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THE POSTWAR EVOLUTION
OF COMPUTER PRICES

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ABSTRACT

This study constructs new hedonic price indexes for electronic computers covering the period 1951-84. Regressions are estimated for four data sets, two used in previous studies by G. Chow and E. Dulberger, and two new data sets used for the first time in this study. Coverage is limited to mainframes until the late 1970s, but includes both "super-mini" computers and personal computers in the 1980s. The end result is a price index that exhibits a 1951 index number, on a base 1984 = 100, of 147,692, implying an annual rate of price change over the 33 years of -19.8 percent.

Price changes for personal computer (PC) processors during the 1982-86 period appear to have been similar to those for mainframe computers during the 1977-84 period, in the range of -20 to -25 percent per year. Evidence for PC peripheral equipment is limited to 1984-86 and indicates a faster rate of price decline than for processors, particularly if the increasing availability of "clones" is taken into account.

The paper places considerable emphasis on problems of weighting price indexes for computers together with price indexes for other types of "Office, Computing, and Accounting Machinery" (OCA) and other types of producers' durable equipment (PDE). The methodology used to construct the implicit price deflators in the National Income and Product Accounts, with a fixed 1982 base year, leads to a significant downward bias in the implicit OCA and PDE deflators after 1982, and an upward bias prior to 1982. A particularly disturbing aspect of the present national accounts is a spurious rise in the implicit OCA deflator of 157 percent between 1957 and 1971, despite the fact that its computer component exhibits a price decline and its non-computer component increases by only 8 percent. The paper recommends adoption of a chain-linked Laspeyres index number for any price index aggregate that includes computers. A properly weighted PDE deflator, using our computer price index, declines relative to the official implicit PDE deflator by 0.74 percent per year during 1957-72 and 0.87 percent per year during 1972-84.

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"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]

I. INTRODUCTION

It is now 35 years since the first delivery of the UNIVAC I electronic computer, and 32 years since the introduction of IBM's first electronic computer model.[3] It is well known that 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 that mainframes costing a million dollars or more in the 1950s.[4] Yet to this day, the Bureau of Labor Statistics (BLS) in its Producer Price Index (PPI) includes no price index for computers (either mainframe or personal), despite its inclusion of many hundreds of

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

[2] Forbes, December 22, 1980, p. 24, attributed to Computerworld magazine.

[3] The UNIVAC I was the first commercial electronic computer. The first deliveries to government agencies began in 1951 and the first sale to a commercial customer took place in 1954. In 1953 IBM offered its first machine, the IBM 701, and in late 1954 delivered the IBM 650, the first machine to be produced in quantity. See Sharpe (1969, p. 187). A further description of the UNIVAC I and the IBM 701 is included in Part II below.

[4] The implications of a price decline by a factor of 1,000 is startling to consider, for this would imply a 1954 price deflator of 100,000 on a base of 1982 = 100. Fisher, McGowan, and Greenwood (1983, p. 137) give examples of price declines along several dimensions by a hundred fold or more from the mid 1950s to late 1970s.

commodity indexes for less important types of mechanical and electrical machinery. And only in its December, 1985, benchmark revision did the Bureau of Economic Analysis (BEA) introduce a deflator for the computer component of producers' durable equipment (PDE) dating back to 1969, after more than two decades of publishing national income and product accounts (NIPA) based on the assumption that the prices of electronic computers remained fixed year after year.[5] The NIPA still assume that computer prices remained fixed before 1969.

This paper 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 four different data sets. Two of these are obtained from other authors (Chow 1967 and Dulberger 1987), allowing us to duplicate their results and explore the sensitivity of the implied hedonic price indexes to changes in specification. The other two data sources (Phister 1979 and Computerworld magazine) are studied for the first time in this paper.[6] Coverage is limited to mainframe computer processors until 1977, but since 1977 "supermini" computers are included as well. This is the first study of computers to cover such a long sample period.[7] No hedonic regression equations are developed for personal computers (PCs), but a preliminary matched-model index

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[5] 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).

[6] The BEA also uses Computerworld data to update its computer price index for years after 1984.

[7] The only other hedonic price index that covers both the 1950s and the late 1970s is based on a single regression equation containing a single computer attribute as an explanatory variable. This is the Knight (1983) index, as quoted by Alexander and Mitchell (1984, Table 9, p. 48). Triplett's (1987) survey paper summarizes results of other studies over our period but does not present new research results.

of price changes for PCs for the short 1982-86 interval is provided at the end of the paper.

Because our four data sets refer to differing time periods, the empirical section of the paper divides the postwar era into four sub-intervals, and our "final" hedonic price index uses differing data sources for each of the intervals. The original Chow data set is preferred for 1954-65, Phister for 1965-72, Dulberger for 1972-77, and a merged data set that combines the Dulberger and Computerworld data for 1977-84.[8] The end result is an index that exhibits a 1951 index number, on a base 1984 = 100, of 147,692, implying an annual rate of change over the 33 years of -19.8 percent.[9]

The desire for complete time coverage of the postwar period is partly dictated by a desire for consistency, since this paper is part of a larger research project that has compiled more than one hundred price indexes covering the 1947-83 period from data sources outside the BEA/BLS reporting system. 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 relationship (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 aggregate U. S. economy slowed in the 1980s to something between zero (Denison, 1985) and 1.0 percent (Gordon, 1984)? Any contribution of the possible

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[8] The index is extended back from 1954 to 1951 by using the Phister data set.

[9] 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 55,370, for an annual rate of change over 30 years of -19.0 percent. These indexes are presented in Table 18 below on a base of 1982 = 100.

mismeasurement of PDE deflators to the productivity slowdown puzzle requires not just the identification of a price measurement bias, but rather depends on identifying either a change in the bias and/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 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 paper begins with three sections providing background material. Part II 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. Part III briefly treats the theoretical issues that pertain to the deflation of expenditures on computers, while Part IV 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.

Part V provides an introduction to our four data sets and includes tables that exhibit the mean values of price and quality characteristics over the years. Part VI discusses the hedonic regression estimates and the issues involved in choosing one equation in preference to another. Part VII discusses weighting issues involved in converting a price index for computers into a deflator for the "Office, Computing, and Accounting" (OCA) component 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 OCA and PDE. The Paasche index number formula used by the

BEA to compute implicit deflators of PDE and its components convert a -13.1 percent annual rate of change in the BEA electronic computer index between 1969 and 1982 into a mere -3.5 percent annual rate of change in the OCA deflator over the same period.[10] By using weights based on output measured in constant 1982 dollars, the Paasche weighting method essentially treats the computer industry as non-existent before 1970, even though the current-dollar weight for computers in OCA is 41 percent as early as 1963.

The same index number problem also distorts the postwar evolution of the implicit OCA deflator. For the period 1957-82, the rate of change of the BEA implicit deflator for OCA is positive and is identical to the rate of change of non-computer products in OCA; the Paasche implicit deflator methodology causes BEA's own measured price decline for computers to be totally ignored. For the period 1957-71, we find the even more startling phenomenon that the deflator for the computer component of OCA, which declines by 29 percent, and the non-computer component, which rises by just 8 percent, are aggregated into an implicit OCA deflator that exhibits an increase of 157 percent! After all the ink that has been spilled over conceptual debates and hedonic methodology in this field, it seems highly ironic that issues in index-number weighting procedures are overwhelmingly the most important source of differences between the BEA implicit deflator for OCA and the alternative deflator developed in this paper.[11]

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[10] These rates of change are computed from an unpublished BEA worksheet dated July 30, 1986, which provides the calculation of the total 1969 OCA deflator and of its computer and non-computer components.

[11] The statements in this paragraph refer to the BEA's implicit deflator for OCA, not to the fixed-weight OCA deflator published in NIPA Table 7.13. However, only the implicit deflator was exhibited or discussed by Cartwright (1986), and by definition any index-number problem involved in the construction of the implicit OCA deflator applies by definition to the behavior of real OCA

There are a number of studies that have created price indexes that may be compared to ours, including Knight (1983), Chow (1967) as extended by Miller (1980), Archibald and Reece (1979), Cole et. al. (1986), and Dulberger (1987). 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-Nicoletti, 1974; Ratchford-Ford, 1976; Stoneman, 1978; Brock, 1979; Michaels, 1979; Fisher-McGowan-Greenwood, 1983). Other studies of technological change (Alexander-Mitchell, 1984; Bresnahan, 1985) and of functional form (Horsley-Swann, 1983) have used the previous hedonic studies by Chow and/or Knight rather than producing their own. To limit its scope, this paper provides only a selected comparison of our results with the previous literature, and for a complete survey defers to Triplett's companion paper in this volume (1987), which discusses some of the papers listed here and others as well.

II. 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 55,000 to 100 over a span of 30 years is probably unprecedented in economic history (although changes in the opposite direction from 100 to 55,000 over shorter periods have occurred in hyperinflations). A bit of intuition to support these startling

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investment. The absence of any influence of the computer on the 1957-82 change in the OCA deflator implies that price changes for computers are ignored in calculating the change of OCA real investment between 1957 and 1982 (NIPA Table 5.7).

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, 10 feet high, and 3 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.[12]

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 our hedonic regression sample from the Phister (1979) data source.[13] IBM's first machine was the model 701, initially installed in 1953, and this machine was both the first machine with a random-access memory (1,024 bits) and the earliest machine designed to fit into detachable boxes that allowed for multiple assembly-line manufacture rather than construction on-site in the customer's computer room. However, the real "model T" of the computer industry was the IBM 650, first introduced in 1954, of which 1,800 were eventually produced. The IBM 701 appears in the Chow data set used in our hedonic regression equations below (albeit miscoded with a 1954 vintage rather than 1953), and the IBM 650 appears

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[12] This section is based on Cole et. al. (1986), the conference draft of Dulberger (1987), Einstein-Franklin (1986), and Fisher, McKie, and Mancke (1983).

[13] 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.

in both the Chow and Phister data sets.

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 transitors, 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 Dulberger data sample for the period since 1972 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 1 to 64 kilobits per chip.

The evolution of the computer industry is quantified in Table 1, which displays domestic purchases (i.e., including imports and excluding exports) for mainframes, minicomputers, and micros (mainly PCs in the 1980s). Both numbers of units and the value of shipments are exhibited for each group.[14] 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

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[14] The source for Table 1 defines the breakpoint between micros and minis at $20,000 per units and between minis and mainframes at $250,000. Nevertheless our Phister data set does not distinguish between minis and mainframes, including numerous machines with prices below $250,000.

Table 1

U.S. Domestic Purchases of Electronic Computers, 1955-84

(Value in millions of dollars)

	Mainframes		Minis		Micros		Total	
	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	1150	475					1150	475
1960	1790	590					1790	590
1961	2700	880					2700	880
1962	3470	1090					3470	1090
1963	4200	1300					4200	1300
1964	5600	1670					5600	1670
1965	5350	1770	250	29			5610	1799
1966	7250	2640	385	40			7635	2680
1967	11200	3900	720	69			11920	3968
1968	9100	4800	1080	100			10180	4900
1969	6000	4150	1770	152			7770	4302
1970	5700	3600	2620	210			8320	3810
1971	7600	3900	2800	218			10400	4118
1972	10700	5000	3610	271			14310	5271
1973	14000	5400	5270	369			19270	5769
1974	8600	6200	8880	577			17480	6777
1975	6700	5410	11670	642	5100	77	23470	6128
1976	6750	5580	17000	816	25800	374	49550	6770
1977	8900	6600	24550	1203	58500	761	91950	8563
1978	7500	7590	29550	1596	115600	1098	152650	10284
1979	7200	7330	35130	2038	160000	1488	202330	10856
1980	9900	8840	41450	2487	250500	2104	301850	13431
1981	10700	9540	44100	2699	385100	2503	439900	14842
1982	10600	10300	47820	2821	735000	4190	793420	17311
1983	9985	10480	45420	3330	1260000	5300	1315405	19110
1984	10700	10360	72130	4185	2100000	7750	2182005	22295

Source: 1960-84: Einstein and Franklin (1986), Table 1.
1955-59: Phister (1979), Table II.1.21.

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 1, we stress the importance of the shift from mainframes to minis and micros; the 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. It is interesting to note that BEA weighting procedures treat the mainframe computer industry as essentially non-existent before 1969, yet Table 1 demonstrates that by that year mainframe shipments had reached almost half of their 1984 value.

In addition to mainframes, this study covers so-called "super-minis", at least for the period since 1977, and it collects evidence on the rate of price decline of PCs in the final section. Offsetting this aspect of coverage is the absence of coverage of peripherals, for which hedonic regression equations are estimated in Cole et. al. and included in the new BEA deflator. We discuss differences in the rate of price change for central processors and peripherals in our section on weighting issues.

How important are computer shipments in the context of the aggregate economy? Total 1984 shipments of $22.3 billion in Table 1 (which excludes peripherals) correspond roughly to the preliminary BEA estimate for domestic computer purchases of $25.7 billion (including peripherals), which has lately been revised upward to $31.1 billion.[15] Of this, $28.3 billion is PDE, making up 72 percent of the OCA category of PDE ($39.1 billion),[16] and 10 percent of total PDE. Domestic computer purchases of $31.1 billion amount to just 0.8 percent of GNP. These figures are important for perspective on the results of this paper; the radical decline in the implicit deflator for computers and for the OCA component of PDE has a modest impact on the deflator for total PDE but only a minor effect on the overall GNP deflator. Even if the pre-1985 computer deflator had an upward bias of 20 percent per year, this would translate into only 0.16 percent per year for the GNP deflator. The importance of new computer price indexes lies not in a revision of indexes of overall inflation, but rather in such key indicators as the capital/output and investment/output ratio, as well as indexes of output and productivity in the durable manufacturing sector of the economy. The scope of this paper extends only to developing a new deflator for the OCA component of PDE; broader implications for measures of investment, capital, and output, are discussed in the my forthcoming book that combines these new computer indexes with indexes for many other products.

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[15] See Cartwright (1986), p. 10, Tables 1 and 2.

[16] This consists of the $32.9 billion in the 1986 NIPA benchmark revision from the NIPA May, 1986, tape plus the upward $5.4 billion revision reported in Cartwright (1986), p. 10, Table 2.

III. CONCEPTUAL ISSUES IN PRICE MEASUREMENT

"Matched Model" vs. Hedonic Regression Indexes

Several years ago a paper on the development of computer price indexes for use in the NIPA would have required a substantial conceptual section. This would have addressed the stated opposition of the BEA to the inclusion in the NIPA of computer price indexes based on the hedonic regression methodology. In the last few years, however, the BEA has dropped its previous conceptual objections to regression-based price indexes. Convergence has occurred to such an extent that there are no conceptual issues that separate the three papers on computers in this volume, nor the indexes developed here from those that are now included in the NIPA for the period since 1969. Any differences involve choices made in empirical implementation, and the critical issues of weighting involved in in aggregating a hedonic index for computer processors into a deflator for broader categories of investment and output. This section provides a summary of the distinction between "matched model" and hedonic price indexes and, for historical purposes provides a brief interpretation of the BEA's pre-1984 objections to the inclusion of hedonic price indexes for computers in the national accounts.

Triplett (1986) has provided an admirably 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 Consumer Price Index (CPI) and the Producers Price Index (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 (a) firms may sell old models at a discounted price but report list prices to the compiler of the price index or (b) 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.

The "Resource Cost" Criterion

Until as recently as 1983 (as expressed in Jaszi, 1971, and Department of Commerce, 1983), it was the position of the BEA that the declining prices of new computer models should not be taken into account in the NIPA.[17] For

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[17] To help date the change in position at the BEA, the 1983 draft of the U. S. Department of Commerce paper was not published the form cited here and is superseded by the work of Cole et. al. (1986) and Cartwright (1986).

Jaszi, the absence of a computer price deflator was not just an unfortunate omission necessitated by the failure of the BLS to produce a suitable commodity price index. Instead, Jaszi defended his agency's practice of setting the price deflator for computers equal to 1.00 by arguing that quality adjustments should not be made when an increase in computer performance relative to price was made possible by a technological innovation.

> Recognition that we try to implement [the principle that quality changes must be reflected in real cost increases] is relevant in connection with R. J. Gordon's criticism of our assumptions about the prices of electronic computers. He does not document his statement, but he may be referring to an article by G. C. Chow [1967]. The measurements presented in that article do not seem to be based on the principle to which OBE and most experts subscribe, viz, that quality improvements can be quantified only to the extent that they are accompanied by real cost increses. After extensive consultations with representatives of the computer industry, OBE came to the conclusion that the convention it adopted was a closer approximation of the underlying concept it sought to implement" (1971, p. 203).[18]

At the time he was writing, Jaszi was correct that the price of a given computer model tended to remain the same throughout its lifetime.[19] However,

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[18] This paragraph was a response to my criticism of the BEA (then the Office of Business Economics, or OBE) for the absence of a computer deflator. See Gordon (1971a).

[19] Sharpe (pp. 262-3) notes that while "the rental charged for older equipment should decrease over time in order to keep such equipment competitive . . . the facts are greatly at odds with this simple view. By and large the monthly rental charged for a given piece of equipment remains the same throughout the period over which it is offered for lease." Supporting this view

the basic issue is whether the NIPA deflator should take account of the sharp decline in price per unit of characteristics when a new model is introduced and the old model is no longer in production. A resolution of this issue revolves around the definition of the appropriate unit of measurement, and the crucial distinction between movements along cost functions and shifts in those functions.

Such cost functions are displayed in Figure 1, where the horizontal axis takes the appropriate unit of measurement of output to be the quality characteristic (e.g., memory and MIPS), not the computer "box", and the quantity of characteristics is designated y. The vertical axis represents the cost of production (V), and the two upward sloping schedules represent two alternative technologies for producing computer characteristics, with the schedule running through point A having the higher cost per unit of characteristics. For a given quantity of characteristics at any given level of technology, say λ_0 in Figure 1, an increase in the quantity of characteristics is "accompanied by real cost increases," as the Jaszi criterion requires. Thus there is no controversy about the desirability of making quality adjustments in price indexes when larger, more expensive computers replace smaller, less expensive computers at a given level of technology. But such cases are seldom observed, since more powerful computers are typically introduced without a price increase to signal the need for a traditional "resource-cost" adjustment. Instead, a computer manufaturer typically

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is the Chow data set summarized in Table 3 below, which shows absolutely no year-to-year change in rentals for identical machines which appear in his sample for more than one year. However, Cole et. al. (1986) display a matched-model index that exhibits a decline for most of the 1972-84 period. One reconciliation of this conflicting evidence is simply that rentals on old models remained fixed before 1970, but that the shift from leasing to direct sale allowed greater price flexibility on old models to occur in the 1970s and 1980s.

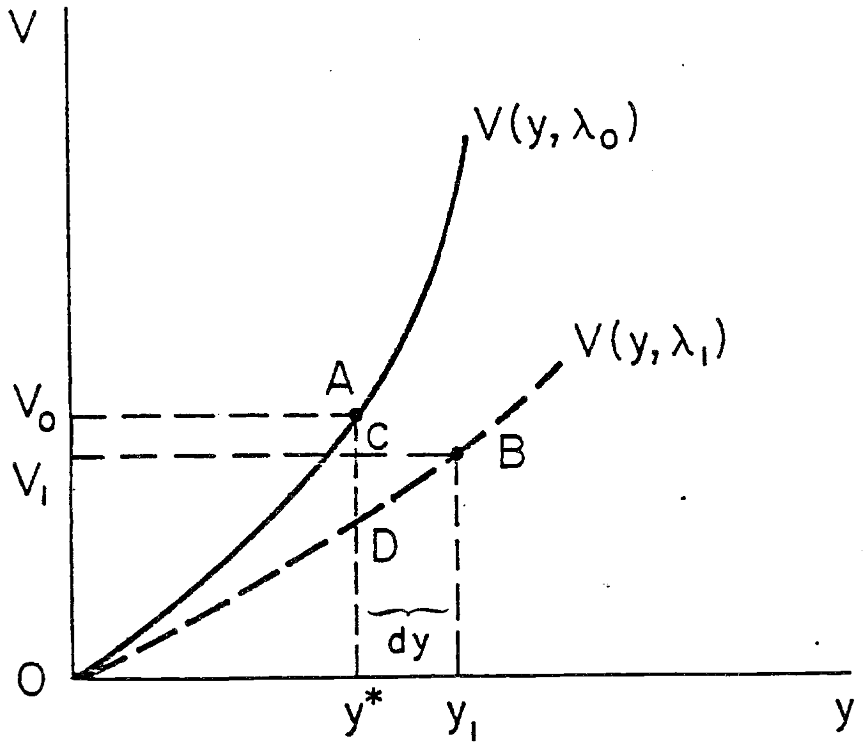

Figure 1

introduces a new model containing, say, twice as much memory or speed with little or no increase in the computer's price. The opposition to quality adjustments to price indexes for computers by Jaszi and other adherents of the "resource cost" criterion of quality change stemmed from a failure to recognize that the price per characteristic declines whenever there is a downward shift in the cost function, i.e., a shift from λ_0 to λ_1 in Figure 1.

A search of the literature reveals no convincing argument that a quality adjustment should not be made in the case of a declining price per characteristic, as in Figure 1.[20] Most adherents of the resource-cost approach refer back to Denison's famous (1957) article, but upon closer inspection Denison's basic argument against the characteristics approach is not based on logical principle. Indeed, he calls an approach which equates units of capital having the same number of characteristics "coherent and of extreme interest." Instead, he objects on grounds of infeasibility, that the characteristics approach "simply cannot be measured," but this pessimistic assessment was written before Griliches' (1961) paper that demonstrated the feasibility of the hedonic regression technique. In those cases where objective evidence is available on the appropriate unit of measurement to define the characteristic, there seems to be no case in the literature for ignoring downward shifts in the cost function generated by reductions in the cost of producing quality characteristics.

In Jaszi's defense, many participants in this debate believed that the hedonic regression technique represented a "user-value" criterion of quality change that was incompatible with the preferred "resource-cost" criterion, until

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[20] The details are given in Chaper 2 of The Measurement of Durable Goods Prices, pp. 2-21 through 2-32.

Rosen's important (1974) article showed that in principle the hedonic technique traced out a price-quality locus that represented a series of successive tangency points of indifference (user-value) and production possibility (resource-cost) curves. A full reconciliation of the user-value and resource-cost criteria, restated in terms of "characteristics space", was achieved by Triplett (1983), whose work formed the basis for my own alternative exposition in Gordon (1983).[21]

The preceding section attempts to clarify the context of the pre-1984 debate regarding the advisability of including hedonic price indexes for computers in the NIPA. Most observers, both outside and inside BEA, now believe that agency waited too long to introduce computer prices into the national accounts. However, the position taken by the BEA on the correct quality <u>criterion</u> had no influence on advance planning for the PPI and cannot explain the lack of development of a computer price index in the BLS price index program. Over the postwar period the BEA has acted as a user of price indexes developed by the BLS (both CPI and PPI components), but BEA attitudes about the issues discussed above have not fed backwards to determine how the BLS measured prices or what prices were measured.

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[21] As a historical footnote, the first draft of the theoretical chapter in my durable goods monograph, written in 1972, provided a graphical analysis like that of Figure 1, illustrating the downward shift in the cost function for computers, represented on a diagram plotting price per computer characteristic ("computation") against the quantity of characteristics. However, each of these cost functions was horizontal. Triplett's (1983) insight was to recognize that along any given production function, an increase in the quantity of computer characteristics was "resource-using", i.e., required an increase in cost, as along either "V" function in Figure 1. This showed that a given product could simultaneously exhibit "resource-using" quality change when moving along a single "V" function, but also a reduction in price per unit of quality when the "V" function shifted downwards.

It should also be emphasized, as at the beginning of Part III, that differences between the BEA and others on the desirability of including price indexes for computers in the NIPA are no longer relevant to the discussion of alternative price indexes for computers, or broader categories like OCA or PDE, since both the BEA and outside investigations (like this study) use hedonic regression equations to create price indexes for computers in roughly the same way. The major differences between the BEA price indexes for broader categories, like OCA and PDE, and our alternatives, involves the choice among traditional index number formulae rather than the theory of the price indexes themselves.[22]

III. THE HEDONIC REGRESSION MODEL

Basic Features

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. It assumes that the price of a product observed at a given time is a function of its quality characteristics, and it estimates the imputed prices of such characteristics by regressing the prices of different models of the product on their differing embodied quantities of characteristics. Thus the hedonic price approach does not represent a new concept in the measurement of quality change, but is an alternative to the manufacturers' cost

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[22] A discussion of the important distinctions between input and output indexes, and between the quality-adjustment criterion and the estimator actually used to adjust price indexes, appears in Triplett (1983) and Gordon's alternative exposition (1983) of Triplett's model. The first distinction is also treated in Triplett (1986).

estimates used for quality adjustment in most of the "matched-model" commodity price indexes compiled by the BLS for the PPI and CPI, to be used when practical factors make it more suitable.

A common approach to the estimation of quality-adjusted price change is to include time dummy variables (D_t) in cross-section regressions explaining price (p_{it}) for two or more years:

$$(1) \qquad \log p_{it} = \alpha_0 + \sum_{t=1}^{N} \delta_t D_t + \sum_{j=1}^{m} \beta_j \log y_{ijt} + u_{it}, \qquad (i = 1, \ldots, n;\ t = 0, \ldots, N)$$

Here again y is the quality characteristic, as in Figure 1. In equation (1) we choose a log-linear (or "double log", referring to the presence of logs on both sides of the equation) specification, following the majority of hedonic regression studies of computers. An alternative would be a semi-log specification, with the log of price of the left and the unlogged values of the y variables on the right. Other alternatives to (1) would be, first, to develop separate price indexes for the prices of the characteristics (β_j) or, second, to estimate the price of characteristics in a base year and then to use these estimated prices to compute the real quantity of characteristics in other years at base-year prices.[23]

Leaving aside these alternative methods, which are not used in this paper, and returning to equation (1), we can obtain an aggregate index of price change either from the series of δ_t coefficients obtained in a single regression for a number of years, or from a string of δ_t coefficients obtained

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[23] The first alternative method is carried out for computers in Cole et. al. (1986). The second alternative method is used by Chow (1967) for computers and by Triplett-McDonald (1977) for refrigerators.

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 latter adjacent-year technique allows the regression coefficients on the y_{ijt} to change frequently and is preferable. The disadvantage of the adjacent-year technique is that sample sizes are sometimes too small to make it feasible, and estimated coefficients on the quality characteristics jump erratically from year to year and may even change sign.[24] To the extent that the estimated implicit prices of characteristics (β_j) shift from year to year, the results of the adjacent-year regressions will differ from a pooled regression like (1) fit to the same time interval. In the implementation of the hedonic technique in this paper, our results are based on regression equations pooled over short sample periods determined by the availability of various data sets (1954-65, 1965-72, 1972-77, and 1977-84). However, we also experiment with estimates of both pooled and adjacent-year equations for our Phister data set over the period 1951-72.

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 may have a lower price than an older model containing the same

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[24] Chow's (1967) study displays erratically shifting coefficients in the adjacent-year regressions, indicating that his sample size was too small to make the adjacent-year technique feasible. The final Chow hedonic price index exhibited in that study and picked up by the subsequent literature is based on a pooled regression. Horsley and Swann (1983) also criticize Chow for erratic shifts in coefficients.

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 represents not just its own effect on price, but also that of the omitted variable(s). Thus the estimated β 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 (M_k) or "make effects." Make effects have been studied not just for computers but also for other products, including automobiles. In an adjacent-year regression, with a single time dummy (D_1) for the second year, make effects would enter as follows:

$$(2) \qquad \log p_{itk} = \alpha_0 + \delta_1 D_1 + \sum_{k=1}^{r} \mu_k M_k + \sum_{j=1}^{m} \beta_j \log y_{ijt} + u_{it}.$$
$$(i = 1, \ldots, n;\ k = 0, \ldots, r)$$

Many hedonic studies of electronic computers have been concerned not so much with the β or δ coefficients, but with the μ make effect coefficients, particularly in connection with the possibility that purchasers were willing to pay more for IBM machines as a result of better software, reputation, or other attributes not included in the $\underline{y}$ vector. We note that the specification (2) allows a make effect only to shift the constant term rather than to shift both the constant and the implicit prices (β) of the characteristics. An alternative to (2) would be to estimate separate regressions in format (1) for each separate make. Since our major emphasis is on changes in computer price indexes over time, our investigation of make effects is limited to the inclusion of IBM make-effect dummy variables for some of our regression equations.

Related to make effects is the question of commodity boundaries. In a sense our 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.[25] 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 include "superminis" in our post-1977 sample and ask whether they lie along the same hedonic function as mainframes; in principle it should be possible to treat personal computers in the same way if suitable data were available.

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."[26] Old inferior models do not just 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.

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[25] Fisher, McKie, and Mancke (1983, p. 3) report that the first electronic computer, the ENIAC, carried out calculations between 100 and 500 faster than punched card machines with electro-magnetic relays.

[26] Fisher, McGowan, Greenwood (1983, p. 149).

Functional Form

In the 1940s, Herbert R. Grosch asserted that for computer equipment average cost decreases substantially as size increases.[27] If we write the relationship between the price of a computer system (p) and its "effectiveness" (y = total characteristics embodied in the system), as follows,

$$(3) \qquad p = K y^{b}, \text{ or } \qquad \log p = \log K + b \log y,$$

where K is a constant, then "Grosch's Law" asserts that b = 1/2. A number of early studies of the cost-effectiveness relationship found that the validity of the Grosch "square-root" law depended on the measure of effectiveness. For instance, in one study the b coefficient was 0.26 for matrix inversion, 0.47 for statistical computations, and 0.70 for sorting. Greater economies of scale seemed to be available for scientific than for commercial computing.[28]

Perhaps because of the influence of the early literature on Grosch's Law, most of the hedonic studies of electronic computers have adopted the log-linear functional form. Knight added a term in the square of the log, but it added little explanatory power.[29] Others have chosen the semi-log form, including Archibald-Reece (1979) and Michaels (1979). The first draft of this paper provided estimates of both the log-linear and semi-log specifications and found that the former fits much better in both the Phister and Computerworld data sets. This finding confirms Dulberger's (1987) similar finding on her own data set. However, Dulberger has found that the sum of

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[27] Sharpe (1969, p. 315) states that Grosch did not publish this finding, but Bresnahan (1985) cites Grosch (1953).

[28] Sharpe (1969, pp. 316-22).

[29] Sharpe (1969, p. 339).

the coefficients on memory and speed (MIPS) in her data set sum to unity in the log-linear specification of (3), thus contradicting Grosch's Law predicting that b = 0.5.

V. THE DATA

<u>The Four Data Sources</u>

The results in this study are based on four overlapping data sources. For the years 1954-79 we have the compilation by 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 95 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 20 lines of information on prices and rental rates.

For the period 1977-84 our data source is <u>Computerworld</u> magazine, published by the International Data Corporation (IDC), which also publishes the bimonthly <u>EDP Industry Report</u>, the source of data in several earlier studies, including U. S. Department of Commerce (1983). We were attracted to <u>Computerworld</u> because of its annual hardware issue, which makes available all the required information in a single place for each year of the sample period. Later we discovered that the annual hardware issue began only in 1981, making an issue-by-issue search necessary for earlier years. It was possible to search only back to 1977 by the time the deadline for this paper approached.

As for the other two data sources, Gregory Chow provided the data used in his original 1967 article, and the BEA provided the data used by Ellen Dulberger (1987) and Cole et. al. for computer processors. In the following sections we describe the Phister and Computerworld data in some detail, since these are used here for the first time, and devote less attention to the Chow and Dulberger data, since these are described by those authors.

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 catalogues, 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.

The Phister data includes, 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. Since we did not know the typical memory configuration of each model, we took the apparently straightforward approach of transcribing just the system price. Later we discovered that several machines were priced at a zero level of memory, i.e., just including the processing unit. Fortunately information was given on the incremental price of memory, and so for each such machine we created three observations, corresponding to the price and characteristics of models configured with minimum, maximum, and mean memory sizes (each of the three would have an identical operating speed). 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.

Seven indexes of speed are provided by Phister, including memory cycle time and several different measures of addition and multiplication speed. Initially we included memory cycle time and multiplication speed, as did Chow (1967), but soon found that they are highly collinear in the Phister sample. Because the only overlapping speed variable available in the Computerworld data is memory cycle time, we omitted multiplication speed from the results presented in part VI of this paper, 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"[30] in the early 1960s, the weighting factors may be obsolete, and so we prefer to let the weights on memory and speed be freely estimated and do not include the Knight indexes as explanatory variables. However 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.[31]

The Computerworld Data

The Computerworld data set for 1977-84 includes several quality attributes not available from Phister, including minimum and maximum memory size, minimum and

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[30] Phister (1979), p. 358.

[31] Phister (1979), pp. 339, 359, and 631.

maximum number of input-output channels, and cache buffer size. 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.[32] Because these additional variables are available in the Computerworld sample but not in the Phister sample, we estimated separate equations for each sample and did not pool them.[33]

Other Data Sources

In addition to our new data from Phister and Computerworld, we have also obtained two other data sets, the original Chow data covering 1954-65 used in his article (1967), and the Dulberger (1987) data set covering IBM and compatible machines for 1972-84 (provided on a PC diskette by the BEA). The Chow data set is considerably larger than the Phister sample for the years of overlap, and we shall find that it gives more satisfactory results. We use the Dulberger data set as our primary source for 1972-77. After 1976 we have both the Dulberger and Computerworld samples, and we merge these to maximize sample size and coverage. In the merged sample the Dulberger source is used for all IBM machines, and Computerworld is used for all other machines. A defect of the merged sample is that we do not have Dulberger's technological class variables for computers other than IBM and plug-compatibles, and we do not have some of the special Computerworld variables (input-output channels, cache buffer size) for the IBM models. Thus our results for

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[32] Phister (1979), p. 524.

[33] Also available from Computerworld starting in 1980 is a dummy variable for the presence of "bus architecture." This was not included in our regressions due to its omission from the 1977-79 portion of the Computerworld data.

the merged sample do not use all of the available information in the separate samples.

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 but is the most carefully developed for the consistency of price and quality characteristics. The Phister data set is relatively small and leads to hedonic price indexes that display implausible year-to-year jumps. We use the Phister data mainly for the 1965-72 period, when we have no overlap from other data sets, and as a check on the secular rate of price decline for other periods.

Data Issues

•New Models vs. All Models. The Phister source has the great advantage that everything is in one place. The disadvantage is the limitation of the data to new models rather than all models sold in a given year, although our previous discussion pointed out that the computer market is characterized by perpetual disequilibrium, with manufacturers maintaining intact the original prices of equipment which has been made obsolescent by newer machines. For this reason, Fisher, McGowan, and Greenwood (1983) argue forcefully that a hedonic regression study should include only new models, a requirement satisfied by the Phister data at the cost of a relatively small sample size.

Because the Dulberger and Computerworld data include models introduced both in the current year and in previous years, it is possible to address the issue of the pricing behavior by manufacturers of older models. We have estimated regressions covering only models in their year of introduction, and in addition we have construct a BLS-type specification index of matched models, i.e., of price changes on models in each year of their production starting in the year after their introduction. We find, not surprisingly, that the price index for new models declines much faster than the index for matched models. As found by Cole et. al., the matched model index does not remain stationary but rather declines over time, at a rate slower than the price index for new models. Since our matched model index for the post-1972 period duplicates that of Cole et. al., we do not report it in this paper to save space.

However, we do explore the implications of the inconsistency created by the inclusion of both old and new models in the Dulberger and Computerworld data sets for the period since 1972, as contrasted to the inclusion of only new models in the Chow and Phister data sets that cover the earlier period (a few old models are included by Chow during 1954-59). Based on the evidence that before 1970 the rental rates of computers remained constant over their lifetime (see footnote 19 above), we construct an "augmented sample" for the Phister data which includes each model for four successive years at a constant price, in contrast to the "new-only" Phister sample that includes each model for just the year of introduction. The hedonic price indexes developed from the augmented Phister sample display rates of price change that are slower and smoother than those developed from the new-only Phister sample.

• Weighting by market shares. Ideally it would be desirable to run adjacent-year regressions for each pair of the 31 years in the full 1954-84 period and to weight each observation by market share in each year. However, the requisite market share data are not available from our 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. Our regression equations weight each 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 represents only about half of the observations in the Phister sample and only about 18 percent of the observations in the Computerworld sample. It is doubtful that this is a serious limitation, however, since the rate of price decline for 1977-84 is roughly the same for IBM products as for the full sample.

• Rental Rates vs. Purchase Prices. The dependent variable in all our regressions is the log of purchase price. How different would be the results 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 is falls within the range of 40 to 60 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 almost exactly the same results as those exhibited in Part V.

• 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), suggests that the rate of price decline was less than that for mainframe processing systems. Sufficient data exist in Phister's book to provide a price index for each major type of peripheral going back well before the 1972 starting date of Cole et. al., but this exercise is beyond the feasible research scope of the present paper.[34]

• Software. Our 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, our hardware prices

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[34] The study by Archibald-Reece (1979) is one of the few that includes prices and attributes of peripherals in a hedonic regression equation for mainframe computer systems.

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.[35]

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 which 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.[36]

Summary Statistics

Table 2 displays summary statistics for the Phister data covering the period 1954-1979. A total of 91 computer models is included, of which 44 are IBM and 47

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[35] Facts in this paragraph come from Phister (1979), pp. 26-27.

[36] Facts in this paragraph come from Fisher, McKie, and Mancke (1983), pp. 173-9.

Table 2

Means for Phister sample, 1951-77

	Price (k$) (1)	Machine Cycle Time (Ms) (2)	Memory Size (kbytes) (3)	Observations (4)
1951	750.00	220.00	8.00	1
1954	146.20	5450.00	15.20	2
1955	931.32	13.25	86.00	4
1957	531.35	5020.00	13.45	2
1958	748.57	349.20	69.40	5
1959	1017.75	11.80	151.15	4
1960	386.46	8.69	23.31	7
1961	759.56	7.01	59.57	10
1962	354.50	4.50	79.65	4
1963	778.38	4.00	81.57	7
1964	1328.01	2.33	246.67	3
1965	708.83	1.55	312.00	10
1966	60.98	2.53	14.00	3
1967	250.91	.93	95.67	9
1968	51.45	6.00	9.60	1
1969	1672.25	.96	1774.67	9
1970	14.35	1.41	10.00	4
1971	924.03	.40	236.00	4
1972	963.31	.70	486.00	12
1973	124.20	.69	56.00	2
1974	59.49	.03	506.67	6
1975	862.57	.71	268.00	6
1976	76.04	1.03	112.00	6
1977	366.72	.57	528.00	2

are non-IBM. Included are all of the general purpose systems and many of the "minis" which were important in the sense that their number in use, value in use, or total operations per second ranked them first or second in any given generation of computers. Also included are some IBM computers and all non-IBM computers whose number or value exceeded one percent of total worldwide computer installations in some year. The table displays yearly means for system price, memory included in that price, and machine cycle time. Average system price in 1979 is almost the same as in 1954, but memory included is 85 times higher, while speed is 6800 times faster.

The Chow data are summarized in Table 3. Here we note the larger sample than Phister for the 1954-65 period, and generally much smoother year-to-year changes. The exception is a sharp decline in access time between 1962 and 1963, and a smaller but still sharp decline in multiplication time in the same year. The price jumps in 1954-55 and 1956-57 seem closely related to movements in the same direction of memory. A comparison of the two tables suggests that the Chow data will yield a computer price index with a smoother rate of price decline, and indeed this proves to be the case.

The Dulberger data are summarized in Table 4. The sample is comparable in size to that of Chow in the 1970s and considerably larger in the 1980s, but the number of observations includes not just new machines (of which the Chow sample is primarily comprised) but also machines in their second, third, and sometimes fourth year of production. This repeated appearance by the same machine over several years helps to account for the smoothness of the changes in price and quality averages from one year to the next, particularly in comparison with the Phister data in Table 2. A particular advantage of the Dulberger-BEA data set is the inclusion of variables indicating the technology class of a processor; these variables are highly significant in

Table 3

Means for *Chow* Sample, 1954-65

	Monthly Rental (K$)	Access Time	Multiplication Time	Memory Size	Observations (total)	Observations (New Models)
	(1)	(2)	(3)	(4)	(5)	(6)
1954	10.76	6631.43	87279.14	722.86	7	7
1955	6.83	8468.56	98961.56	86.36	9	6
1956	9.29	9829.91	84599.46	187.93	11	6
1957	16.80	6594.26	38491.11	293.96	9	3
1958	18.87	3385.89	38899.00	321.17	9	6
1959	21.25	2206.00	10515.20	516.89	10	6
1960	12.79	1509.48	24359.80	403.82	10	9
1961	22.86	1456.36	4242.98	1471.43	12	12
1962	17.73	2331.55	4917.44	544.55	11	11
1963	14.20	6.28	386.31	890.13	15	15
1964	15.26	5.26	126.05	1064.00	18	18
1965	10.80	227.80	2464.22	1030.05	16	16

(2) (3) in microseconds

(4) in thousands of binary digits

Table 4

Means for *Dulberger* sample, 1972-84

	Price (k$)	MIPS	Memory Size (Mbytes)	Observations
	(1)	(2)	(3)	(4)
1972	1143.64	.59	.79	10
1973	1659.91	.73	1.72	10
1974	1463.56	.62	1.47	12
1975	2469.52	1.34	2.58	10
1976	2052.40	1.16	2.28	12
1977	2617.18	1.92	4.18	14
1978	2169.93	2.47	4.78	16
1979	2116.43	2.89	6.03	18
1980	1706.25	2.98	7.71	24
1981	7319.45	2.79	9.62	34
1982	2174.43	5.80	15.45	40
1983	2726.25	8.58	21.83	48
1984	2740.79	10.35	28.33	48

the regression equations shown in Tables 12 and 15, but unfortunately they are not available for our other three data sets.

The Computerworld data are summarized in Table 5. There are two classifications, the IBM models that we take over from the Dulberger data set, and the Computerworld data for the non-IBM models. The IBM sample contains larger machines than the non-IBM sample, reflecting the inclusion of "super-mini" computers in the latter. There is a continued downward trend in price per unit of included memory in the non-IBM sample, but much less of an improvement in the average values of the quantity characteristics than in the IBM portion of the sample.

VI. REGRESSION RESULTS

The regression results are presented beginning in Table 6 for the 1951-65 period, where we compare results using the Chow and Phister data sets. The specification is log-linear, with t ratios shown in parenthesis next to the coefficients on the quality attributes, and with asterisks used to designate the significance levels of the time dummies, so as to avoid an excessive clutter of numbers in the tables. The time dummy coefficients are defined on a base of 1954 = 0. For the Chow data, "new" means the subset of observations for the first year when they appear, and "all" means all observations in the data set without editing. For the Phister data, we determined from his book that the typical model was in production for four years, and the Phister "augmented" sample consists of each observation repeated four times. This assumption that the price of old models remains constant over their lifetime (at least before 1970) seems consistent with the evidence in the Chow data set that each model included in the sample for more than one year maintains a fixed rental rate.

Table 6 includes several explanatory variables. Memory is common to both the

TABLE 5

Means for 1977-84 sample

	All Models			Dulberger Sample (IBM models only)			Computerworld non IBM		
	Price	Memory	MIPS	Price	Memory	MIPS	Price	Memory	MIPS
1977	2093.79	3.63	1.85	1586.94	2.44	0.94	3107.50	6.20	3.68
1978	2144.01	3.90	2.60	1642.88	3.75	2.02	2501.97	4.20	3.31
1979	833.43	2.11	1.67	1515.38	4.85	2.08	733.14	1.70	1.61
1980	802.87	3.26	1.35	1628.65	7.88	2.92	629.02	2.29	1.02
1981	1228.15	5.24	4.20	1934.16	12.67	4.04	1103.57	3.92	4.23
1982	1169.54	6.17	3.72	2069.97	15.67	5.51	1005.83	4.44	3.39
1983	1444.92	6.18	4.11	1634.80	15.17	4.52	1408.17	4.44	4.03
1984	922.74	5.95	4.65	2078.01	22.75	6.76	858.99	5.03	4.54

Table 6

Comparison of Hedonic Results, 1951-1965: Chow sample vs. Phister sample
(t-ratios in parentheses)

	Chow sample all models	Chow sample with IBM dummy	Chow sample New Models only	Phister sample Augmented	Phister sample New models only	Phister sample, model dummies
	(1)	(2)	(3)	(4)	(5)	(6)
Memory	0.52 (18.8)	0.51 (19.1)	0.54 (17.2)	0.63 (14.0)	0.63 (14.9)	0.63 (14.9)
Mach. Cycle Time	----	----	----	-0.26 (-3.87)	-0.26 (-3.87)	-0.31 (-3.90)
Access Time	-0.16 (-8.09)	-0.14 (-7.12)	-0.15 (-6.46)	----	----	----
Mult. Time	-0.006 (-2.74)	-0.07 (-3.15)	-0.07 (-2.86)	----	----	----
IBM dummy	----	0.27 (3.26)	----	----	----	----
Constant	1.39 (4.83)	1.29 (4.62)	1.31 (4.18)	5.36 (14.4)	5.51 (7.85)	5.89 (7.49)
IBM 305(57)	----	----	----	----	----	0.80 (1.62)
UNIVAC 2(57)	----	----	----	----	----	0.11 (0.18)
BGH 220(58)	----	----	----	----	----	-0.03 (-0.05)
IBM 709U(62)	----	----	----	----	----	-1.31 (-2.78)
1951	----	----	----	0.98	1.22*	1.07
1952	----	----	----	0.98	----	----
1953	----	----	----	0.98	----	----
1954	base	base	base	base	base	base
1955	-0.07	-0.07	-0.03	-0.48	-0.60	-0.90
1956	-0.21	-0.20	-0.33	-0.48	----	----
1957	-0.28	-0.28	-0.22	-0.31	0.55	----
1958	-0.46**	-0.47**	-0.51**	-0.40	-0.60	-0.84
1959	-0.69**	-0.62**	-0.75**	-0.53	-1.03*	-1.34*
1960	-1.13**	-1.09**	-1.14**	-0.68*	-1.01	-1.33*
1961	-1.24**	-1.14**	-1.24**	-0.84*	-1.09*	-1.43*
1962	-1.62**	-1.49**	-1.61**	-0.98**	-1.78**	-1.80**
1963	-1.73**	-1.66*	-1.73**	-1.00**	-1.23*	-1.60*
1964	-1.98**	-1.82**	-1.99**	-1.11**	-1.85**	-2.24**
1965	-2.30**	-2.24**	-2.30**	-1.54**	-2.34**	-2.75**
R^2	0.910	0.917	0.903	0.807	0.887	0.899
S.E.E.	0.368	0.355	0.379	0.497	0.425	0.401
Observations	137	137	119	184	59	59

Chow and Phister data sets, but the measures of speed differ and are listed separately. Also included are "model dummies" (e.g., "IBM 7094") for one or more specific models in a particular year. These are entered only for particular variants of the Phister results for new-only models in an attempt to smooth out erratic jumps in the hedonic price index implied by the new-only Phister sample. The results begin in column (1) of Table 6 with the full Chow sample and Chow's three original quality characteristics, memory, access time, and multiplication time. Column (2) adds a make dummy for IBM models, which is highly significant in the Chow sample but makes little difference to the rate of price decline. Also, the rate of price decline and the coefficients are the same in the new-only Chow subsample, which is not surprising since the number of observations drops only from 137 to 119 as a result of editing the sample to include only new models.

The results for the Phister data source during the 1951-65 interval are displayed in the three right-hand columns of Table 6. The augmented sample, displayed in column (4), includes each model for the year of its introduction and for the following three years. While the coefficients on memory and speed are very close to those for the Chow sample in the first three columns, the 1954-65 price decline is substantially slower. This is to be expected, since the presence of old models in the sample damps the rate of price decline. For the "unaugmented" or new-only Phister sample in column (5), the 1954-65 rate of price decline is almost identical to the basic Chow result in column (1), with 1965 time dummy coefficients of -2.34 and -2.30, respectively. The decline from 1954 to 1960 is also very similar (-1.07 and -1.13, respectively). The Phister estimates, however, exhibit two sharp jumps that are not present in the Chow estimates. The first occurs in 1957, with a time dummy coefficient of +0.55, preceded and followed by coefficients of -0.60 in 1955 and 1958.

The second occurs in 1962, when the time dummy drops from -1.09 to -1.78, and then climbs back to -1.23.

One modification was made to the specification in column (5) to identify the source of the jumps in the Phister sample of new models. Four models were identified that seemed to have a price-performance ratio very different from other models in 1957, 1958, and 1962. These are the IBM 305 (1957), UNIVAC 2 (1957), Burroughs 220 (1958), and IBM 7094 (1962). Column (6) exhibits the modified pooled regression for the new Phister sample. Because both 1957 models in the same are dummied out, there is no time dummy coefficient shown for 1957. The jump from 1962 to 1963 is reduced substantially, from 0.55 to 0.20. While only one of the model dummy coefficients is significant in Table 6, all are included here to be consistent with the adjacent-year regressions for the same sample in Table 7, where all the four model dummy variables are significant. Unlike the pooled equations, which restrict the coefficients on memory and speed to be the same for the entire 1951-65 period, the adjacent-year equations in Table 7 allow these coefficients to shift. The coefficient on memory is quite stable at about 0.4 until 1961-62, when it rises to an average of 0.66 for the last four equations in the table. The coefficient on speed is quite unstable, with much higher values between 1959 and 1963 than either before or after. In the adjacent-year equations there is no time dummy for 1957, since both 1957 models are dummied out, while the 1962-63 jump is almost completely eliminated.

Table 8 displays the price indexes implied by the time dummy coefficients in Tables 6 and 7. The left-hand column presents Chow's (1967) basic index as published, calculated as the ratio of nominal rentals to a hypothetical real rental in 1960 prices, based on estimates of coefficients on characteristics from a pooled regression for 1960-65. Then columns (1) through (6) present price indexes calculated

Table 7

Adjacent Year Hedonic Regression Equations for Phister Sample of New Models 1951 - 65

	1951 -55	1955/a -58	1958 -59	1959 -60	1960 -61	1961 -62	1962 -63	1963 -64	1964 -65
Memory	0.40 (7.71)	0.44 (8.84)	0.41 (12.4)	0.37 (2.56)	0.40 (3.54)	0.61 (5.37)	0.48 (6.06)	0.71 (8.42)	0.76 (9.71)
Mach. Cycle Time	-0.31 (-2.87)	-0.14 (-6.78)	-0.29 (-13.1)	-0.67 (-2.59)	-0.85 (-3.76)	-0.42 (-1.88)	-0.60 (-2.98)	-0.13 (-0.54)	-0.14 (-0.41)
Constant	6.56 (7.12)	5.38 (25.6)	5.86 (29.9)	6.57 (6.07)	6.29 (8.53)	4.70 (6.75)	4.58 (9.54)	3.86 (7.63)	3.02 (5.51)
IBM 305 (57)	----	0.99 (6.34)	----	----	----	----	----	----	----
UNIVAC 2 (57)	----	0.81 (8.56)	----	----	----	----	----	----	----
BGH (220)	----	-3.72 (-3.09)	----	----	----	----	----	----	----
IBM 7094 (62)	----	----	----	----	----	-1.37 (-3.15)	-1.30 (-5.89)	----	----
1951	0.92								
1954	base								
1955	-0.60	base							
1956		----							
1957		0.00							
1958			base						
			-0.32*						
1960				base					
				-0.56					
1961					base				
					-0.19				
1962						base			
						-0.37			
1963							base		
							0.01		
1964								base	
								-0.64*	
1965									base
									-0.42
$\bar{R}^2$	0.987	0.993	0.991	0.769	0.864	0.900	0.979	0.960	0.943
S.E.E.	1.02	0.082	0.086	0.496	0.430	0.354	0.176	0.319	0.422
Observations	7	11	9	11	17	14	11	10	13

Table 8

Price Indexes (1965 = 100)

(Columns 1 to 6 correspond to the same columns in Table 6)

	Chow Index As Published	(1)	(2)	(3)	(4)	(5)	(6)	Adjacent-Year Phister from Table 7 (7)
1951	----	----	----	----	12.43	35.16	45.60	54.05
1952	----	----	----	----	12.43	----	----	----
1953	----	----	----	----	12.43	----	----	----
1954	9.53	9.97	9.39	9.97	4.66	10.38	15.64	21.54
1955	8.67	9.30	8.76	9.68	2.89	5.70	6.36	11.82
1956	7.49	8.08	7.69	7.17	2.89	----	----	----
1957	6.78	7.54	7.10	8.00	3.42	17.99	----	----
1958	5.95	6.30	6.23	5.99	3.13	10.38	6.75	12.06
1959	4.65	5.00	5.67	4.71	2.75	3.71	4.10	8.76
1960	3.13	3.22	3.16	3.20	2.36	3.78	4.14	5.00
1961	2.65	2.89	3.00	2.89	2.01	3.49	3.74	4.14
1962	2.01	1.97	2.12	1.99	1.75	1.75	2.59	2.85
1963	1.67	1.77	1.79	1.77	1.72	3.03	3.16	2.89
1964	1.23	1.40	1.52	1.36	1.54	1.63	1.67	1.52
1965	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Source for first unnumbered column:

Chow (1967), Table 2, Column 3, p. 1124, rebased to 1965.

from the time dummy coefficients in the corresponding columns of Table 6, while column (7) displays the price index implied by the time coefficients from the adjacent-year regressions of Table 7. Taking only the years 1954 and 1965, the rate of price decline of the published Chow Index is quite close to that computed from the time dummies of the various hedonic regressions performed on the Chow sample from columns (1)-(3). For our "final" price index for computers used in calculations at the end of the paper, we must choose one of these indexes. To maintain comparability with the years after 1965 we prefer an index based on time dummies, as in columns (1) through (3) rather than the index Chow computed in the left-hand column. Of the three sets of time dummies, we prefer column (2), since this version includes a dummy for IBM models that is of a plausible magnitude and is highly significant.

The price index for the augmented Phister sample displays a much slower decline in price at an average rate of -13.1 percent per annum, as constrasted with -18.4 percent for the index based on Chow data in column (2). This is not unexpected, since each model appears in the augmented Phister sample 4.0 times but in the Chow sample only 1.15 times. Thus the augmented Phister sample damps the rate of price decline, since it includes more old models than the Chow sample. While one might argue that the augmented Phister sample is more comparable to the Dulberger and Computerworld samples used for the post-1972 period, since these include old models, the augmented Phister sample may overly damp the rate of price decline of computers for two reasons. First, by assuming that there are no price changes on old models, the augmented Phister sample may ignore price reductions that occur in the latter years of production of old models. Second, at the end of the period in 1965 the augmented Phister sample contains roughly three-quarters old models, whereas in 1954 it contains only a single 1951 model. Thus the importance of old models is greater at the end than the beginning, helping to damp the rate of price decline registered in column (4) of Table 8.

The remaining columns show the behavior of price indexes developed from the Phister sample of new models. The price decline exhibited for 1954-65 in column (5) is similar to that for the Chow sample, but there are large and implausible jumps in 1957 and 1963. The two right hand columns -- (6) for the pooled regression and (7) for adjacent years -- are based on equations containing four model dummies. Here the jumps evident in column (5) are eliminated, and the rate of price decline increases substantially. This occurs because the process of dummying out the "problem models" tends to increase the absolute value of the coefficient on speed, which in turn increases the extent of the price decline that is estimated to occur when new, faster models are introduced.

Table 9 shows the regression results for 1965-72 for both the augmented and new-only versions of the Phister sample (recall that we have no other data source covering this period). The augmented and new-only results are similar, except that the rate of price decline is much smoother in the augmented sample. The coefficient on machine cycle time is insignificant throughout, as are the IBM and size dummies, except for the dummy for small memory size in the augmented sample (column 3). The results in columns (4) and (5) for the Phister sample of new models display upward jumps in time dummy coefficients in 1968 and 1971, while in the augmented sample these years exhibit not an upward jump but a relatively slow rate of price decline.

As in the previous 1951-65 sample period, further tests of the Phister new-model sample were carried out for the 1965-72 period in an attempt to create smoother time dummy coefficients. First, in column (6) of Table 9 a pooled regression

Hedonic Results, 1965 - 1972: Phister sample

	All Models	All Models, IBM dummy	All Models, size dummies	New Models	New Models, IBM dummy	New Models, with model dummy
	(1)	(2)	(3)	(4)	(5)	(6)
Memory	0.77 (29.8)	0.78 (29.3)	0.67 (11.6)	0.83 (8.97)	0.81 (8.70)	0.88 (14.8)
Machine Cycle Time	-0.01 (-0.18)	-0.01 (-(0.17)	0.01 (0.15)	-0.12 (-0.40)	-0.10 (-0.37)	----
IBM Dummy	----	0.11 (0.96)	----	----	0.68 (1.46)	----
Mem < 100	----	----	-0.54 (-2.62)	----	----	----
Mem > 500	----	----	-0.20 (-0.00)	----	----	----
Constant	2.93 (15.1)	2.86 (13.8)	3.65 (10.2)	2.32 (4.17)	2.43 (4.41)	2.08 (6.41)
MD1970	----	----	----	----	----	-1.41 (-1.72)
1966	-0.06**	-0.06	-0.05	-0.08	-0.60	-0.02
1967	-0.54**	-0.52**	-0.51**	-0.39	-0.40	-0.34
1968	-0.61**	-0.54**	-0.59**	-0.06	-0.13	-0.13
1969	-0.93**	-0.89**	-0.91**	-0.71	-0.64	-0.99
1970	-1.10**	-1.07**	-1.08**	-1.74**	-2.12**	-0.55
1971	-1.11**	-1.10**	-1.11**	-0.38	-0.84	-0.19
1972	-1.25**	-1.23**	-1.21**	-1.53**	-1.60**	-1.27**
$\bar{R}^2$	0.865	0.865	0.869**	0.826	0.833	0.873
S.E.E.	0.651	0.651	0.642	0.838	0.821	0.712
Observations	176	176	176	52	52	52

"MD1970" is a dummy variable equal to 1.0 in 1970 for the following three models: IBM S3/10; Digital Equipment PDP11; and General Automation SPC16/40.

is estimated in which a dummy variable is included for several 1970 models that seem to be underpriced. This make dummy for 1970 ("MD 1970") is almost significant in the pooled regression and eliminates most but not all of the implausible drop and rebound of the time dummy coefficients for 1970 and 1971 evident in both columns (4) and (5) of Table 9. Then in Table 10 adjacent-year regressions are estimated that are identical in specification to Table 9, column (6). The MD 1970 variable is included and the machine cycle time variable is excluded, since it is insignificant in Table 9 and since it jumps around implausibly when included in the adjacent-year equations.

The price indexes for the 1965-72 period are shown in Table 11. The first three columns list the indexes implied by the time dummy coefficients in Table 9 for the augmented Phister sample. The annual rate of price change in column (3), our preferred variant, is -15.9 percent, somewhat less than the -18.4 percent rate of price change for 1954-65 in the preferred equation for the Chow sample. The rate of price decline is similar in columns (1) through (3), all referring to the augmented Phister sample. For the new sample in columns (4) and (5) the rate of price decline is faster but displays implausible jumps in 1968 and 1971. Columns (6) and (7) display, for the pooled and adjacent-year regressions respectively, the results when the MD 1970 dummy is included and the speed variable is excluded. This specification yields a slightly smoother index and a slower rate of price decline in the pooled results, and a much smoother index with a much faster rate of price decline in the adjacent-year results. Interestingly, the ten-fold decline in the adjacent-year index in column (7) of Table 11 is quite similar to Miller's geometric index for the same period, which has 1965 = 10.75 on a base of 1972 = 1.00 (see Table 16 below) By taking column (3) rather than column (7) of Table 11 as our "final" index for this period, we may be understating the rate of price decline.

Table 10

Adjacent-Year Hedonic Regression Equations for Phister Sample of New Models 1965-72

	1965 -66	1966 -67	1967 -69	1969 -70	1970 -71	1971 -72
Memory	0.74 (10.2)	0.74 (7.06)	0.70 (8.07)	0.61 (6.82)	1.02 (4.79)	1.16 (12.3)
Constant	2.63 (8.02)	2.34 (6.49)	2.34 (6.78)	2.87 (7.52)	1.23 (1.70)	0.49 (0.85)
MD70	----	----	----	-1.35 (-1.69)	-1.44 (-2.20)	----
1965	base					
1966	-0.28	base				
1967		-0.15	base			
1968			0.02			
1969			-0.08	base		
1970				-0.77	base	
1971					-0.06	base
1972						-0.96*
						-0.87*
$\bar{R}^2$	0.914	0.829	0.882	0.915	0.940	0.916
S.E.E.	0.503	0.497	0.575	0.694	0.569	0.683
Observations	13	12	19	13	8	16

"MD70" is identified in the note to Table 9.

Table 11

Price Indexes, 1965 - 1972 (1972 = 100)
(Columns 1 to 6 correspond to the same columns in Table 9) -

	(1)	(2)	(3)	(4)	(5)	(6)	Adjacent-year new Phister sample from Table 10 (7)
1965	3.49	3.42	3.35	4.62	4.95	3.56	9.58
1966	3.29	3.22	3.19	4.26	2.71	3.49	7.24
1967	2.03	2.03	2.01	3.13	3.32	2.53	6.23
1968	1.89	1.90	1.86	4.35	4.35	3.13	6.36
1969	1.38	1.40	1.35	2.27	2.61	1.32	5.87
1970	1.16	1.17	1.14	0.81	0.59	2.05	2.72
1971	1.15	1.14	1.10	3.16	2.14	2.94	2.56
1972	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Next we turn to the 1972-77 period in Table 12. Note that there is a highly significant IBM dummy in both the Dulberger and Phister samples. Also, without the technology variables, the Dulberger sample registers a price increase in 1973-75 over 1972, and very little price decline from 1972 to 1977. The rate of price decline in the Phister sample with no dummies is actually smoother than in the best Dulberger equation (col. 3), but a jump in the coefficient on the 1973 time dummy occurs in the augmented Phister sample with either the IBM dummy or size dummies included.

To maintain comparability to the Dulberger sample for this period, we present only the results for the augmented Phister sample that contains old models. We do not present a companion set of results for new Phister models only, since we learned that the hedonic price indexes derived from the Phister sample of new models for this period display implausible jumps, and we were not able to eliminate these jumps even after experimentation with model dummies and adjacent-year equations. The price indexes for 1972-77 are displayed in Table 13. The two preferred price indexes are in columns (3) and (4). The price index for the Dulberger sample with technology variables included (column 3) displays an annual rate of change of -15.6 percent, and for the augmented Phister sample (column 4) -22.1 percent.

Finally, we have the 1977-84 period in Table 14. The Dulberger sample is run separately, because we have the technology class variables available only for those observations. Also, we did not have data on MIPS for the non-IBM sample for 1977-80 but instead created it. First, a regression of MIPS on machine cycle time was run for 1981-84 (since we have both MIPS and machine cycle time for that period) and then the estimated coefficients are used to create values for MIPS for 1977-80, when we know only machine cycle time. The sample is tripled in size when the Dulberger observations for IBM machines are merged in column (4) with the rest of the

Table 12

Comparison of Hedonic Results, 1972 - 1977: Dulberger sample vs. Phister sample

	Dulberger Sample All Models	Dulberger Sample with IBM dummy	Dulberger Sample with technical classes	Phister sample All Models	same as (4) with IBM dummy	same as (4) with size dummies
	(1)	(2)	(3)	(4)	(5)	(6)
Memory	0.23 (4.76)	0.31 (4.53)	0.24 (6.00)	0.84 (13.8)	0.87 (15.9)	1.10 (8.40)
Mem < 100	----	----	----	----	----	0.66 (1.60)
Mem > 500	----	----	----	----	----	-0.61 (-1.52)
Machine Cycle Time	----	----	----	-0.66 (4.28)	-0.47 (-3.29)	-0.72 (-4.61)
IBM dummy	----	0.28 (2.50)	----	----	1.06 (5.56)	----
MIPS	0.67 (13.5)	0.71 (14.1)	0.69 (16.3)	----	----	----
Core 72	----	----	-0.53 (-3.86)	----	----	----
BP1K73	----	----	0.25 (1.77)	----	----	----
BP1K74	----	----	0.27 (2.09)	----	----	----
FET2K75	----	----	0.35 (2.00)	----	----	----
FET2K76	----	----	0.41 (3.05)	----	----	----
FET1K77	----	----	0.16 (1.07)	----	----	----
FET2K77	----	----	0.33 (2.39)	----	----	----
Constant	7.48 (85.0)	7.24 (56.5)	7.85 (71.1)	1.11 (3.14)	0.74 (2.30)	-0.37 (-0.41)
1973	0.23*	0.23*	-0.20	-0.12	-0.21	-0.12
1974	0.22*	0.23*	-0.19	-0.59	-0.64*	-0.65*
1975	0.05	0.10	-0.57**	-0.76**	-0.79**	-0.81**
1976	-0.04	0.01	-0.65**	-1.19**	-1.50**	-1.23**
1977	-0.33**	-0.24*	-0.85**	-1.25**	-1.62**	-1.27**
$\bar{R}^2$	0.958	0.962	0.973	0.754	0.802	0.760
S.E.E.	0.262	0.251	0.211	1.104	0.990	1.090
Observations	68	68	68	131	131	131

Table 13

Price Indexes, 1972 - 1977 (1977 = 100)
Columns 1 to 6 correspond to the same columns in Table 12

	(1)	(2)	(3)	(4)	(5)	(6)
1972	1.39	1.27	2.34	3.49	5.05	3.56
1973	1.75	1.60	1.92	3.09	4.10	3.16
1974	1.73	1.60	1.93	1.93	2.66	1.86
1975	1.46	1.48	1.32	1.63	2.29	1.56
1976	1.34	1.28	1.22	1.06	1.13	1.04
1977	1.00	1.00	1.00	1.00	1.00	1.00

Table 14

Comparison of Hedonic Results, 1977-1984; Dulberger sample vs. Computerworld sample

	Dulberger Sample All models (1)	Dulberger Sample with IBM dummy (2)	Dulberger Sample with technical classes (3)	Merged Sample all models IBM dummy (4)	Same as (4) Superminis excluded (5)	Computerworld non IBM Non Superminis (6)	Computerworld Superminis only (7)
Memory	0.18 (5.81)	0.18 (5.82)	0.23 (9.33)	0.41 (14.9)	0.19 (7.23)	0.20 (5.45)	0.41 (5.69)
MIPS(a)	0.82 (34.1)	0.83 (33.8)	0.80 (40.2)	0.74 (28.5)	0.90 (38.7)	----	----
IBM dummy	----	0.04 (1.35)	----	0.14 (1.81)	0.18 (2.95)	----	----
FET1K77	----	----	0.39 (3.21)	----	----	----	----
FET2K77	----	----	0.41 (3.45)	----	----	----	----
FET1K78	----	----	0.49 (4.47)	----	----	----	----
FET1K79	----	----	1.23 (6.62)	----	----	----	----
FET2K79	----	----	0.84 (5.57)	----	----	----	----
FET4K79	----	----	0.78 (5.34)	----	----	----	----
FET24K80	----	----	0.49 (5.43)	----	----	----	----
FET2K81	----	----	0.25 (2.88)	----	----	----	----
F16K81	----	----	0.35 (4.50)	----	----	----	----
F16K82	----	----	0.27 (3.98)	----	----	----	----
log Mimimum Channels	----	----	----	----	----	0.43 (7.09)	0.03 (0.49)
log Maximum Channels	----	----	----	----	----	0.31 (6.28)	0.18 (2.48)
Cache Buffer Size		----	----	----	----	0.002 (4.81)	0.004 (2.82)
log Machine Cycle Time		----	----	----	----	-0.63 (-10.7)	-0.20 (-1.85)
Constant	2.18 (10.4)	7.15 (10.0)	6.88 (85.2)	6.81 (35.8)	6.97 (48.2)	15.0 (35.4)	12.42 (19.8)
1978	-0.38**	-0.38**	-0.28**	-0.40	-0.42*	-0.10	----
1979	-0.69**	-0.69**	-1.24**	-1.00**	-1.15**	-0.26	----
1980	-1.04**	-1.03**	-1.21**	-1.12**	-1.06**	-0.35	----
1981	-1.23**	-1.22**	-1.16**	-1.33**	-1.12**	-0.83**	0.0(b)
1982	-1.38**	-1.38**	-1.27**	-1.63**	-1.46**	-1.07**	-0.69**
1983	-1.57**	-1.58**	-1.40**	-1.63**	-1.42**	-0.95**	-0.50*
1984	-1.76**	-1.76**	-1.60**	-2.09**	-1.86**	-1.54**	-0.59**
$\bar{R}^2$	0.981	0.951	0.969	0.825	0.879	.811	0.534
S.E.E.	0.235	0.233	0.184	0.436	0.482	0.614	0.592
Observations	242	242	242	658	489	355	108

(a) see text for the procedure used to proxy this variable in columns (4) to (5) on non-IBM models from 1977 to 1980.

(b) No data for 1977-80; 1981 used as base year.

Computerworld observations. The main differences in results for the large sample are that the IBM dummy is close to significance and that the coefficient on memory jumps. Unlike the Dulberger sample, which displays the property that the coefficients on memory and MIPS sum to unity, the sum for the Computerworld sample in column (4) 1.15.

Several other regression equations with the Computerworld data are included in columns (5) through (7) of Table 14. When the pooled equation in column (4) is compared with separate equations for non-super-minis (column 5) and super-minis (column 7) decisively rejects aggregation, with a F(6,544) ratio of 55.7. However, a similar test for the aggregation of IBM and non-IBM mainframes (i.e., nonsuper-minis) accepts aggregation. While there is no need to run a separate regression for the non-IBM and non-super-mini subset of the Computerworld sample, it is interesting to note in column (6) that the rate of price decline is somewhat slower for this subset. In addition, for this subset (and for super-minis) we include three additional variables beyond the usual measures of speed and memory: maximum and minimum channels and "cache buffer size." The coefficients on these additional variables are highly significant and of the correct sign.

The price indexes for this final period are presented in Table 15. The annual rate of change for the Dulberger sample with technology variables (column 3) is -20.4 percent over 1977-84, for the merged sample in column (4) is -25.8 percent, for the sample excluding super-minis in column (5) is -23.4 percent, for the non-IBM mainframes in column (6) is -19.7 percent, and for the super-minis in column (7) for 1981-84 only is -17.7 percent. Note that the rate of price change for non-IBM models from the Computerworld sample is very close to the result from the Dulberger sample for IBM machines. These results suggest that the rate of price decline for computer

Table 15

Price Indexes, 1977 - 1984 (1982 = 100)
Column numbers correspond to the same columns in Table 14)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1977	3.97	3.97	3.56	5.10	4.31	2.92	----
1978	2.72	2.72	2.69	3.42	2.83	2.64	----
1979	1.99	1.99	1.03	1.88	1.36	2.25	----
1980	1.40	1.42	1.06	1.67	1.49	2.05	----
1981	1.16	1.17	1.12	1.35	1.40	1.27	1.99
1982	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1983	0.83	0.82	0.88	1.00	1.04	1.13	1.21
1984	0.68	0.68	0.72	0.63	0.67	0.63	1.11

processors accelerated in the late 1970s and early 1980s from the rate observed in the previous 20 years.

VII. WEIGHTING ISSUES

Numerous price indexes for computer processors have been developed in this study for four separate time periods, 1951-65, 1965-72, 1972-77, and 1977-84. In this section we choose one index from each of the periods and combine them into a single index covering the 1951-84 period. The "final" price index developed here is then aggregated together with BEA price indexes for other products to form a new deflator for the OCA (Office, Computing, and Accounting Machinery) component of PDE, and for PDE itself. As suggested in the introduction to this paper, 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.

Comparison with Other Results

In his survey paper in this volume, Triplett (1987) displays a wide variety of hedonic price indexes for computers. Tables 16 and 17 compare the main results of this study with alternative price indexes for the same sample periods. Table 16 covers the period through 1972, and Table 17 covers the period since 1977. The first three columns of Table 16 link together our Phister indexes from Tables 8 and 11. These are compared in column (4) to an index developed by Flamm (by an alternative methodology that does not include the estimation of explicit hedonic regression equations) from the Phister data; in column (5) to Triplett's "best practice" index that combines Chow's results with those of Knight, and the hedonic results of Miller (1980) that extends Chow's data set through 1972.

TABLE 16

Comparison of Alternative Phister Indexes with Flamm, Triplett "Best Practice," and Miller, 1953-72

	This Study					
	Phister Augmented Sample Pooled (1)	Phister New-Only Pooled (2)	Phister New-Only Adjacent Year (3)	Flamm (4)	Triplett Best-Practice (5)	Miller Geometric (6)
1953	1243	---	---	---	---	---
1954	466	1564	2154	---	1139	---
1955	289	636	1182	---	1010	---
1956	289	---	---	---	862	---
1957	342	---	---	1427	761	---
1958	313	675	1206	1086	689	---
1959	275	410	876	844	591	---
1960	236	414	500	538	435	---
1961	201	374	414	427	332	---
1962	175	259	285	379	239	---
1963	172	316	289	252	183	---
1964	154	167	152	148	139	---
1965	100	100	100	100	100	100
1966	94	98	76	44	38	76
1967	58	71	65	25	27	36
1968	54	88	66	19	24	43
1969	40	37	61	19	24	21
1970	33	58	28	17	23	20
1971	33	83	27	12	18	18
1972	29	28	10	8	15	9

Sources by column:

(1)	Table 8, col. (4) and Table 11, col. (1)
(2)	Table 8, col. (6) and Table 11, col. (6)
(3)	Table 8, col. (7) and Table 11, col. (7)
(4)	Triplett (1987), Table 4-A, col. (7) and Table 6-A, col. (5)
(5)	Triplett (1987), Table 6-A.
(6)	Miller (1980), Table 2-B.

TABLE 17

Comparison of Alternative Indexes from This Study with Indexes of Dulberger and Cartwright

	This Study				
	Phister Augmented Sample		C-World excl. s-minis (IBM dummy)	Dulberger with tech. dummies	Cartwright all models
	No IBM Dummy	IBM Dummy			
	(1)	(2)	(3)	(4)	(5)
1972	100.0	100.0	--.-	100.0	100.0
1973	88.5	81.2	--.-	105.9	95.8
1974	55.3	52.7	--.-	82.3	83.1
1975	46.7	45.3	--.-	80.1	57.5
1976	30.4	22.4	--.-	78.6	53.3
1977	28.7	19.8	19.8	50.5	48.1
1978	--.-	--.-	13.0	26.5	41.9
1979	--.-	--.-	6.2	24.5	30.3
1980	--.-	--.-	6.8	17.9	22.4
1981	--.-	--.-	6.4	11.5	16.8
1982	--.-	--.-	4.6	10.1	13.0
1983	--.-	--.-	4.8	9.2	12.0
1984	--.-	--.-	3.1	7.8	--.-
Addendum: Percentage Growth Rates					
1972-77	-22.0	-27.7	--.-	-12.8	-13.6
1977-84	--.-	--.-	-23.3	-23.4	-20.7 (1977-83)

Sources by column:

(1) Table 13, column (4)
(2) Table 13, column (5)
(3) Table 15, column (5)
(4) Triplett (1986), Table 9, column (1)
(5) Triplett (1986), Table 9, column (4)

For the period 1958 through 1972, the overall rate of price decline in our new-only adjacent year index from Phister (column 3) is very close to Flamm's index. While columns (3) and (4) differ in the timing of price declines from 1965 to 1972, the behavior of our column (3) index in 1965-66 and 1971-72 receives some corroboration from Miller's index. Triplett's index displays a similar rate of price decline to column (3) in 1955-65, but differs sharply from 1954 to 1955. Also, Triplett's index shows a much faster rate of price decline between 1965 and 1966 than any of our indexes or Miller's. The Phister augmented index in column (1) shows a slower overal rate of price decline than any of the other indexes, both before and after 1965.

The comparison for the period since 1972 in Table 17 compares our indexes with Dulberger's index as estimated for the full 1972-84 period (in contrast to our re-estimate with her data for the separate 1972-77 and 1977-84 periods in Tables 12 and 14), and with Cartwright's index based on a larger sample than Dulberger's. Our results with the augmented Phister sample, shown in columns (1) and (2), show a much greater rate of price decline for the 1972-77 period than either Dulberger or Cartwright. For the period since 1977, our Computerworld index that excludes super-minis declines at exactly the same rate as Dulberger's index, and at a slightly faster rate than Cartwright's index. In the next section we discuss the selection of preferred indexes to be included in our "final" computer index.

The "Final" Price Index for Computer Processors

To compile a single price index for the 1954-65 period, we combine four indexes with a piece of a fifth. A list of these indexes and their location in the preceding set of empirical tables is contained in the notes to Table 18. The first index, covering 1954-65, is our estimated equation from Chow's data that includes an IBM dummy. We prefer Chow's data set to the Phister data set, simply because its sample size is larger, and it yields smoother price indexes. For 1965-72 we use an equation for the augmented Phister sample that contains dummy variables for large and small memory sizes. While this index declines much slower than the adjacent-year index for the new Phister sample, we feel that the reliance by other investigators (including Triplett and Miller) on data sets that include only new models yields inconsistent results with the preferred indexes for the period since 1972 that include both new and old models. Since our chosen index for 1965-72 declines more slowly than any of the other indexes in Table 16, our "final" index probably understates the overall postwar rate of price decline.

The 1972-77 equation is for the Dulberger data, using her technology variable. This equation does not duplicate the final regression index in Dulberger's paper, shown in Table 17, column (4), since she estimates a single equation over the full 1972-84 period rather than breaking that interval into two sub-periods as in this paper). The equation used for 1977-84 is for the merged Dulberger and Computerworld data set. This equation seems preferable to relying exclusively on Dulberger's results, since our merged sample size is much larger than hers, and includes not just mainframes but also super-minis (recall from Table 1 that in 1984 the value of mini-computer sales had reached 40 percent of mainframe sales). While this equation includes super-minis, which should not be combined with mainframes according to the F test described above, we adopt it as a short-cut to avoid the necessity of weighting together separate mainframe and super-mini indexes. Finally, the "final" index is extended back from 1954 to 1951 by using the time dummy coefficient from the equation estimated on the augmented Phister data for 1951-65.

The resulting "final" index is displayed in Table 18, where it is compared with the IBM regression index estimated by Cole et. al. (this is the same as Dulberger's

Table 18
Alternative Price Indexes
(1982 = 100)

	Computer Processors		Computers + Peripherals	Office Computing Accounting Machinery		
	IBM	This Study	BEA	BEA	Hybrid	This Study
	(1)	(2)	(3)	(4)	(5)	(6)
1951		93046	617	63	63	1448
1952		93046	617	63	63	1448
1953		93046	617	66	66	1515
1954		34883	617	66	66	1471
1955		32543	617	69	69	1523
1956		28569	617	73	73	1601
1957		26377	617	73	73	1599
1958		23144	617	73	73	1574
1959		21064	617	72	72	1514
1960		11739	617	83	84	1385
1961		11145	617	93	95	1425
1962		7876	617	92	96	1200
1963		6650	617	112	120	1114
1964		5647	617	124	135	1059
1965		3715	617	128	141	851
1966		3538	617	134	148	825
1967		2229	617	144	160	647
1968		2063	617	144	160	604
1969		1497	617	159	175	515
1970		1264	552	177	202	469
1971		1220	474	188	226	467
1972	990	1109	408	185	233	435
1973	1048	912	369	157	187	378
1974	815	912	291	140	173	382
1975	792	637	265	145	178	319
1976	778	585	231	139	179	303
1977	499	510	200	133	175	281
1978	262	342	169	129	171	223
1979	243	188	146	123	141	153
1980	177	167	118	109	135	143
1981	113	135	107	104	122	123
1982	100	100	100	100	100	100
1983	90	100	77	83	101	101
1984	77	63	69	74	69	71

Source by column:
(1) Cole *et. al.* (1986), Table 7, column (4).
(2) Linked index of 1951-54, Table 8, column (4);
1954-65, Table 8, column (2);
1965-72, Table 11, column (3);
1972-77, Table 13, column (3);
1977-84; Table 15, column (4).
(3) Cartwright (1986), Table 1, column (1).
(4) NIPA May 1986 tape.
(5) (6). See text and Tables 20 and 21.

index for 1972-84 with technology variables included). Also included in the comparison is the index for computers and peripherals used by the BEA to deflate the OCA segment of PDE, which extends back to 1969 and is assumed to remain unchanged before that year. It is interesting to note that the rate of change of our index and the IBM index over the 1972-84 period is much faster than the BEA index, which includes peripherals as well as processors. While we do not have the underlying components of the BEA index, we can assess its plausibility by comparing it with indexes for peripherals published by Cole et. al. (1986):

	Annual Rate of Change, 1972-84
Computer Processors, This Study	-21.3
Computer Processors, IBM (Cole et. al.)	-19.2
Disk Drives	-16.9
Printers	-15.5
Displays	- 7.3
Weighted average peripherals[37]	-14.7
Computer Processors and Peripherals, BEA	-13.8

One reason for the relatively slow rate of decline of the BEA index is the use of "composite" indexes based on matched models when a model exists in both the current year and base year and hypothetical prices from hedonic equations for models that did not exist in the base period. The IBM composite indexes for both processors and peripherals decline more slowly than the corresponding regression indexes based on

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[37] Weights used were 60 percent for disk drives, and 20 percent each for printers and displays, based on current value figures listed in Current Industrial Reports, Office, Computing, and Accounting Machines, 1973.

estimated time-dummy coefficients, with a difference of 1.4 percentage points at an annual rate for processors, 4.3 points for disk drives, 1.8 points for printers, and 0.0 points for displays. Nevertheless, the rate of decline of the BEA index seems implausibly slow.[38]

Since this paper does not create new price indexes for peripherals, and since such indexes are not available before 1972, we will proceed on the assumption that our index for processors can be used for the aggregate of processors and peripherals. While the IBM indexes for peripherals decline more slowly than the IBM indexes for processors, there are three offsetting factors that cause our price indexes to understate the rate of decline of computer prices. First, we make no allowance at all for the value of reduced repair, energy, and maintenance costs on computers. In a study of postwar price changes of TV sets, I have found that allowance for the value of such cost savings increases the rate of price decline over the 1947-84 period from -4.2 to -6.6 percent per annum, and I would be surprised if savings of a similar magnitude were not achieved on computer equipment. 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. We shall present information on price changes for PCs in Table 23, discussed below. Third, Table 1 above documents that 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

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38. If a weight of 50 percent is given to processors and the remainder is distributed among peripherals with the weights given in the previous footnote, the weighted average of the IBM composite indexes registers an annual rate of change of -14.8 percent, not the -13.7 percent registered by the BEA index.

users found that the increased power of minis and micros allowed them to perform certain tasks at a lower cost. 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 paper or by others.

Aggregating the Computer Index into a Deflator for OCA

The three right-hand columns of Table 18 display three alternative deflators for the OCA component of PDE. The first is the implicit BEA deflator, and the second is a "hybrid" deflator that combines our computer processor index with the BEA index for "other OCA" (i.e., non-computer products within OCA like cash registers and typewriters), using BEA weights and the implicit deflator methodology for combining the two components of the OCA deflator. The BEA and hybrid OCA deflators are identical until 1960, despite the marked difference in the underlying computer indexes displayed in columns (2) and (3) of Table 18. This occurs because the BEA uses the following formula for computing the implicit OCA deflator:

$$P^{BEA} = W^{C}(P^{C}) + W^{O}(P^{O}),$$

where $W^{C} = V^{C}/P^{C}$ and $W^{O} = V^{O}/P^{O}$,

and where each variable refers to the current time period, and the price indexes "P" are expressed with 1982 as base year. Here "W" is the weight expressed in 1982 prices, "V" is the value of shipments in current dollars, the superscript "BEA" stands for the BEA's OCA deflator, the superscript "C" stands for computers, and the superscript "O" for other products within OCA.

The components of the calculation are shown for the BEA deflator in Table 19 and for the hybrid deflator in Table 20. The procedure of computing the "W" weights

Table 19

Calculation of BEA Deflator for OCA

Year	Weight of Computers	Deflator for Computers	Weight of Other	Deflator for Other	Implicit Deflator for OCA	BEA Fixed Weight Deflator for OCA
1947	.00	617.30	100.00	59.55	59.55	---
1948	.00	617.30	100.00	54.14	54.14	---
1949	.00	617.30	100.00	66.17	66.17	---
1950	.00	617.30	100.00	59.55	59.55	---
1951	.00	617.30	100.00	63.16	63.16	---
1952	.00	617.30	100.00	63.16	63.16	---
1953	.00	617.30	100.00	66.17	66.17	---
1954	.00	617.30	100.00	66.17	66.17	---
1955	.00	617.30	100.00	68.71	68.71	---
1956	.00	617.30	100.00	72.78	72.78	---
1957	.00	617.30	100.00	73.13	73.13	---
1958	.06	617.30	99.94	72.81	73.13	---
1959	.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

Table 20

Hybrid Deflator for OCA Combining Computer Price Index from This Study With BEA Weights and Method

Year	Weight of Computers	Deflator for Computers	Weight of Other	Deflator for Other	Deflator for OCA
1947	.00	93046.00	100.00	59.55	59.55
1948	.00	93046.00	100.00	54.14	54.14
1949	.00	93046.00	100.00	66.17	66.17
1950	.00	93046.00	100.00	59.55	59.55
1951	.00	93046.00	100.00	63.16	63.16
1952	.00	93046.00	100.00	63.16	63.16
1953	.00	93046.00	100.00	66.17	66.17
1954	.00	34883.00	100.00	66.17	66.17
1955	.00	32543.00	100.00	68.71	68.71
1956	.00	28569.00	100.00	72.78	72.78
1957	.00	26377.00	100.00	73.13	73.13
1958	.00	23144.00	100.00	72.81	73.17
1959	.01	21064.00	99.99	70.73	71.80
1960	.09	11739.00	99.91	73.23	84.10
1961	.16	11145.00	99.84	77.07	95.22
1962	.32	7876.00	99.68	70.70	95.62
1963	.74	6650.00	99.26	70.94	119.75
1964	1.13	5647.00	98.87	72.49	135.49
1965	1.98	3715.00	98.02	69.13	141.18
1966	2.31	3538.00	97.69	68.21	148.40
1967	4.18	2229.00	95.82	69.85	160.12
1968	4.73	2063.00	95.27	65.97	160.34
1969	7.22	1497.00	92.78	72.30	175.14
1970	10.69	1264.00	89.31	74.50	201.62
1971	12.90	1220.00	87.10	79.29	226.43
1972	15.06	1109.00	84.94	77.98	233.22
1973	13.03	912.00	86.97	78.19	186.82
1974	11.17	912.00	88.83	80.34	173.23
1975	16.63	637.00	83.37	86.85	178.33
1976	18.51	585.00	81.49	86.37	178.65
1977	20.48	510.00	79.52	88.30	174.67
1978	32.13	342.00	67.87	90.66	171.41
1979	50.85	188.00	49.15	92.37	141.00
1980	55.93	167.00	44.07	94.79	135.18
1981	66.34	135.00	33.66	95.93	121.85
1982	72.20	100.00	27.80	100.00	100.00
1983	73.27	100.00	26.73	103.98	101.06
1984	81.97	63.00	18.03	98.03	69.32

in 1982 prices mean that the current value weight of computers is divided by larger and larger P^c numbers as one proceeds back into the 1970s and 1960s. The BEA's own current-value weight for computers within OCA is 45 percent for 1962, but the computer weight W^c (expressed in 1982 prices) is just 4 percent for that year. Worse yet, price changes from one year to the next are not calculated by averaging changes of component indexes. Instead the level of the OCA deflator is calculated relative to 1982 separately for each year. This means that the change of the OCA deflator from 1957 to 1982 is identical to that for "other" products, since the computer weight is zero for 1957, and the price decline of computers between 1957 and 1982 has absolutely no impact on the recorded change of the OCA deflator over that interval. For a year like 1971 when computers have a substantial 33 percent weight, the computer deflator of 474 is averaged together with the "other" deflator of 79, to yield an OCA deflator of 188.

Because the implicit deflator methodology treats separately each year relative to 1982, year-to-year changes produce nonsensical results. As the weight on the computer deflator increases through the 1960s, the BEA deflator for OCA increases rapidly even though computer prices are fixed and "other" prices increase very slowly. For instance, in 1962 the BEA deflator increases at an annual rate of 21.2 percent, which bears no resemblance to an average of the zero rate of change assumed for computers and the 8.4 percent decline for "other" products in OCA. It is important to note that this implicit deflator weighting technique will create nonsensical results for any computer index, not just the BEA index. Table 20 illustrates the same rapid rise in the "hybrid" OCA deflator, which uses our new computer processor index, occurs in 1959-72.

It should be emphasizes that the implicit deflator is only one of two indexes for

OCA published by the BEA. Table 7.13 of the NIPA publishes a fixed-weight deflator for OCA which, as shown in the right-hand column of Table 19, does not display the nonsensical properties of the implicit deflator. We emphasize the pitfalls of the implicit deflator methodology in this section for two reasons. First, the implicit deflator for OCA was the only deflator displayed by Cartwright (1986) 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. Thus any evaluation of the effects on real OCA investment or real PDE investment of introducing computer prices into the NIPA will be flawed for the same reasons that the implicit deflator is flawed.

The results of a much more sensible method of weighting are illustrated in Table 21. To avoid dependence of the results on a particular base year like 1982, the percentage changes in our computer price index and in the BEA "other OCA" deflator are weighted together using current value weights for the share of computers and other within OCA.[39] This technique can be called a "chain-linked Laspeyres" index, since the value weight used is for year t when the percentage change of each component is calculated from year t to year t+1. The resulting OCA index falls relative to the BEA index, as shown in the comparison of the implicit BEA deflator in Table 19 with the right-hand column of Table 21. Three graphs are provided to summarize these results. Figure 2 shows how the BEA weighting technique causes its OCA deflator to rise relative to either of its components between 1958 and 1971.

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[39] We use the BEA weights from 1966 to 1984. For 1951-65, we have created our own weights by taking the ratio of the value of U. S. computer shipments from Phister (1979) to total current-dollar OCA, 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, our current-dollar weight for computers in OCA in 1958 is 15 percent, as compared to the BEA's implausibly small value of 0.5 percent.

Table 21

New OCA Deflator Combining Computer Price Index From This Study With BEA Deflator for "Other", Weighted with Chain-Linked Laspeyres Method

Year	Weight of Computers	Deflator for Computers	Weight of Other	Deflator for Other	Deflator for OCA
1947	.00	93046.00	100.00	59.55	1365.04
1948	.00	93046.00	100.00	54.14	1240.95
1949	.00	93046.00	100.00	66.17	1516.72
1950	.00	93046.00	100.00	59.55	1365.04
1951	1.00	93046.00	99.00	63.16	1447.77
1952	2.00	93046.00	98.00	63.16	1447.77
1953	3.00	93046.00	97.00	66.17	1515.31
1954	3.00	34883.00	97.00	66.17	1471.36
1955	4.00	32543.00	96.00	68.71	1523.04
1956	7.00	28569.00	93.00	72.78	1601.22
1957	9.00	26377.00	91.00	73.13	1599.38
1958	15.00	23144.00	85.00	72.81	1574.33
1959	20.00	21064.00	80.00	70.73	1514.46
1960	22.00	11739.00	78.00	73.23	1385.35
1961	33.00	11145.00	67.00	77.07	1425.27
1962	45.00	7876.00	55.00	70.70	1199.61
1963	39.00	6650.00	61.00	70.94	1113.75
1964	46.00	5647.00	54.00	72.49	1058.82
1965	50.00	3715.00	50.00	69.13	851.22
1966	55.00	3538.00	45.00	68.21	825.12
1967	58.00	2229.00	42.00	69.85	646.87
1968	61.00	2063.00	39.00	65.97	603.80
1969	62.00	1497.00	38.00	72.30	514.57
1970	67.00	1264.00	33.00	74.50	468.64
1971	70.00	1220.00	30.00	79.29	467.16
1972	72.00	1109.00	28.00	77.98	434.80
1973	64.00	912.00	36.00	78.19	377.98
1974	59.00	912.00	41.00	80.34	381.69
1975	59.00	637.00	41.00	86.85	318.87
1976	61.00	585.00	39.00	86.37	302.57
1977	60.00	510.00	40.00	88.30	280.68
1978	64.00	342.00	36.00	90.66	223.19
1979	68.00	188.00	32.00	92.37	153.21
1980	69.00	167.00	31.00	94.79	142.52
1981	74.00	135.00	26.00	95.93	123.52
1982	72.00	100.00	28.00	100.00	100.00
1983	73.00	100.00	27.00	103.98	101.10
1984	75.00	63.00	25.00	98.03	71.02

Figure 3 contrasts the hybrid and chain-linked OCA deflators, both using our computer index and the BEA "other OCA deflator", from Tables 20 and 21. The following is a summary of the growth rates of the three alternative OCA deflators over selected intervals:

	Annual Percentage Rate of Change		
Alternative Deflators for OCA	1947-57	1957-72	1972-84
BEA Implicit (table 19)	2.08	6.39	-7.34
BEA Fixed Weight (table 19)	-.--	-2.49	-13.20
Hybrid (table 20)	2.08	8.05	-9.62
This Study (table 21)	1.60	-8.32	-14.01
BEA Implicit PDE Deflator (table 22)	4.91	2.31	6.47
PDE Deflator using our OCA (table 22)	4.75	1.57	5.60
Difference: our OCA minus BEA Impl. OCA	-0.48	-16.37	-4.39
Difference: our PDE minus BEA PDE	-0.16	-0.74	-0.87

Thus the difference between our index for OCA and the corresponding BEA index is negligible before 1957, and is much larger between 1957 and 1972 than after 1972. This is not surprising, since the BEA lacks a computer price index before 1969, and the implicit deflator weighting technique yields a spurious increase in the OCA deflator during this interval.

As for the PDE deflator implied by these OCA deflators, it is necessary to make the calculations using the chain-linked Laspeyres method, since a recalculation of the PDE deflator using the BEA's method with a 1982 base-year yields the same type of distortion as occurs in their calculation of the OCA deflator. As shown here, the difference between our PDE deflator and the BEA deflator for PDE is roughly the same in 1957-72 as in 1972-84. This occurs because the large difference between the

FIGURE 2
BEA IMPLICIT PRICE DEFLATORS FOR COMPUTERS, "OTHER" AND OCA

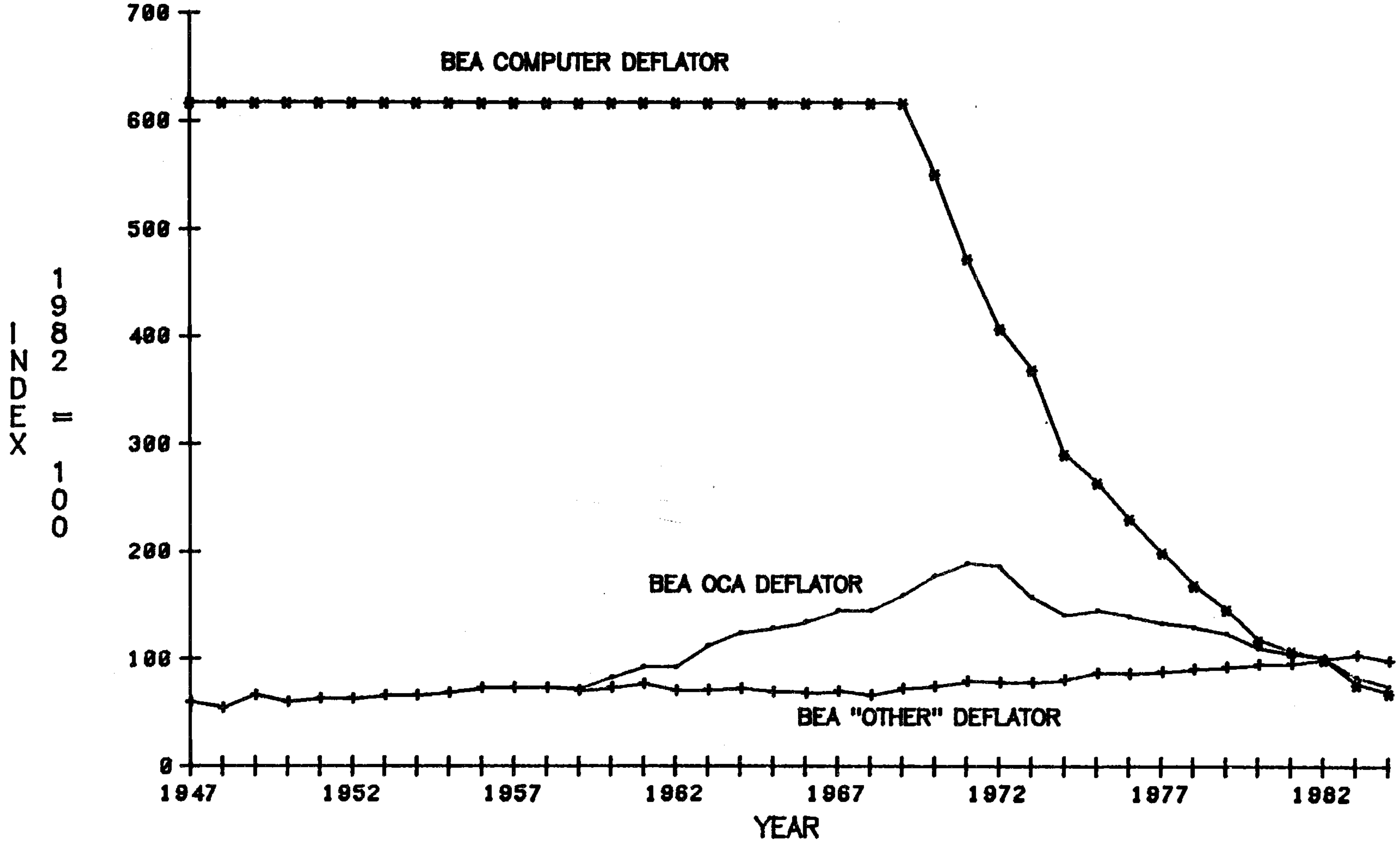

FIGURE 3
HYBRID OCA DEFLATORS COMBINING THIS STUDY'S COMPUTER PRICE INDEX WITH BEA DEFLATOR FOR "OTHER"

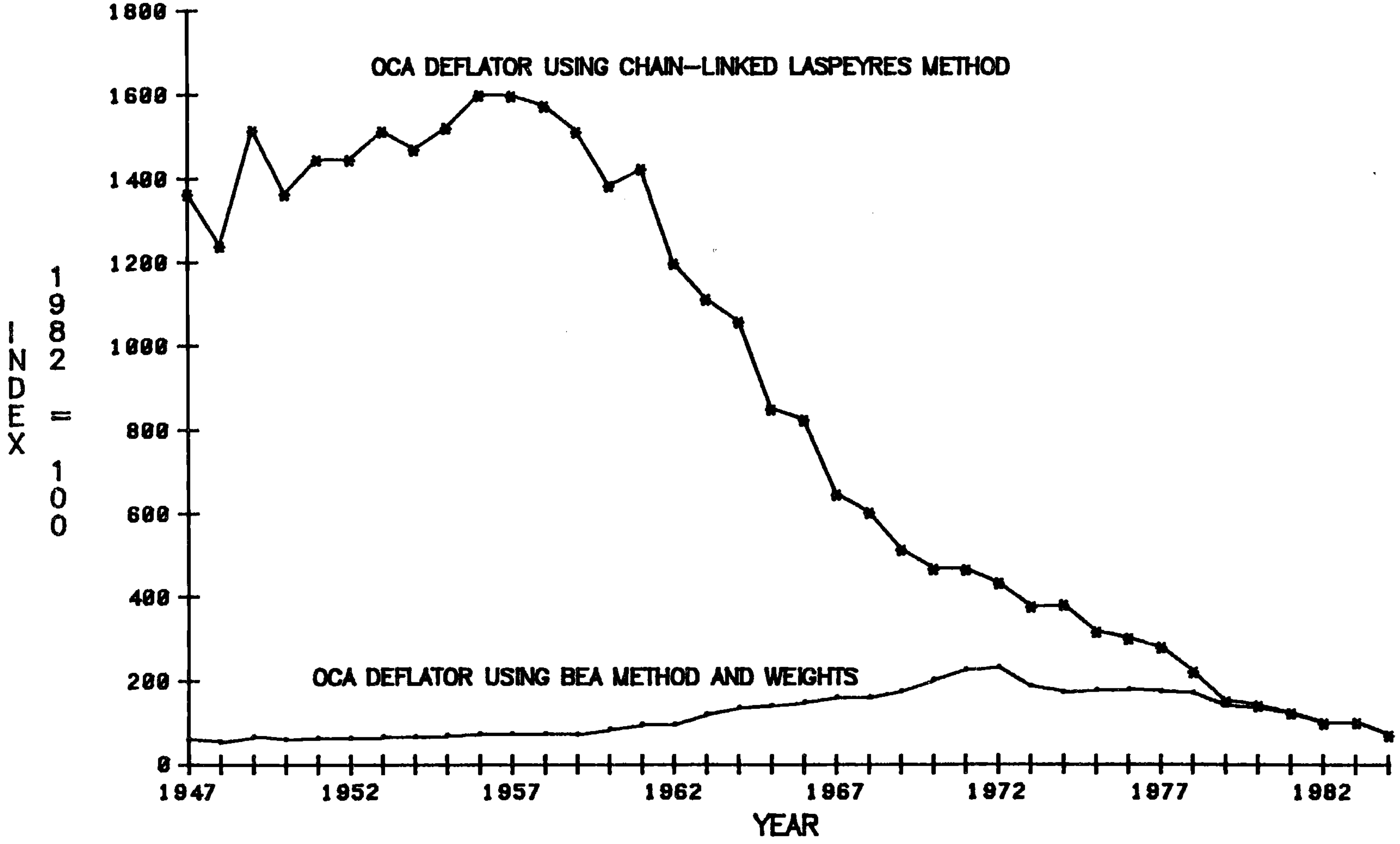

FIGURE 4

PRICE DEFLATORS FOR COMPUTERS AND OCA FROM THIS STUDY USING CHAIN-LINKED LASPEYRES METHOD

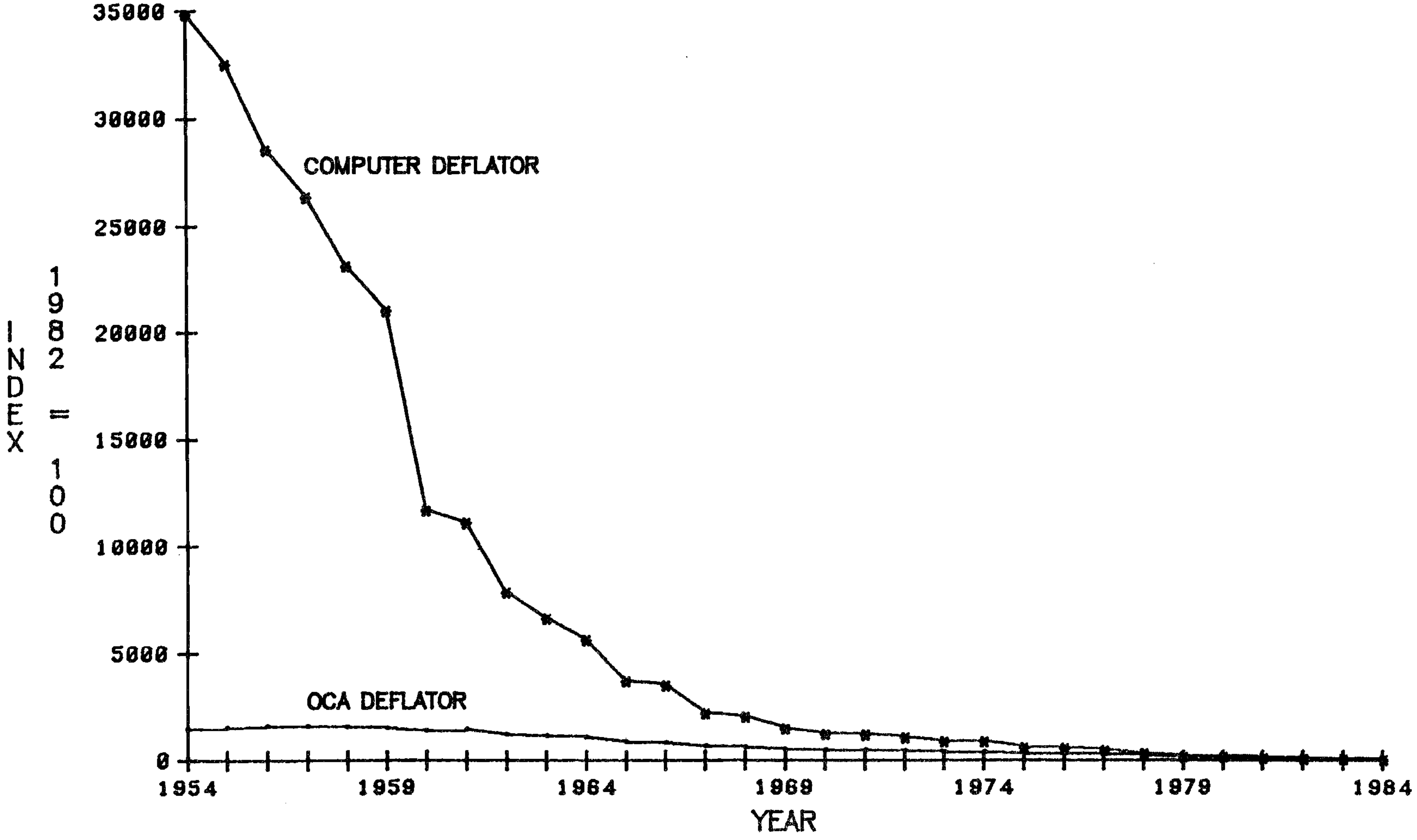

Table 22

New PDE Deflator Combining OCA Price Index From Table 19 With BEA Deflator for "Other" PDE, Weighted with Chain-Linked Laspeyres Method

Year	Weight of OCA	Deflator for OCA (Table 19)	Weight of Other PDE	Deflator for Other PDE	New PDE Deflator	Official PDE Deflator
1947	3.92	1365.04	96.08	20.08	25.95	20.62
1948	3.47	1240.95	96.53	22.03	28.26	22.50
1949	3.82	1516.72	96.18	23.37	30.13	23.97
1950	3.37	1365.04	96.63	24.50	31.40	25.00
1951	3.52	1447.77	96.48	25.91	33.21	26.46
1952	3.55	1447.77	96.45	26.32	33.71	26.88
1953	3.72	1515.31	96.28	27.06	34.68	27.67
1954	3.85	1471.36	96.15	27.97	35.77	28.61
1955	3.77	1523.04	96.23	28.61	36.60	29.25
1956	4.18	1601.22	95.82	30.22	38.65	30.98
1957	4.90	1599.38	95.10	32.38	41.29	33.29
1958	5.62	1574.33	94.38	32.91	41.91	33.97
1959	4.59	1514.46	95.41	33.79	42.87	34.64
1960	5.05	1385.35	94.95	34.60	43.67	35.65
1961	4.84	1425.27	95.16	34.81	43.98	35.90
1962	4.05	1199.61	95.95	35.20	44.08	36.11
1963	5.23	1113.75	94.77	34.87	43.55	36.17
1964	5.17	1058.82	94.83	34.82	43.38	36.17
1965	4.80	851.22	95.20	35.13	43.26	36.41
1966	5.85	825.12	94.15	35.62	43.76	37.22
1967	5.96	646.87	94.04	36.75	44.44	38.47
1968	5.47	603.80	94.53	38.32	46.03	39.93
1969	6.13	514.57	93.87	39.66	47.13	41.58
1970	6.20	468.64	93.80	41.17	48.53	43.23
1971	5.82	467.16	94.18	43.45	51.04	45.50
1972	6.24	434.80	93.76	44.66	52.16	46.87
1973	5.93	377.98	94.07	45.36	52.46	47.34
1974	6.37	381.69	93.63	48.99	56.44	51.11
1975	5.72	318.87	94.28	57.69	65.03	59.75
1976	6.09	302.57	93.91	62.24	69.64	64.39
1977	5.90	280.68	94.10	66.33	73.59	68.34
1978	6.52	223.19	93.48	71.17	77.58	73.31
1979	7.13	153.21	92.87	76.44	80.92	78.55
1980	7.99	142.52	92.01	84.41	88.28	85.97
1981	9.02	123.52	90.98	92.71	95.14	93.63
1982	9.31	100.00	90.69	100.00	100.00	100.00
1983	11.47	101.10	88.53	102.83	102.66	99.87
1984	12.03	71.02	87.97	104.80	100.27	99.50

OCA deflators in 1957-72 receives a relatively small weight (based on the current-dollar share of OCA in PDE), whereas the smaller difference in 1972-84 receives a much larger weight.

VIII. CONCLUSION

Personal Computers

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 a "pilot study" are shown in Table 23. 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 and 1985-86, we have access to issues of PC magazine for early November in each of the three years.

As explained in the notes to Table 23, price changes for 1984-85 and 1985-86 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 labelled "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

Table 23

Price Changes for Personal Computers and Peripherals, 1982-86

(Numbers of models indicated in parentheses)

	1982	1983	1984	1985	1986
Processors					
1. Matched Model	-20.4(1)	-23.1 (1)	-22.7 (1)	-16.7 (3)	-26.3 (5)
2. Matched Characteristics	---	---	---	---	-38.9 (5)
Peripherals					
3. Printers - Matched Model	---	---	---	-30.7 (4)	-12.0(16)
4. Hard Drives - Matched Characteristics	---	---	---	-62.7 (1)	-12.3 (2)
5. Other - Matched Model	---	---	---	-21.1 (4)	-14.9 (4)
6. Other - Matched Characteristics	---	---	---	-47.8 (4)	-31.5 (3)

Notes for Table 23

Code for source notes: PCN refers to ads for PC Network in PC Magazine, issues for Nov. 27, 1984, Nov. 12, 1985, and Nov. 11, 1986. PCL refers to ads for PC's Limited, same issues, LS refers to ads for Logic Soft, same issues.

Source by line ("1985" refers to comparison of 1984 with 1985, etc.):

1. 1982-84. Business Week, March 25, 1985, p.29.
   1985. Above source combined with PCN for IBM basic unit and IBM-XT.
   1986. Four models from PCN (IBM basic, IBM-XT, Compaq portable 20MB, Compaq Deskpro 20MB harddrive with 10MB tape), and an AT clone from PCL.

2. Replaces IBM basic and IBM-XT with PC Network clones.

3. 1985. PCN: Epson FX-80 (FX-85 in 1985), LQ-1500, Toshiba 1340 and 1351.
   1986. PCN: Citizen MSP-10, MSP-15, MSP-25, Epson FX-85, NEC 2050, 3550, 8850, and Toshiba P351.
   LS: Citizen MSP-10, MSP-15, MSP-20, MSP-25, Okidata 182P, 192P, 2410P, and Toshiba P351.

4. 1985. PCN: Tandon 10MB internal hard drive.
   1986. PCN: Clone 10MB internal and 20MB internal.

5. 1985. PCN: Hayes Smartmodem 1200B, AST 6 Pak, Hercules monochrome card, and 10 DSDD diskettes.
   1986. PCN: Same as 1985

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.

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 slightly more rapid than the IBM computer processor index in Table 18, and about the same as for our final processor index. The results for peripherals are mixed, with much faster rates of price decline in 1984-85 than for the peripherals studied by Cole et. al. (1986) for 1972-84, but quite similar rates of price decline in 1985-86 as in the Cole study. The next research task should be an attempt to collect analogous MM and MC measures of price change for years before 1984-85.

Implications and Agenda for Future Research

This study has developed new price indexes for mainframe computers covering the period 1951-84, including supermini computers for the period 1979-84. The resulting rates of price change are almost identical to the original Chow study in 1954-65, somewhat slower during 1965-77, and more rapid again during 1977-84. The new price index for computer processors is aggregated into a deflator for the Office, Computing, and Accounting Machinery (OCA) component of Producers' Durable Equipment (PDE), using both the BEA implicit deflator weighting methodology and the more sensible chain-linked Laspeyres alternative. 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 some other studies covering parts of the postwar period, but the finding that the implicit BEA deflator for OCA overstates the rate of price increase at an annual rate of 16.4 percent during the period 1957-72. Primarily weighting issues also account for a 4.4 percentage point excess in the rate of price decline in our OCA deflator than in the BEA OCA deflator for the more recent 1972-84 period.

When these alternative OCA deflators are aggregated into deflators for all of PDE, the differences are much more modest, amounting to about three-quarters of one percent for the period since 1957. There is little difference in the contribution of our new indexes to the PDE deflator for 1957-72 and 1972-84, since the growing weight of OCA offsets the shrinking size of the difference between our OCA deflator and that of the BEA. The fact that our 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 paper have few if any implications for the post-1972 slowdown in U. S. productivity growth.

However, this paper is only a small part of a much larger study of durable goods prices covering the entire postwar period. Preliminary results from that study indicate that our new deflator for PDE, based on more than 100 products covering 15 of the 22 components of PDE (including OCA), increases at an annual rate 3 percentage points less than that of the current BEA PDE deflator. Of this difference, the results for computers account for about one-quarter (i.e., for 0.75 times 3.0), and the remaining revisions are accounted for by the remaining products.

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