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3 Sources of Price Decline in Computer Processors: Selected Electronic Components

Ellen R. Dulberger

Technological change in electronic components has been largely responsible for the increased capabilities of products to process and store information. The rapid pace of technological change embodied in chips and the packages in which they are connected makes their lives short. This creates difficult problems in measuring the output and prices of these products and hence value-added in industries consuming them. These measurement problems may be responsible for large errors in components of the producer price index (PPI) resulting in price declines far smaller than actual and hence inconsistent with larger declines in the implicit deflator for computing equipment in the national income and product accounts (NIPA).

This paper focuses on those electronic products used in the manufacture of computer processors. Evidence is presented that supports the view that prices of these products decline much more rapidly than measured by the PPI for these products and, as should be the case, even more rapidly than prices for computer processors. Provided first is a description of the electronic products used in computer processors. Next the (un)reasonableness of price changes in components of the PPI as compared with those in newly developed measures is explored. Alternative price indexes for selected electronic products constructed here are examined for differences arising from choice of formula, and an explicit assessment of the effect of delayed introduction of new products is provided. Finally, the alternative indexes are assessed for consistency with the NIPA deflator for computer equipment purchases. Section 3.1 contains descriptions and discussions of electronic components used in the manufacture

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of computer processors and the technological change that these products have undergone. Section 3.2 presents the data, describes the alternative price indexes constructed, and examines their credibility.

3.1 Products

Electronic packages contain many electrical circuit components that become circuits when interconnected. The lowest-level semiconductor device that contains circuits or circuit components is the chip. The complexity and cost of an electronic package increase with the number of chips interconnected and the number of interconnections in the package.[1] The first-level package provides the support and protection for the small, fragile chip terminals. Cards on which chips are mounted are the most common second-level package. These simple packages are used in the manufacture of many consumer products such as compact disc players and hand calculators where the total chip count is likely to be less than ten. When used in higher-level packages, cards (sometimes called daughter boards) are plugged into third-level packages (sometimes called mother boards). These third-level packages are the guts of personal computers (such as the IBM PS/2 and the Apple PC) today. The total number of chips in these third-level packages is usually in the tens.

The microelectronic packages described thus far are simple and inexpensive compared with those in high-performance computer processors. These packages consist of relatively few chips, and the amount of heat that they generate does not require additional chip cooling within the electronic package.

The logic of large general purpose computers today is made of complex electronic component packages of thousands of chips. To achieve the speeds at which they process instructions, the packages and chips interconnected therein are very different from the products described earlier in design, materials, and production processes used.[2] Examples of the logic packages produced by two manufacturers of large general purpose processors illustrate two different ways of achieving high levels of integration. In the case of the Hitachi 680, the chips are mounted in multichip modules (MCMs), which are then connected to polyimid-glass (P-G) cards. These P-G cards are in turn cable connected to P-G boards, which are air cooled (see Tummala and Rymaszewski 1989, table 1-2, p. 26). A very different logic package is used in an IBM 3090 processor. It contains chips mounted on multilayer ceramic substrates in water-cooled thermal conduction modules (TCMs). The TCMs are connected using a pin-through hole process onto epoxy-glass boards, which are cable connected and water cooled.[3]

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[1] For a discussion of the complexity and cost of interconnections, see Noyce (1977).

[2] For a discussion of complex high-level ceramic packages, see Black (1986).

[3] For an analogous discussion of electronic packaging hierarchy as it pertains to communication equipment, see Mayo (1986).

3.1.1 Technological Change

Major improvements in the performance of these products, that is, in the speed at which instructions are executed and in the capacity to store information in main memory, have come from increased density at the chip level (more circuits and bits on the chip) and denser interconnections on the package. Technological advances in density result when finer lines can be drawn closer together, shortening the distance the electrons travel yet not generating so much heat that the circuits melt.

Main Memory

The first product to be manufactured once a new level of density has been achieved is the memory chip. The reason for this is based on the differences in function between memory and logic. Memory elements are infrequently actively used in an operation, and they are much simpler physically than are logic circuits (most often called gates), so a memory cell occupies less area on a silicon chip than does a logic circuit and will require fewer chip-to-chip connections, making it easier to manufacture. Therefore, for a given technology, defined in terms of chip density and materials and process, such as complementary metal-oxide semiconductor, CMOS, the first product manufactured will be memory chips. The relation between density, application, and interconnections is reproduced in figure 3.1.

In general, main memory in processors of all sizes is composed of the same MOS (metal oxide on silicon) dynamic random access memory (DRAM) chips, although the final memory package will differ with the memory size in the final product. The same is not true for logic. Logic packages in high-performance and low-end processors differ all the way down to the chips themselves. In low-end processors, the logic chips are often made using the same manufacturing process and, indeed, are manufactured on the same production lines as the memory chips. As is the case for CMOS chips, improvements in logic parallel improvements in memory, as illustrated in figure 3.2. Quality-adjusted price declines in CMOS logic chips will be at least as steep as those in memory, but they will be steeper when design changes permit more work to be accomplished in a cycle.

In 1974, DRAMs stored 4k (kilobits) of data. 64k DRAMs were in use in 1979, and by 1985 1 Mb DRAMs were widely used. The Dataquest history of prices and quantities of DRAMs is provided in the upper panel of table 3.1. For each density, it is observed that quantities shipped have increased at a rapid pace for at least four years after introduction and that, during that time, prices decline rapidly as well. The lower panel of table 3.1 presents the value shares of shipments by density through time. Indeed, in three of the four cases shown, the market share of chips embodying new technology exceeds 20 percent just one year after introduction.

Transformations of the entries in table 3.1 to refer to kilobits rather than

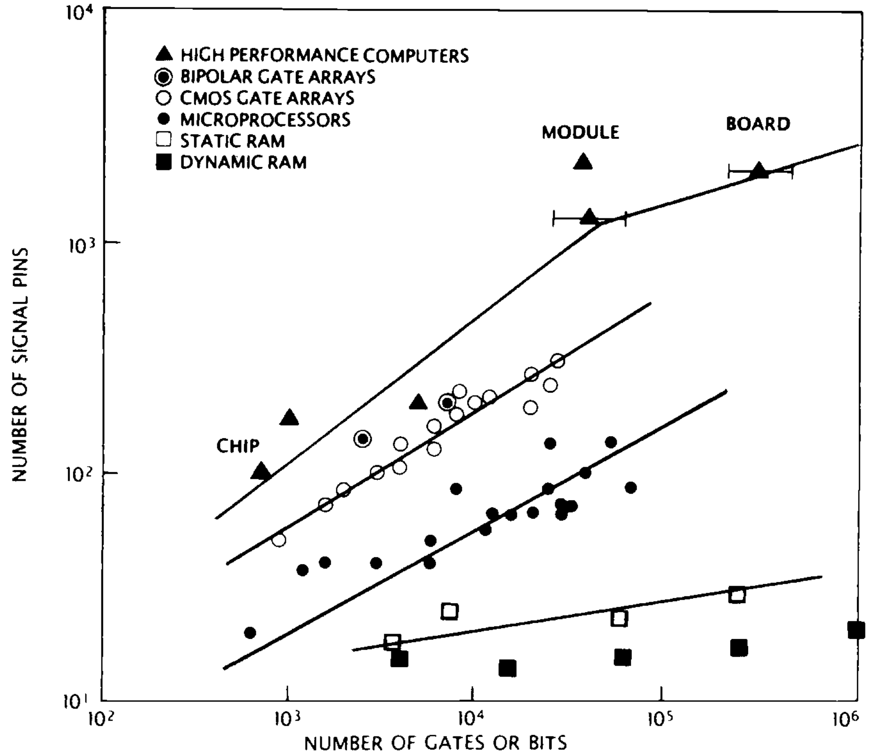

Fig. 3.1 Rent's rule

Note: Rent's rule describes the relation between the number of logic circuits on a chip and the number of pins (leads) needed to connect the chip to the rest of the system. The rule is empirical, worked out in the 1960s as experience with chips was accumulated. Rent's rule forms part of an overall model linking the properties of materials, devices, and circuits with those of the system in which they work.
Source: Meindl (1988).

chips are presented in table 3.2. Although new, denser chips are introduced at higher prices per kilobit than the prevailing prices of those against which they compete, it usually takes less than two years for the new chip to offer the lowest price per kilobit. It should be noted that computers need not have used each of these chips in each year they were available. Indeed, indicated in table 3.2 by parentheses are observations that are not relevant to the main memories in computer processors according to Dulberger's (1989) sample, which was used in the Bureau of Economic Analysis (BEA) price deflator for computing equipment.[4] If this sample is representative of the use of DRAMs by the universe of computer processor manufacturers, then prices in parentheses would

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[4] This sample is composed of large and intermediate IBM and plug-compatible processors.

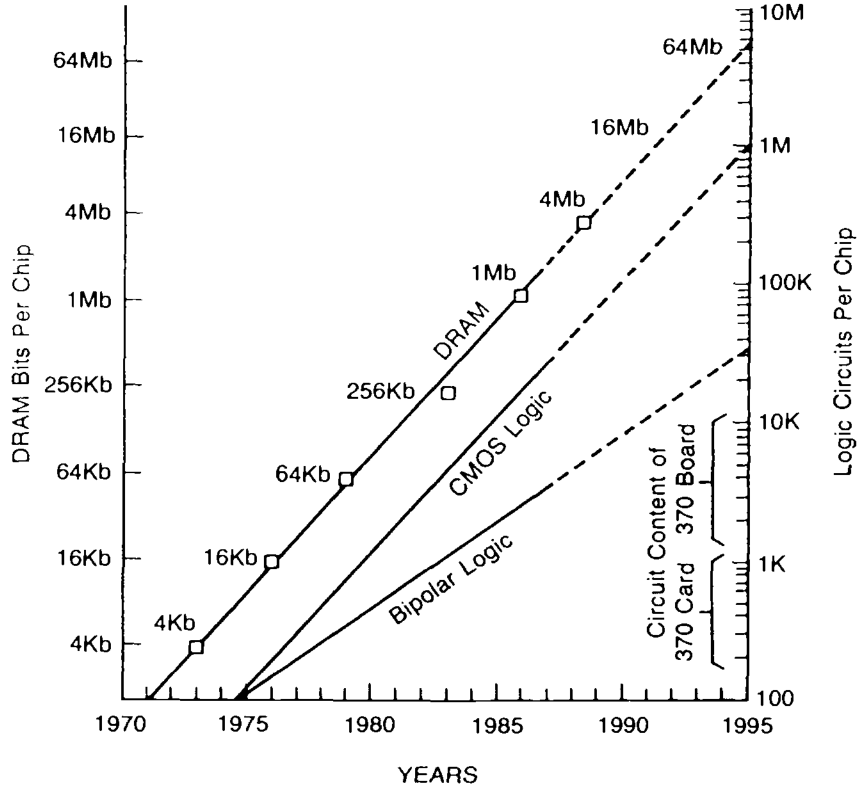

Fig. 3.2 Levels of integration: logic and memory chips

Note: Progress in level of integration. By 1980, circuits per single random logic chip matched the circuit content of an IBM 370 card, introduced ten years earlier. In another five to ten years, the circuits per single chip reached those of an IBM 370 board.

Source: Tummala and Rymaszewski (1989).

not enter a price index of inputs to processors. Indeed, the big price increases at the end of the 4k chip's life would not enter the price index.

The success of the new chips introduced at a higher than prevailing price per kilobit is in need of explanation. Common sense suggests that something is missing; only products offering lower quality-adjusted prices should drive existing products out of production. Although the important attribute of these chips is the amount of data they store, their use in higher-level packages may justify their higher price. By reducing amounts of other resources that manufacturers will consume in making the final product, final memory package cost may be lowered.

For example, to achieve the same maximum memory capacity with new chips that are four times as dense as the previous generation requires one-

Table 3.1 **DRAMs Used in Main Memories of Selected Large General Purpose Processors, Merchant Market**

	4k		16k		64k		256k		1Mb	
Year	P	Q	P	Q	P	Q	P	Q	P	Q
1974	(23.00)	.62								
1975	7.25	5.29								
1976	4.44	28.01								
1977	2.75	57.42								
1978	1.83	77.19								
1979	2.00	70.01			117.50	0.04				
1980	1.93	31.17	(7.88)	1.12	62.50	0.44				
1981	1.71	13.04	4.13	5.71	14.38	12.63				
1982	1.68	4.64	2.33	23.24	5.69	103.97				
1983	(2.75)	2.40	1.96	57.40	3.86	371.34	69.00	1.70		
1984	(3.00)	2.25	2.06	40.60	3.21	851.60	21.50	37.98		
1985	(3.75)	2.35	(1.63)	20.91	1.09	509.67	4.98	201.58		
1986					1.03	404.91	2.31	618.53	34.50	5.66
1987					(1.10)	152.60	2.35	766.30	15.13	42.60
1988					(1.60)	96.90	(3.06)	947.00	16.71	211.60
Average annual rates of change in prices, selected periods										
1975–82	−18.9									
1982–84	(33.6)		(−6.0)		−24.9					
1984–88					(−16.0)		−38.6			
1975–84	−9.3									

	Value Shares of Shipments, Percentage of Total by Year				
	4k	16k	64k	256k	1Mb
1974–78	100.0				
1979	97.1		2.9		
1980	62.3	9.1	28.6		
1981	9.8	10.4	79.8		
1982	1.2	8.3	90.5		
1983	0.4	6.7	85.8	7.0	
1984	0.2	2.3	75.1	22.4	
1985	0.6	2.1	34.6	62.7	
1986			20.3	70.1	9.6
1987			6.4	68.9	24.7
1988			2.3	44.0	53.6

Note: Parentheses indicate values available from Dataquest that would not enter an input price index for computer processors according to Dulberger's sample. P = dollars/chip. Q = thousands of units.

Source: Dataquest, *Semiconductor Industry Service.*

Table 3.2 **DRAMs Used in Main Memories of Selected Large General Purpose Processors, Merchant Market Prices (dollars/kilobit)**

Year	4k	16k	64k	256k	1Mb (1,024k)
1974	(5.750)				
1975	1.813				
1976	1.109				
1977	0.688				
1978	0.456				
1979	0.500		1.836		
1980	0.481	(0.492)	0.977		
1981	0.428	0.258	0.225		
1982	0.419	0.145	0.089		
1983	(0.688)	0.123	0.060	0.270	
1984	(0.750)	0.129	0.050	0.084	
1985	(0.938)	(0.102)	0.017	0.019	
1986			0.016	0.009	0.034
1987			(0.017)	0.009	0.015
1988			(0.025)	(0.012)	0.016

Average annual percentage change in lowest price/kilobit, selected periods, chips used in processors

1975–82	−35.0	(4k in 1975 compared with 64k in 1982)
1982–84	−25.0	(64k in both periods)
1984–87	−43.5	(64k in 1984 compared with 256k in 1987)
1987–88	77.8	(256k in 1987 compared with 1Mb in 1988)
1975–84	−32.9	
1975–87	−35.7	

Note: Entries are computed by dividing Dataquest prices in table 3.1 by the number of kilobits per chip. Parentheses indicate values available from Dataquest that would not enter an input price index for computer processors according to Dulberger's sample.

fourth the number of chips. Packaging fewer chips requires fewer interconnections, less complex packages, and sometimes fewer levels of packaging. In this way, the previous maximum size of main memory costs less per unit of capacity (commonly measured in megabytes) to manufacture, thus enabling producers to pass along these lower costs to their customers.

By the time the new chips have come down in price to where they offer the lowest price per kilobit, their use is widespread in smaller processors and other products with smaller packaging requirements. This widespread use hastens the disappearance of previous generations. A price index constructed on the basis of kilobits as the only attribute may be biased in the direction of understating the quality-adjusted price declines in these products.

If quality-adjusted prices of higher levels of packaging kept pace with those of the chips, we would see similar price declines in the price per megabyte of main memory. Some evidence is provided by Cole et al. (1986), who found that the change in the price per megabyte of main memory was −23.6 percent per year for the period 1975–84. This suggests that the declines in the quality-adjusted prices of higher levels of packaging were close but did not quite keep pace with those of chips.[5]

It is important to recognize that packaging is often as important as the chip in producing lower quality-adjusted prices. Examples of some packages are useful in understanding the complexity of packages that resulted in capacities shown in table 3.3.[6] In 1975, one main memory package was composed of 32,000 2k chips packaged on four-chip modules packaged on thirty-two-module cards, eight of which plugged into each of four boards that were cable connected. By the mid-1980s, a card, 250 × 170 millimeters, could hold 160 chips. This meant card capacities of 4MB with 256k DRAMs and 16MB with 1Mb chips. Half a gigabyte was achieved by connecting 16MB on both sides of sixteen cards at the board level (4,000 1Mb chips) (Tummala and Rymaszewski, 1989, 57).

Logic

Comparisons of performance in logic chips and packages in high-end processors are not easily made. Improvements at the chip level reduce the inter-level connections. Improving packaging achieves a reduction in wiring length, thus shortening the distance traveled. This is key to improving CPU (central processing unit) cycle time, a major determinant of processor speed. Table 3.4 provides CPU cycle time and processor speed measured in 370 equivalent MIPS for selected large general purpose processors.[7] In addition, for three processors, the contributions to CPU cycle time of the chips and the packages are shown. A comparison of performance characteristics of selected processors and embodied chips and packages is shown in table 3.4.[8]

Table 3.4 shows that the relation between CPU cycle time and processor speed may be different across manufacturers. In addition, improvements in chips may occur at a different rate than improvements in the package. The Amdahl 470 processor was 50 percent faster in terms of 370 equivalent MIPS

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[5] The price indexes produced by Cole et al. (1986) were used by BEA in deflating purchase of computing equipment in the NIPAs, 1972–84.

[6] For a detailed description of the main memory of the IBM 370/168, see Rajchman (1977, 1225).

[7] MIPS, millions of instructions per second, is a widely used measure of processor speed in which each instruction is weighted by its frequency of use in a specific job mix. For more discussion of 370 equivalent MIPS with respect to its adequacy as a measure of processor speed and its comparability across processors, see Cole et al. (1986, 41–42).

[8] For a given manufacturer, within a family of processors (not shown in table) it is not unusual to find members with the same CPU cycle time rated at different MIPS. Models selected for inclusion in table 3.4 are those with the highest MIPS ratings in their family. Smaller (slower) members of a family are products made with less hardware. In these products, more CPU cycles are used to accomplish the same work done in one cycle of the bigger boxes.

Although the technological "race" is often discussed in terms of the fastest uniprocessor because it represents the shortest time to do any activity, it should be noted that manufacturers vary in their ability to lash multiple processors together to produce a single system image. During the 1980s, it was not uncommon to find that the manufacturer with the fastest uniprocessor was not the same as the one that made the fastest single system image. Similarly, manufacturers vary in their ability to design hardware that gets the most work done in one cycle.

Table 3.3 **Memory Chips Used in Maximum Main Memory Capacity Selected Large General Purpose Processors**

Year First Shipped	Maximum Memory Capacity	Memory Chip Included (bits/chip)
1975	8MB	2k, 4k
1979	16MB	2k, 4k
1980	16MB	2k, 4k, 16k
1981	16MB	64k
1982	32MB	64k
1983	32MB	64k
1984	32MB	64k, 256k
1985	32MB	1Mb
1986	1GB	1Mb
1987	1GB	1Mb
1988	1GB	1Mb
1989	1GB	1Mb, 4Mb

Note: These are maximum main memory capacities available on uniprocessors available in Dulberger's sample, 1975–84, updated through 1989. For single system images achieved with multiple processors, the maximum main memory is usually equal to the number of processors multiplied by the maximum for each. In 1986, a new member of the memory hierarchy called expanded storage was introduced. Expanded storage is composed of DRAMs, too, but is not within the same package as main memory. If included in the table, chip density of the maximum each year would be the same as shown, but maximum capacity would be much larger in 1988 and 1989.

Table 3.4 **Elements of Performance Improvements in Logic: Selected Large General Purpose Processors**

First Year Shipped	Mfr.	Model	CPU Cycle Time (ns)	Chip (ns)	Package (ns)	370 Equivalent MIPS
1973	IBM	168	80	40	40	2.3
1975	Amdahl	470	32			3.45
1978	IBM	3033	57	29	28	5.9
1982	IBM	3083	26	17	9	7.9
1982	Amdahl	580	26			13.0
1987	IBM	3090E	17.2			18.0
1987	NAS	XL60	18			21.0

Note: These are single processors, to be distinguished from multiple processors closely coupled in a single system image. ns = nanoseconds.

Sources: Entries for CPU cycle time, chip delay, and package delay for the years 1978 and 1982 are from Balderes and White (1989); 1973 values are from private discussions with D. Balderes (March 1990). 370 equivalent MIPS ratings are from Cole et al. (1986) updated thorugh 1987. CPU cycle times for Amdahl and NAS processors were taken from trade press reports.

than was the IBM 168 against which it competed, even though its CPU cycle time was more than 2.5 times shorter. Comparison of two competing processors with the same CPU cycle time, IBM's 3083 and Amdahl's 580, reveals that the 3083 was rated at executing 4.1 million fewer instructions in one second than the 580.

These comparisons illustrate that CPU cycle time is an inadequate measure of processor speed because it does not account for differences in design that affect speed. This inadequacy is true for products of the same manufacturer as well as across manufacturers. Furthermore, although a benchmark test such as that used in measuring 370 equivalent MIPS may be based on a work load not representative for some applications, such speed measures do provide a measure of each processor's ability to accomplish the same work.

Improvements in chips and packages are not always parallel. For example, for the processors in table 3.4, improvements made from 1973 to 1978 were about the same. But packaging improvements made from 1978 to 1982 were far greater. The importance of design and the proprietary nature of logic from the chips through the highest packaging level makes quality comparisons at lower levels most difficult.

At the chip level, density improvements in high-end (bipolar) logic have not kept pace with the rate of improvements in low-end (CMOS) logic. This was shown in figure 3.2 above. If it follows that quality-adjusted price declines in bipolar chips did not keep pace with CMOS chips, higher-level packaging improvements may make up a good part of the difference. Cole et al. (1986) offer some indirect evidence that logic packages in large general purpose processors did not decline in price quite as rapidly as did main memory. Their estimate of average price change was −21.0 percent for speed and −23.6 percent for main memory capacity during the period 1974–84. One would expect the difference to be greater after 1984, when the pace of technological improvement in CMOS memory and logic picked up.

3.2 Price Indexes for Selected Electronic Components

3.2.1 Publicly Available Price Indexes

Publicly available price indexes for the chip level, higher-level packages, and computer processors are shown in table 3.5. The price indexes for chips and higher-level packages are components of the PPI published by the Bureau of Labor Statistics (BLS). The processor price index is a component of the price deflator for office and computing equipment used by BEA in the NIPAs.

Table 3.5 shows the magnitude of inconsistency between price indexes of key inputs to computing equipment published by BLS and BEA's implicit price deflator for computer processors. The price changes in tables 3.1 and 3.2 above, although not aggregated into an index, suggest much more rapid price declines than are found in the PPI component. For example, the average price decline from 1984 to 1988 in the PPI component for MOS memories was 7.3 percent, while price declines (recorded in table 3.1) for the dominant chips of that period, the 64k and the 256k, were 16.0 and 38.6 percent, respectively. In the next section, additional evidence is compiled and explored.

Table 3.5 **Selected PPI Components and Implicit Deflator for Computer Processors (1982 = 100)**

	Chips		Higher-Level Packages	Final Product
Year	PPI: MOS memories (code 11784221)	PPI: Logic/ Microprocessors (code 11784225)	PPIR: Printed Circuit Boards and Circuitry on Passive Substrates (code PPU3679#H02)	Computer Processor Component of Price Index for Computing Equipment
1972				855.9
1973				924.5
1974				788.6
1975	. . .			703.7
1976	212.1			655.3
1977	. . .			473.6
1978	186.5			242.0
1979	168.8			204.9
1980	. . .			147.2
1981	. . .			118.6
1982	. . .	. . .	. . .	100.0
1983	. . .	96.3	99.9	93.9
1984	101.3	100.9	103.9	76.9
1985	73.4	. . .	106.5	51.2
1986	61.7	. . .	108.2	47.3
1987	63.5	80.4	110.2	40.3
1988	74.9	77.2	113.9	38.2
1989	82.8	80.3	115.4	36.3
Annual average rates of change				
1976–82	. . .	. . .	. . .	−26.9
1982–84	. . .	. . .	. . .	−12.3
1984–88	−7.3	−6.5	3.3	−16.0
1988–89	10.5	4.0	1.3	−5.0
1976–84	−8.8	. . .	. . .	−23.5
1976–89	−7.0	. . .	. . .	−20.0

Note: Ellipses points indicate one or missing data points within the year prohibiting the calculation of an annual average.

3.2.2 The Effects of Alternative Index Formulas

At this point, constructing some price indexes from the Dataquest data on MOS memory chips is helpful in illustrating the magnitude of price declines in these data and the sensitivity of price indexes for these products to the index number procedure employed. A logical starting point would be to replicate BLS methodology using these alternative prices, but, since BLS can release neither the weights nor the dates of entry of products embodying new technology into the index, we may construct a price index in the spirit of BLS procedure only.[9]

Dataquest Data

A brief description of the Dataquest data is worthwhile before proceeding. According to Dataquest analysts specializing in the semiconductor industry, the price data collected by chip and density are average prices paid compiled from interviews with purchasers. This source is used because producers are usually unwilling to provide prices.[10] These price "averages" need not refer solely to shipments of products manufactured in the United States. It is the opinion of these analysts that since, the prices by type and density vary so little (which makes sense for commodities), this procedure is not likely to produce misleading estimates of prices.[11]

The shipments data are collected from firms that produce them. Dataquest organizes the data by geographic location of the firm's headquarters, which is an increasingly poor approximation for production as this industry becomes more global. For example, the shipments from an establishment in Europe of a U.S.-based firm will be included in Dataquest's U.S. shipments.

In addition, shipments are those of merchant manufacturers only, which is important to note because captive production of these products is significant. As gathered, because these data differ from what is needed to calculate price indexes comparable to the PPI component, one would expect the value shares calculated to differ from those actually used by BLS. A comparison of the year-to-year relatives in the Laspeyres chain calculated from Dataquest prices and value shares (weights) from the Dataquest data and Census data is discussed later in section 3.2.2 and presented in table 3.9 below.

BLS Procedure for PPI Component

A short digression here to explore BLS procedure for estimating the PPI component for these products is helpful in understanding the nature of the published index and the basis for the index constructed in its spirit. The MOS memory component of the PPI is considered a "cell." This means that this is the lowest level at which a price index is calculated and then aggregated using a fixed weight. From December 1974 through June 1981, the index uses equal weights for all products for which prices are reported. For the period July 1981 through June 1986, the weights used would be based on the value share

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[9] BLS's refusal is based on concerns about violating the guarantee of respondent confidentiality. To encourage pursuit of the issues raised here, these data have been given to BLS on diskette.

[10] With respect to data organization, however, prices for the same density do vary because organization affects the number of interchip connections required. A true price index of models with matched characteristics would require organization as a characteristic. The importance of organization as an attribute is minor compared with capacity. For additional discussion of organizations, see Flamm (chap. 5 in this volume).

[11] Dataquest analysts generously provided their insights. The discussions took place throughout 1988.

of shipments of respondents in 1979. From July 1986 through the present, the weights are based on the value share of shipments in 1984. The published index is the result of chaining together three Laspeyres indexes, each with its own base period weights, and then normalizing the index to set it equal to 100 in 1982.

According to BLS, the weights as determined by importance of a particular product to the value of shipments of the respondents should approximate the product's importance as published by the Census Bureau in the Current Industrial Report (CIR). However, I was told that BLS does not routinely check its weights against those that could be calculated from Census data, and for these products such a check was not done.[12] Nor would BLS make available its weights for outside verification.

Price Indexes

Price indexes constructed from Dataquest data. It is clear that it would be preferable to use CIR rather than Dataquest to estimate the value shares needed for the price index calculations. However, detail by chip type and density were not shown in the CIR until 1984. In order to capture the spirit of BLS procedure and apply it to the Dataquest data on both prices and value share of shipments, I have proceeded as follows: (1) Treat the cell as the lowest level of detail for which data are available; for example, the price of the 256k DRAM will be weighted by its value share of the shipments in the year appropriate for the index formula. (2) For the period 1977–82, changes in a Laspeyres index with 1977 weights are used; thereafter, the index is Laspeyres with a 1982 base. This formula will be referred to as "Spirit" for the remainder of the paper and all tables.

Table 3.6 presents average compound growth rates for the period 1977–88 for each of five index formulas and six types of chips and aggregates. The formulas employed are Laspeyres, Paasche, Fisher Ideal, Tornqvist, and Spirit. The price indexes calculated are normalized to a reference year of 1982 and use Dataquest shipments as weights.

The similarity in average price change for all formulas except the Spirit is striking. In contrast, the price decline registered in the Spirit index is about half the rate of all the others. The most similar in formula, the Laspeyres chain and the Spirit, produce very different rates of price decline. The entire difference between these two is produced by the frequency with which the base period changes. The alternative chain formulas produce price declines that are more like each other for each chip type and across chip types than any of them compared with the Spirit.

The similarity across chip types is consistent with the fact that the dominant

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[12] This report of BLS methodology and how it is implemented for these products is a summary of discussions with James Sinclair and Brian Catron of BLS.

Table 3.6 **Alternative Price Indexes, All MOS Memories by Chip Type, Average Annual Compound Growth Rates, 1977–88 (1982 = 100)**

	Laspeyres Chain	Paasche Chain	Fisher Ideal Chain	Tornqvist Chain	Spirit
DRAMs	−30.3	−41.8	−36.3	−36.0	−16.6
Slow SRAMs	−20.2	−33.4	−27.1	−26.3	−7.5
Fast SRAMs	−27.6	−32.9	−30.3	−30.0	−23.0
ROMs	−23.8	−32.8	−28.5	−28.5	−12.6
EPROMs	−30.1	−40.2	−35.3	−34.7	−18.4
EEPROMs	−14.8	−20.5	−17.7	−16.1	−14.1
Total	−26.5	−38.0	−32.5	−32.0	−12.3

Note: SRAM = static random access memory. ROM = read only memory. EPROM = electrically programmable read only memory. EEPROM = erasable electrically programmable read only memory.

forces in all are the same improvements in lithography. While the time frame in which the next generation within each type adopts the improvements will vary a little bit, overall one would expect that, over time, the effects on price would be close.[13]

Table 3.7 contains values for alternative price indexes for MOS memory chips aggregated across all types of chips. The lower panel of table 3.7 displays average price declines for selected subperiods for all index formulas shown in the upper panel. The PPI component falls at a much slower pace than even the Spirit index, for all subperiods shown. It appears that the index formula probably accounts for only part of the difference in the PPI component and these alternatives.

The effect of introduction delay on price indexes. These price indexes would be affected much more and the rates of decline would be much slower the greater the delay in introducing a chip with a new density into the index. Using DRAMs as an example, this point is illustrated in table 3.8. Compound growth rates for the period 1982–88 (a subperiod for DRAMs presented in table 3.6 above), calculated with introduction delays from zero to five years, are presented in the table. The earliest year in which entries by density appear in table 3.1 above correspond to an introduction delay equal to zero. A one-year delay means that each density first enters the index in the second year that it appears in table 3.1.

Table 3.8 shows that each additional year of delay reduces the rate of price decline. For all index formulas shown, a five-year introduction delay produces price indexes that fall at approximately one-tenth the annual rate of indexes in which products enter promptly. Indeed, the PPI component's 4.4 percent com-

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[13] For further discussion of lithography and its effect on semiconductor electronics, see Keyes (1977).

Table 3.7 **Alternative Price Indexes, All MOS Memories (1982 = 100)**

Year	Laspeyres Chain	Paasche Chain	Fisher Chain	Tornqvist Chain	Spirit	PPIR MOS Memories
1974	5,637.4	12,075.0	8,250.5	8,014.9	2,078.2	286.9[a]
1975	1,777.0	3,806.2	2,600.7	2,526.4	655.1	. . .
1976	1,087.6	2,329.7	1,591.8	1,546.3	393.0	212.1
1977	676.7	1,472.0	998.0	969.8	248.5	209.8[b]
1978	432.3	788.7	583.9	567.7	158.7	186.5
1979	383.9	640.2	495.8	480.4	163.3	168.8
1980	282.2	442.1	353.2	343.6	123.3	. . .
1981	146.6	188.7	166.3	164.6	100.6	. . .
1982	100.0	100.0	100.0	100.0	100.0	100.9[b]
1983	75.9	66.5	71.0	71.6	75.9	. . .
1984	66.5	45.2	54.8	56.7	74.4	101.3
1985	29.5	15.8	21.5	22.5	57.5	73.4
1986	20.5	9.0	13.6	14.2	48.4	61.7
1987	19.7	6.9	11.7	12.4	50.9	63.5
1988	22.7	7.6	13.2	14.0	58.6	74.9
Average annual rates of change: selected periods						
1977–82	−31.8	−41.6	−36.9	−36.5	−16.6	−5.4
1982–88	−21.9	−34.9	−28.7	−27.9	−8.5	−4.4
1977–84	−28.2	−39.2	−33.7	−33.3	−15.8	−4.3
1984–88	−23.5	−35.9	−30.0	−29.5	−5.8	−5.9
1977–88	−26.5	−38.0	−32.5	−32.0	−12.3	−4.9

Note: Ellipses points indicate value not calculated because fewer than eleven months available.

[a] December 1974 value (earliest value published).

[b] Average of values, January–November.

Table 3.8 **Effect of Late Introduction, Alternative Price Indexes, MOS Memories: DRAMs used in Main Memories of Selected Large General Purpose Processors, Compound Growth Rate, 1982–88**

Introduction Delay in Years	Laspeyres Chain	Paasche Chain	Fisher Chain	Tornqvist Chain
0	−27.5	−38.6	−33.3	−32.7
1	−26.2	−32.1	−29.2	−29.4
2	−24.7	−27.6	−26.2	−26.3
3	−19.9	−20.4	−20.1	−20.1
4	−7.1	−7.2	−7.1	−7.1
5	−1.8	−1.7	−1.8	−1.7

pound growth rate, 1982–88 (shown in table 3.7), would be matched by an introduction delay of between four and five years in the Dataquest data.

Furthermore, delaying introduction means that price changes in important products (in terms of market share in the lower panel of table 3.1) are not being measured directly and are estimated by price changes in products whose market share may be quite small. Consider the case of a three-year delay: the 64k chip does not enter until 1982, although its share was about 80 percent the prior year; the 256k chip would enter in 1986, although its market share was over 62 percent in 1985; and the 1Mb chip with over half the value of shipments in 1988 would not be in the index that year. One observes that the rate of price decline is most rapid for the products with the largest shares of the market. It is the products that are no longer important that register small price changes.[14] A comparison of the dates of entry into the PPI component of products having densities shown in table 3.1 with the dates of introduction in table 3.1 would be a useful undertaking for BLS to pursue.[15]

Limited Verification: Comparisons Using Dataquest and Census Data

Dates of product introduction and value shares used in the PPI component are needed to determine the source of the difference between the PPI for these products and the indexes shown here. However, the Census Bureau does publish some data in the MA36Q Current Industrial Report that can be used to judge the reasonableness of the weights derived from the Dataquest data set.

The entries in table 3.9 are the relatives that enter a Laspeyres chain calculation for DRAMs based on Dataquest data. Each entry is the ratio of the price index in each period divided by its value in the prior period. The calculations differ in the source and detail at which the weights (value shares) are calculated. The column heading "MA36Q" identifies the Census MA36Q reports as the source for weights used in calculating the relatives in the first column. The columns under the "Dataquest" heading use Dataquest estimates of shipments for U.S.-based manufacturers. Dataquest columns 1 and 2 differ in the level of detail at which one performs the calculations because Dataquest provides information in greater detail than is published in the MA36Q. Entries in Dataquest column 1 lump together the 256k and the 1Mb chips as is done in the seven-digit SIC. In Dataquest column 2, these densities enter separately, each with its own weight. For each of these three years, the relatives (and hence the price indexes that would be produced) are very much alike, lending some credibility to the rates of change in the price indexes offered in this paper.

3.2.3 Electronic Components Input to the Manufacture of Computing Equipment

Assessment of whether the quality-adjusted price declines in electronic products could result in the quality-adjusted price declines in the implicit de-

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[14] I am indebted to Jack Triplett for his suggestion to make explicit the effect of introduction delay.

[15] Refreshing the sample more frequently has been suggested by BLS as a way to ensure that younger products are being priced. However, the time interval between new frontiers is not regular, and data reporters need not introduce products embodying the new technology at the same time. To be certain that products embodying new technology are identified early, data reporters could be asked to alert BLS to the introduction of such products.

Table 3.9 **Laspeyres Relatives with Alternative Weights, MOS Memories: DRAMs, Selected Years**

		Dataquest	
$t/t-1$	MA36Q	(1)	(2)
t = 1985	.410	.382	.424
t = 1986	.718	.662	.772
t = 1987	.820	.825	.916

flator for computer processors requires an estimate of the importance of these products in materials consumed in the manufacture of processors. Ideally, one would use data on the consumption of each level package in the manufacture of the next level package up to processors. Unfortunately, such data are not available.

1987 Census of Manufactures: Office and Computing Equipment

The tabulation of the 1987 Census of Manufactures for industry 3571, electronic computers, in table 7, "Material Consumed by Kind," reveals that line items identifying the products described in this paper are missing. Selected line items from this table in the tabulation of the Census are shown in table 3.10, items in lines 367002–357003. Sixty-eight percent of the cost of materials consumed is accounted for by two line items. Ten line items account for 92 percent of the cost of materials consumed. The small value originally tabulated for line item 367002, whose definition included electronic components, suggested that a problem arose in the reporting of materials consumed data. According to the Bureau of the Census, the line item titled "Semiconductors" was intended to include chips. The title "Resistors, capacitors, transducers, and other electronic-type components and accessories, except semiconductors" was intended to include higher-level packages. After an investigation by the Census Bureau following the preliminary tabulation, it was decided that the values for these items would not be shown separately because, in many cases, respondents were not aware that line 367002 included complex electronic products such as printed circuit boards and consequently reported values for them in other lines such as those called "Parts . . ." (lines 357002, 357201, 357701, 357501, 366130, and 357003 in table 3.10) and the two line items for those materials not elsewhere listed (lines 970099 and 971000 in table 3.10). Indeed, the problem arose because respondents judged these other line items to have more appropriate descriptors.[16]

Data on the use of electronic components in the production of computer processors are needed to make appropriate input price indexes, and, without

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[16] Ken Hansen at the Bureau of the Census was responsible for the follow-up investigation that prevented the publication of meaningless data in the final report for this industry.

Table 3.10 **Industry 3571, Electronic Computers, Selected Materials Consumed by Kind**

1987 Material Code	Description	Delivered Cost ($billion)	% of Total
367408	Semiconductors	1.600	13.1
367002	Resistors, capacitors, transistors, transducers, and other electronic-type components and accessories, except semiconductors	6.740	55.2
357002	Parts for computers		
357201	Parts for auxiliary storage equip		
357701	Parts for input/output equip		
357501	Parts for computer terminals		
366130	Parts for communication interface equipment		
357003	Parts for other peripheral equipment		
970099	All other materials, components, parts, containers and supplies	1.575	12.9
971000	Materials, parts, containers, and supplies, n.s.k. (not specified by kind)	1.276	10.5
Sum		11.191	91.7
Materials, parts, containers, and supplies		12.205	100.0

reliable information, estimates of value-added cannot be made. We may ask, however, if the data presented thus far are consistent with the estimate of quality and price changes used for some of the products in the computer processor component of BEA's implicit price deflator in the NIPAs.

BEA Input-Output Tables

The input-output (I-O) tables for 1972, 1977, and 1985 published by BEA provide some information on the value of electronic products to the manufacture of the broad category office and computing equipment (OCE). A tabulation of selected elements from these I-O tables is given in table 3.11.

Total intermediate inputs excluding services used in producing OCE is mostly accounted for by two industries that make electronic products—electronic components and accessories and OCE itself. Indeed, the fraction was about .7, .6, and .6 in 1972, 1977, and 1985, respectively. It is reasonable to expect that for computer processors this fraction is substantially higher.

Value-added in the office and computing equipment industry as a share of output declined markedly between 1977 and 1985. This probably reflects in good part the move to assembly of parts away from the manufacture of those parts (Harding 1981, 649). Two distinct phases of production of computers have emerged: one is the fabrication of components, and the other is com-

Table 3.11 **Selected Elements of Inputs and Output of Office and Computing Equipment, I-O Tables: 1972, 1977, 1985 ($billions)**

Year	Output (1)	Value-Added (VA) (2)	VA/Output (3)	Total Intermediate Inputs Less Services (4)	Own Input (5)	Electronic Components Inputs (6)	([5] + [6])/(4) (7)
1972	8.518	3.495	0.41	2.911	1.212	0.765	0.68
1977	15.793	6.611	0.42	6.638	2.544	1.450	0.60
1985	58.324	16.870	0.29	27.780	10.108	6.411	0.59

monly known as BAT (bond, assembly, and test).[17] Some misconceptions and perhaps mismeasurement arise from the problem of determining which industries these belong in. Partly, this is due to the different views of an industry that one gets when looking at establishments rather than enterprises. In 1985, as is still true today, there was a wide range of activities performed across manufacturers of computer processors and other types of computing equipment as well.

Example

Using assumptions drawn from data presented in tables 3.2, 3.3, 3.10, and 3.11 above and based on conclusions drawn thus far, consider an example that uses realistic assumptions to assess the plausibility of price declines in computing equipment on the order of 25 percent per year since actual data required are not available.

For the purpose of example, consider the effect of quality-adjusted price declines in electronic components on the quality-adjusted prices of computer processors produced in two hypothetical establishments representing the extremes with respect to their use and own production of electronic components. It will be shown that, consistent with the estimates of price declines presented in this paper, I-O tables, and the Census of Manufacturers, quality-adjusted price declines in computer processors of about 25 percent per year may be the outcome at both extremes. This outcome may result from an establishment's own production and consumption of electronic components or from the effect of price declines and quality improvements in purchased electronic components. More of the value-added would be attributed to the computing equipment industry in the former case and to the electronic components industry in the latter.

Compare two hypothetical establishments. The output of establishment A is personal computers. Establishment A buys all the electronic products in its PCs. The output of establishment B is large general purpose processors; it

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[17] See the special commemorative issue of *Electronics*, 17 April 1980, 381.

purchases some and manufactures others of the electronic products it consumes in the final assembly of its output.

The values used in the example are chosen as follows: The ratio of value-added to output for establishment B is set to the 1985 value from the I-O table shown in table 3.11. It is set lower to .1 for establishment A because that is more appropriate for assembly-only activities.

The electronic components' share of materials consumed is set at the low value of .68 (the sum of semiconductors and resistors, capacitors, etc. in table 3.10) for establishment B. For establishment A, it is set at .92, the maximum computed in table 3.10.

A 26 percent reduction in the quality-adjusted price of output of establishment A is the outcome of a 33 percent reduction in the quality-adjusted price of its electronic inputs (much like the decline in price/kilobit in table 3.2 for the period 1977–85) and a 7 percent increase in the quality-adjusted price of all other inputs and its value-added:

$$.9[.92(.67) + .08(1.07)] + .1(1.07) = .7388. \tag{1}$$

For establishment B, a quality-adjusted price reduction is set at 30 percent for both the electronics products it consumes and its own value-added. This marginally smaller rate of price change is consistent with the earlier conclusion that quality-adjusted price changes in more complex electronic packages did not quite keep pace with those of the simpler packages. The same 7 percent increase in the prices of all other inputs is used. The result is a 22 percent reduction in the quality-adjusted price of establishment B's output:

$$.7[.68(.70) + .32(1.07)] + .3(.70) = .7829. \tag{2}$$

The example serves to illustrate that price declines and quality improvements in electronic components provided in this paper are consistent with quality-adjusted price declines in computer processors. The processor price decline may be passed along by establishments in the computer industry that contribute little (by comparison) value-added. Or, as in establishments like B, where complex electronic components are manufactured for own consumption, the quality improvements and price declines in the electronic components will take place in establishments in the computing equipment industry.

Companies whose main product is computing equipment often have establishments like both. Digital Equipment Corporation and IBM are examples (see Digital Equipment Corp. 1989). The magnitude of an enterprise's real value-added is very much determined by the degree to which it manufactures the electronic products that are key inputs to its products. Without actual data distinguishing assembly activities from those in which complex components are fabricated, allocating value-added between these two industries is not possible. The example serves to illustrate that electronic components are the important source of quality-adjusted price declines in computer processors and that the industry responsible may be either the electronic components industry or the computing equipment industry, depending on the degree to which the electronic components are produced for consumption within the same establishment.

3.3 Conclusion

Assessment of the limited data presented here on price declines and quality improvements in chips and the complex electronic components into which they are assembled offers some evidence that declines in quality-adjusted prices of semiconductor chips and, by way of example, higher-level packages, are not inconsistent with the processor component of the NIPA deflator for office and computing equipment.

Alternative matched-model indexes presented showed slower rates of price decline, with only two changes in the base year (weights) for the period 1975–88 as compared with rates of decline in price indexes constructed with consecutive changes in the base year (chained indexes), although the slower rates remained far more rapid than registered in the PPI component. More important, it was shown that, in the case of DRAMs, delaying the introduction of new products into the price index results in substantially smaller movements in the index. Indeed, delaying introduction between four and five years creates price index changes comparable to those observed in the PPI component. In addition, it was argued that these matched-model indexes for MOS memories would likely understate price declines in logic, where direct comparisons of quality are more difficult to measure.

There are two important implications to be drawn from the arguments and data presented: (1) the large differences in price changes within a cell for commodity products such as these suggest that price disequilibrium and associated errors in price measurement may be more widespread than is currently believed; and (2) shortening the sample refreshment cycle is likely to reduce the effects of introduction delay but is a solution that is second best to one that makes direct comparisons of quality.

Further, it was shown that price indexes for different types of chips registered similar and rapid price declines that did not differ greatly by choice of index formula. This finding illustrates the importance of improvements in technology, in this case lithography, on quality-adjusted prices.

In the absence of needed measures of value-added, an example was used to illustrate that price declines like those in the NIPA deflator for computer processors are consistent with quality improvements and price declines in electronic components. The source industry, however, may be either the electronic components industry or the computing equipment industry, depending on the degree to which establishments in the computing equipment industry purchase these key inputs or manufacture them for their own consumption.

References

Balderes, Demetrios, and Marlin L. White. 1989. Large general-purpose and supercomputer packaging. In *Microelectronics packaging handbook,* ed. Rao R. Tummala and Eugene J. Rymaszewski. New York: Van Nostrand Reinhold.

Black, John R. H. 1986. Technology and market-trends in multilayer ceramic devices. *Advances in Ceramics* 19:3–11.

Cole, Rosanne, Y. C. Chen, Joan A. Barquin-Stolleman, Ellen Dulberger, Nurhan Helvacian, and James H. Hodge, 1986. Quality-adjusted price indexes for computer processors and selected peripheral equipment. *Survey of Current Business* 66 (1): 41–50.

Digital Equipment Corp. 1989. *Annual report.* Maynard, Mass.

Dulberger, Ellen R. 1989. The application of an hedonic model to a quality-adjusted price index for computer processors. In *Technology and capital formation,* ed. Dale W. Jorgensen and Ralph Landau. Cambridge, Mass.: MIT Press.

Harding, William E. 1981. Semiconductor manufacturing in IBM, 1957 to the present: A perspective. *IBM Journal of Research and Development* 25 (5): 647–58.

Keyes, R. W. 1977. Physical limits in semiconductor electronics. *Science* 195 (March): 1230–35.

Mayo, John S. 1986. Materials for information and communication. *Scientific American* 255 (October): 59–65.

Meindl, James D. 1988. Chips for advanced computing. *Scientific American Trends in Computing,* special issue, 1:98–107.

Noyce, R. N. 1977. Large-scale integration: What is yet to come. *Science* 195 (March): 1102–6.

Rajchman, J. A. 1977. New memory technologies. *Science* 195 (March): 1223–29.

Tummala, Rao R., and Eugene J. Rymaszewski, eds. 1989. *Microelectronics packaging handbook.* New York: Van Nostrand Reinhold.