 Pak, Hercules monochrome card, Amdek 310A monitor, and 10 DSDD diskettes. *1986:* PCN: Same as 1985 with addition of Hayes 2400 modem and Prometheus Promodem. *1987:* LS: Hayes Smartmodem 1200B and 2400B, each with Smartcom, AST 6 Pak Plus and 6 Pak Premium, Hercules monochrome card, Amdek 310A B&W monitor, 722 Color monitor. (6) *1985:* PCN: Replaces AST 6 Pak and Hercules monochrome card with clones. *1986:* PCN: Replaces Hayes Smartmodem 1200B with clone, continues with clones for AST 6 Pak and Hercules monochrome card. *1987:* LS: Replaces Hayes Smartmodem 2400B with clone and two Amdek monitors with clones, continues with clones for Hayes Smartmodem 1200B, AST 6 Pak, and Hercules monochrome card.

6.9 Conclusion

This chapter has developed a single price index for mainframe and mini computer processors over the entire history of the computer industry, extending from 1951 to 1984. The chapter shares with others the conclusion that computer processor prices have declined rapidly, at roughly a 20 percent annual rate. The unique contribution of this chapter is its consistency: the price index is based only on new models in their year of introduction. In contrast, other studies are based on a mixture of only new models (Knight 1966), mainly new models (Chow 1967), or a mixture with old models in the majority (Dulberger 1989). One would expect ex ante that the behavior of new-only and all-model indexes would be different: a new-only price index can exhibit a sharp decline when new technology is introduced, as in my index during 1963–66. An all-model index will introduce the effect of new technology more gradually, reflecting the influence of old models that remain in production. Both types of indexes are useful, a new-only index for indicating changes in the pace of technological change, and an all-model index for the purpose of deflating the nominal value of current computer production. But it is clear that the two types of indexes measure two different concepts, and they should not be compared or mixed across historical eras. This can easily lead to double counting a technological improvement if, for instance, an index for new-only models that incorporates a new generation of computers in year t is linked to an all-model index that incorporates the effect of the growing share of new-generation models in year $t + 1$.

The resulting "final" processor price index for new-only models in this chapter has the additional advantage that it is based on only two data sources, and the overlap between the two in 1977–79 has been handled to avoid double counting the technological improvement that occurred at that time. The plausibility of the final index has been checked against the price-performance history of major IBM mainframe models. Given the dominant market share of IBM in mainframe sales, this cross-check is extremely important to avoid placing undue weight on models having a low market share. The final index tracks an imputation index for IBM mainframes very closely except in the final interval, 1981–84, when the growing share of minis and the rapidly falling prices of minis lead to a somewhat faster decline for the final index than for IBM mainframe prices.

Section 6.6.3 above considered at length several discrepancies between the final results and the results implied by estimating similar equations on the new-only subset of the observations compiled by Chow for 1954–65 and Dulberger for 1972–84. For 1954–65 the final results and Chow's are similar for the period as a whole but differ in the timing of price decline before and after 1960, and the timing of the new index corresponds more closely to the evolution of IBM mainframe models reflecting the greater share of IBM mainframes and smaller share of minicomputers in the present sample than in Chow's. For 1972–77, the final results accord with Dulberger's new-only subsample as long as her technology variables are omitted; the technology variables yield an implausible relation between the quality of the major 1972 and 1977 IBM models and should be excluded in the calculation of price and quality indexes. For 1977–84, the final results are similar to those for the Dulberger new-only subsample but differ radically as to the pace within the period, a discrepancy attributed to the overweighting of two underpriced machines in the Dulberger sample in 1979. Finally, for the "mystery period" 1965–72 that spans the gap between the Chow and the Dulberger studies, the final index produces a result of relatively slow price decline that is confirmed by a detailed quality comparison of IBM 360 and 370 series models.

Proceeding from the price index for computer processors to the price index for systems, the index for computer peripherals is based on the hedonic results of Cole et al., and the nonhedonic results of Flamm for the pre-1972 period. Peripherals and processors are weighted together with a Törnqvist scheme. The annual rate of price change over the 1957–84 period for the "final" index of systems is −19.3 percent per year (col. 5 of table 6.10), which compares to the −20.4 percent for the price decline of processors. Over the same interval, this is slightly slower than the −20.6 percent rate of price change for Triplett's "best practice" index for systems, as developed in his survey based on the same data for peripherals (his tables 13-A and 14).

Several arguments developed in the text suggest that the rate of price decline developed in this study is in fact too slow. These include the failure in this or any study to allow for reductions in energy and maintenance costs; the possibility that mini and micro prices may have declined faster than mainframe prices before 1981; and, by far the most important, the fact that minis and micros provide "computation services" far more cheaply than mainframes. One suggestive example for the 1972–87 period indicates that the rate of price decline for users able to switch from a typical 1972 mainframe to a 1987 PC using a 386 chip would have enjoyed an annual rate of price decline of more than 35 percent, not the 20 or 21 percent that emerges from this study and Triplett's.

The final section of the chapter was concerned with aggregating the new price index for computer systems into a deflator for the OCAM component of PDE, using the Törnqvist index methodology that allows value-of-shipments weights to change each year. Possibly the most dramatic result in this study is not the rate of price decline in the price index for computer processors, which is of the same order of magnitude as in several other studies covering parts of the postwar period, but the finding that the BEA understates the growth rate of real OCAM investment at an annual rate of 14.8 percent during the period 1957–72. Primarily weighting issues also account for a 3.9 percentage point understatement in the growth rate of real OCAM investment in the more recent 1972–84 period.

When these alternative OCAM deflators are aggregated into deflators for all PDE, the differences are much more modest, amounting to about 0.75 percent for the period since 1957. When the Törnqvist index for OCAM is used in the calculation of total PDE, the 1957–72 BEA growth rate of real investment is raised from 4.45 to 5.20 percent; for 1972–84 the BEA figure of 4.33 percent is raised to 4.94 percent. There is little difference in the contribution of the new indexes to the PDE deflator for 1957–72 and 1972–84, since the growing weight of OCAM offsets the shrinking size of the difference between my OCAM deflator and that of the BEA. The fact that my implied PDE deflator registers about the same difference from the BEA deflator for PDE in 1957–72 as in 1972–84 suggests that the results of this chapter have few if any implications for the post-1972 slowdown in U.S. productivity growth, even though electronic computing machines are, among all the products studied in this book, the product with the most dramatic revisions of its price index.

Appendix

Data Sources

Phister 1979, table 2.11, pp. 338–57, continued p. 630 et seq.

Computerworld:
1977: 10 and 17 October, and two other issues.
1978: 16 January, 5 June, and one other issue.
1979: 8 January, 5 and 12 February, 16 July, and 5 November.
1980: 21 January, 17 March, 12 May, 28 July, 22 September, 20 October, 17 and 24 November, and one other issue.
1981: 13 July.
1982: 2 August.
1983: 8 August.
1984: 20 and 27 August, 3 September.

Omitted Observations in Phister Data Set

The following observations were omitted after the discovery that on the first round of the research they yielded actual to imputed prices more than 1.5 times the standard error of the relevant regression equation. Note that only a single IBM model is excluded. Numbers in parentheses are the ratios of actual to imputed prices for the mean memory configuration from the regressions listed in table 6.8, column 10.

1957: IBM 305 (2.11), Univac II (2.43).
1968: Burroughs 500 (2.66).
1969: Univac 1106 (1.93).
1971: NCR 50 (7.69).
1973: Cyber 76 (3.23), Univac 1110 (3.35).
1978: DEC VAX 780 (3.74).