The Role of Semiconductor Inputs in IT Hardware Price Decline:

Computers vs. Communications

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A B S T R A C T

Sharp declines in semiconductor prices are largely responsible for observed declines in computer prices. Although communications equipment also has a large semiconductor content, communications equipment prices do not fall nearly as fast as computer prices. This paper partly resolves the puzzle–first noted by Flamm (1989)–by demonstrating that prices for chips used in communications equipment do not fall nearly as fast as prices for those chips used in computers and that those differences are large enough to potentially explain all of the output price differences.

1. Introduction

Since at least the mid-1980s, economists have toiled steadily at improving price indexes for high tech goods and services. The first fruits of this effort were seen in computers.[1] The use of quality-adjusted price indexes (primarily hedonic price indexes) for computing equipment has now been institutionalized in the national income accounts of the United States and other industrialized nations, and has radically altered our understanding of the macroeconomics of growth and productivity improvement over the last two decades.[2]

As evidence from these studies accumulated, it also became clear that much of the improvement in computer price-performance was based on even more impressive rates of decline in quality-adjusted prices for semiconductors, the major input to computer manufacture.[3] Much recent literature now suggests that changes in semiconductor prices have been a major driver of changes in quality-adjusted computer prices, and even more generally, other types of information technology (IT). Moreover, many have linked an observed quickening in the pace of price declines for semiconductors to an upsurge in the price-performance improvement for information technology, and ultimately to the improvement in U.S. productivity growth that occurred in the mid-1990s.[4]

Juxtaposed against this backdrop, it is almost startling to discover that in communications equipment, an equally high tech product and a similarly ravenous consumer of semiconductor inputs, economic studies have documented vastly lower rates of decline in quality-adjusted price over the same periods in which computer prices have been studied closely.[5] Early studies suggested that the lack of "convergence" in quality adjusted price trends between computers and communications may have been due in large part to regulatory factors.[6] But with the break-up of the Bell System and deregulation of large parts of the communications market in the mid-1980s, the expanding boundaries of real competition in communications equipment markets, and the rapid explosion of growth in the largely unregulated data communications and networking market in subsequent years, regulatory regimes seem a less plausible explanation for observed, continuing differences in rates of quality adjusted price change between computer and communications equipment.

The other possibility that was considered is that quality improvement in communications hardware is simply poorly measured. Mismeasurement of communications equipment prices has the same distorting effects on measurement of productivity improvement and economic growth that have been the case with computers.[7] But even with the improved measurement of quality-adjusted prices documented in recent studies, large differences between computers and communications remain.[8]

These continuing, persistent differences in measured rates of technological innovation between computers and communications are difficult to reconcile. Both computers and communications equipment are heavy users of semiconductor devices, yet prices for these two classes of equipment continue to move very differently, even in recent years.

One possible resolution of this paradox is that the specific types of chips that are used in communications equipment show slower price declines than those used in computers. Semiconductors are actually a broad and diverse group of products. They are intermediate goods that are used in the production of other goods that range from personal computers (PCs), to timers on household appliances, to automotive ignition systems. The prices associated with the different types of chips used in these different types of applications are likely very different.

We construct and compare semiconductor input price indexes for the two industries and show that the price index of semiconductor inputs to the communications equipment industry does, indeed, decline slower than that for the computer industry. Over the 1992-99 period, input price indexes for the semiconductor devices used in communications equipment and in computers fell at a compound annual growth rate of 12 percent and 32 percent per year, respectively. Moreover, we find that these differences in input prices can more than explain the observed differences in the output prices.

We caution that much is omitted from this analysis. Other factors could have caused large changes in these end use prices that may have more than offset, or been offset by, changes in semiconductor input prices. Likely candidates include significant differences in the importance of, and price trends for, other inputs to production (for example, disk drives and displays are important inputs to computer systems, but a relatively minor input in communications gear) and differences in the magnitude and impact of technical innovation originating within the industry itself (as opposed to innovation embodied in components purchased from other industries). This last factor, of course, may also be tied to market structure and competitive conditions in the two sets of industries, another domain in which there may be significant differences.

The next section describes the data and methods used in constructing the input price indexes. Section 3 undertakes some illustrative decompositions of the role of semiconductor prices in explaining user industry price trends for computer and communications equipment, and Section 4 concludes.

2. Construction of the Price Indexes

We construct chained-Fisher indexes of price change for semiconductor devices (denoted *i*) used in different end uses (denoted *e*). The familiar formula for a Fisher price index ($I^e_{t,t-1}$) that measures aggregate price change for end-use *e* over two adjacent periods (t-1 to t) is:

(1) $$I^e_{t,t-1} = \left[\frac{\Sigma_i\ f^e_{i,t-1}(P^e_{i,t} / P^e_{i,t-1})}{\Sigma_i\ f^e_{i,t}(P^e_{i,t-1} / P^e_{i,t})} \right]^{1/2}$$

where the expenditure weights are given by :

(2) $$f^e_{i,t} = \frac{P^e_{i,t}Q^e_{i,t}}{\Sigma_i(P^e_{i,t}Q^e_{i,t})},$$

and the P's and Q's denote prices and quantities, respectively.

The index is a ratio of weighted averages that weigh the price change in each chip by its relative importance in the end use. While (1) measures price change for two adjacent time periods (t-1 to t), price change over longer periods of time (say, time o to time t) is measured by chaining the indexes for adjacent time periods together:

(3) $$P^e_{o,t} = \Pi_{s=1,t} (I^e_{s,s-1}).$$

To form these indexes we need data on nominal shipments–for the weights—and on prices–to form the price relatives: $P^e_{i,t} / P^e_{i,t-1}$.

Two things must be true for input price indexes to vary across end uses: the end uses must use different types of chips and the prices for those chips must show different rates of price change. As shown below, both of these conditions hold—and in a very significant way—in our data.

Nominal Weights

We obtained data on nominal shipments of semiconductor devices broken out by end use from a survey sponsored by the World Semiconductor Trade Statistics (WSTS) program, a cooperative venture sponsored by national semiconductor industry associations around the world. The survey provides data on shipments for 12 aggregate classes of semiconductor devices: five classes of Metal Oxide Semiconductor (MOS) chips (MOS memory, MOS microprocessors, MOS microcontrollers, MOS microperipherals and other MOS Logic); two classes of other types of integrated circuits (Analog, and Bipolar), and five types of single-function "discrete" semiconductors (Power Transistors, Small Signal Transistors, Thyristors and Rectifiers, Optoelectronics, and Diodes and all other discretes).

The data for 1999 are summarized in chart 1. Note that much of the world chip market is made up of MOS devices–well known chips like MOS memory chips (e.g., DRAM) and microprocessors (MPUs, like Pentium chips) and some less visible MOS devices like microperipherals (MPRs) and microcontrollers (MCUs).[10]

One important dimension along which these devices differ is the degree of "high tech-ness." Researchers at the International SEMATECH R&D consortium classify these product categories as "leading edge" or "non-leading edge" according to the manufacturing processes used when they are produced and the percentage of the wafers

[10] See Semiconductor Industry Association (2002) for a detailed descriptions of these devices and their capabilities.

processed in that category that use the latest, leading edge processes. Chart 2 shows the share of total silicon wafer area processed in 1999 for several semiconductor device classes using this indicator. Solid bars correspond to more highly aggregated classes of products, while hollow bars correspond to more disaggregated product categories within the aggregates to their right (and note that the shares are of silicon area processed, not of value of product, within a category). According to this indicator, MOS microprocessors (MPUs) are 90 percent leading edge, MOS memory a little under half leading edge, and microcontrollers, microperipherals, and other MOS logic even less dependent on leading edge manufacturing. Analog, bipolar, and all discrete device categories are entirely produced with more mature technologies that are characterized as non-leading edge.

The analog category—making up 15 percent of world shipments in 1999—is acknowledged within SEMATECH to be poorly characterized within this breakdown, and to require further work. It is actually a combination of some very high tech products produced with leading edge technology, and some relatively mature products, produced with relatively old technology. Since analog chips are a major input to communications equipment, this topic is revisited below.

For each of these classes of semiconductor devices, nominal shipments are further broken out into the following end use categories: computer, communications, consumer electronics, industrial, automotive, and government.[9] As shown in chart 3, the largest end use for semiconductor chips is computers: about half of value of worldwide shipments in 1999 went to computer manufacturers. The next-largest end uses that year were communications equipment (21 percent) and consumer electronics (14 percent). Together, these three groups of end use industries accounted for about 7/8 of semiconductor consumption in 1999, while all other categories together accounted for the remaining 1/8 of shipments.

The disaggregate data show that the composition of semiconductor devices used in computers is very different from that of communications equipment. As shown in chart 4, the bulk–79 percent–of semiconductor shipments to computer-makers are made up of MOS devices that are known to have experienced rapid rates of technological change (memory and microcomponents: MPU, MCU, and MPR). In contrast, the composition of semiconductor devices used in communications equipment is much more diverse and more skewed towards devices where quality-adjusted price trends are less well understood. MOS memories and microcomponents make up only 34 percent of the semiconductor inputs to communications equipment; the next two largest classes of inputs are other MOS logic and analog devices, where significant technological change has also taken place. The remaining 15 percent of inputs are from older, more mature devices. Data for other years in the 1990s show a similar pattern. These differences in composition have implications for price measurement when the prices of individual devices change at different rates.

Price Relatives

Relative prices for individual devices ($P^e_{i,t} / P^e_{i,t-1}$) are empirically measured using price indexes. Because price indexes broken out by device *and* end-use are not available, we assume that the measured price change for each device grouping does not vary by end use ($P^e_{i,t} / P^e_{i,t-1} = P_{i,t} / P_{i,t-1}$). This assumption seems unobjectionable for semiconductor devices that are largely commodity-like (for example, standard memory, logic, and microprocessor components), but is potentially problematic for devices that are customized for particular end uses.

Most of the price indexes we used are either taken from previous studies (Grimm(1998), Aizcorbe(2002) and Aizcorbe, Corrado and Doms (2000)) or recalculated from the sources used in those studies. One important exception is the index for microperipheral chips (MPR). As detailed in the appendix, we used new data to construct an annual quality-adjusted Fisher price index to better capture the rapid technological improvements reported for these devices. The other notable exception is the price index for analog devices. As mentioned earlier, these devices are important in the production of communications equipment and are thought to have poorly measured price indexes. The appendix details the construction of the hybrid index we use for these devices; while we measure price change for the "low-tech" devices in this class using average sales prices at the lowest possible level of disaggregation, we assume that the price change for the "high tech" devices in this class parallels that of devices in the "Other MOS logic" class of chips, and average over the two indexes using Fisher weights to obtain the hybrid index.

All told, we have annual price indexes for 12 classes of semiconductor devices– one for each of the semiconductor classes in chart 1. Price measuresfor these devices--given in the first column of table 1--decline at substantially different rates over the 1992-99 period. For the most part, differences in the rates of price declines exhibited by the devices are intuitively plausible. Devices normally associated with rapid rates of product innovation and technical change do, indeed, show rapid price declines: MOS microcomponents (MPUs, MCUs and MPRs), MOS memory chips, and Other MOS logic. Similarly, more mature chips that have not undergone much change in the last decade do not show much price decline: for example, bipolar devices.

The second and third columns show the nominal shares data associated with each device. As may be seen, prices for semiconductor devices that go into computers tend to fall faster than those that go into communications equipment. Chips whose prices fall more than 30 percent account for about 65 percent of the nominal value of chips that go into computers. Prices of the remaining chips fall much slower–14 percent or less–and have a much heavier weight in communications equipment.

As shown in the top panel of table 2, semiconductor input price indexes differ substantially across end uses.[10] For the period 1992 to 1999, input chip prices for automotive end uses decline the most slowly—declining at about a 12 percent compound annual growth rate (CAGR)—while those of computer chips decline the fastest—at about a 32 percent CAGR over the period. Input prices for communications end uses fell at a 15 percent CAGR over the period—just a bit faster than prices for automobile end uses. The next two columns provide measures of price change for the pre- and post-1995 periods. These price indexes experience faster price declines after 1995 than in the earlier period. But, in either case, there is always a substantial gap between the computer and communications equipment indices.

The indexes discussed thus far use worldwide end user consumption of semiconductors as weights. Alternatively, it is possible to use North American consumption of our 12 classes of semiconductor prices by end-user industry to construct input price indexes for specific industries. The results, shown in the bottom panel of table 2, are very close to those shown above, reflecting the fact that the mix of semiconductors used in U.S. end-use industries is roughly identical to the mix overseas.

Economically, this is a consequence of the fact that semiconductors are sold in what is effectively an integrated global market, with transport costs for this very light and compact product too small relative to the value of the product, to create shelter for regional differentials in prices that might otherwise lead to substitution among device classes and differences in semiconductor input mix across countries.

3. Contribution of Changes in Semiconductor Input Prices to Changes in Output Prices

We have concluded that differences in the composition of semiconductor inputs used in computer and communications equipment account for significant differences in the rate at which the prices of semiconductor *inputs* used in these two industries fell through the 1990s. We can now examine the importance of semiconductor prices for prices of the *end goods* produced by the user industries purchasing these inputs.

Our first step is to sketch out a simple analytical framework. We shall assume constant returns to scale in the production of electronic goods that make use of semiconductors, and allow for imperfect competition and technological change in their using industries. We approximate short-run marginal cost with a unit variable cost function. [11] As a consequence, we can write

(4) $$P^e = (1+\mu)\, g(P_s, P'_z; k', t)$$

where P^e is the price of output for some given industry (or end use), μ is the markup of price over unit variable cost $g(\cdot)$, reflecting imperfect competition and subequilibrium (short-run capital per unit of output diverging from the long-run optimum). Costs are a function of the semiconductor input price for that industry, P_s, a vector of all other relevant input prices, P'_z, a vector of fixed (in the short-run) capital inputs per unit of output, k', and an index representing the possible impact of technological changes and other factors shifting the unit variable cost function over time, t. Taking logs on both sides of this equation, and differentiating with respect to time, we have

(5) $$(dP^e / dt)(1/P^e) = (1/(1+\mu))\,(d(1+\mu)/dt) + (1/g)\,\partial g/\partial P_s\, dP_s/dt$$

$$+ \ \Sigma_{i\neq s}(1/g)\ \partial g/\partial P_{zi}\ dP_{zi}/dt \ + \ \Sigma_j(1/g)\ \partial g/\partial k_j\ \ dk_j/dt \ + \ (1/g)\ \partial g/\partial t$$

Making use of Shepherd's lemma, and the empirical approximation of (dX / dt) (1/X) by the annual percentage rate of change (Δ), we then have:

(6) $$\Delta P^e = \sigma_s\ \Delta P_s + [\Delta(1+\mu) + \Sigma_{i\neq s}\ \sigma_{zi}\ \Delta P_{zi} + \Sigma_j\ \varepsilon_j\ \Delta k_j\ \ +\Delta g]$$

where σ stands for the variable cost share of an input, ε_j is the elasticity of variable unit cost with respect to fixed factor k_j, and changes in g measure technical change. In effect, we have partitioned the annual percentage change in the price of the output of a semiconductor input-using industry into the effect of semiconductor prices (the first term on the right-hand side), and the sum of all other effects (the terms in brackets). These residual determinants of output price changes not accounted for by semiconductor inputs, we note, are likely to be quite important, reflecting changes in markups over variable cost (which we would expect to be affected by demand swings in these highly cyclical industries, as well as secular trends in market structure), other production costs, and changing technology in the user industries.

Our strategy is simply to calculate the first term on the right-hand side of this last equation ($\sigma_s\ \Delta P_s$) and view it as the contribution of semiconductors to the overall price change for semiconductor-using output (ΔP^e). Changes in the industry-specific price indexes for semiconductor inputs that we have just constructed (ΔP_s) are shown in the first column of table 3 for three sectors: consumer audio, computers and communications. As noted earlier, these estimates—for 1998—say that the type of semiconductor chips that went into computers that year show faster price declines than those that went into the other two end uses.

The next three sets of columns show how we estimated the semiconductor cost share in variable cost (σ_s). We estimate this cost share in two steps. First, we pull together industry estimates[12] of the share of semiconductor inputs in the value of *shipments* of each end use sector's electronic equipment—measured as $(P^s\ Q^s)/(P^eQ^e)$. Then, we use Census data to translate that share of shipments into a share of unit *variable cost*. Given the observed data, we actually approximate variable costs as shipments less non-labor value added (i.e., the ratio of shipments/(shipments-value added+payroll) is multiplied by the semiconductor share of shipments).

A range of the available estimates for semiconductor content shares is given in the second set of columns of table 3; the full set of estimates are given in the appendix. Note that we suspect that estimates of semiconductor cost shares are biased downward—electronic equipment shipments data (the denominator) often double-count sales of semi-finished assemblies or re-branded equipment among manufacturers. We show both a low and high estimate here to place rough bounds on the industry estimates. The "high" estimates of semiconductor content seem a conservative choice for reasons just described. In either case, the semiconductor share of shipments is typically twice as large for computers than it is for the other two end uses.

Multiplying this share by the ratio of shipments to variable cost (column 3) yields an estimate of the semiconductor content in variable cost for these industries (column 4). Not surprisingly, the estimated shares are substantially higher for computers (30-45 percent) than for the other two end uses. Multiplying this estimate of semiconductor content by the change in the semiconductor input price index (column 1) gives our estimate of the part of the price change for each end use that can be attributed to changes in semiconductor input prices (the last column). Using our "high" estimates of semiconductor content, declines in semiconductor input prices pushed down computer and communications prices by about 24 and 10 percentage points, respectively.

But, how large is this relative to the declines in end-use prices? That is, how much of the absolute *decline* in the end-use prices is explained by declines in semiconductor prices? Table 4 shows that price declines for semiconductor devices had a large impact on end use prices. Column 1 gives estimates of quality-adjusted price change in 1998 for three end goods: consumer electronics, computers and communications equipment. The estimated effect of semiconductor prices is expressed in both percentage points—the second set of columns—and as a fraction of total equipment price change—the last set of columns. Our analysis suggests that semiconductors can account for roughly 40 to 59 percent of computer equipment price decline, roughly 27 to 36 percent of price declines for consumer audio and maybe a little less for communications equipment in that year.

We can now address the puzzle originally posed: How much of the differences in computer and communication equipment prices can be attributed to the respective differences in the contributions of semiconductors? To do this, we take the difference in the calculated price declines for communications and computers shown in table 4 and partition these differences into price change attributable to semiconductors versus the combined impacts of all other factors. The first column of table 5, for example, shows that quality-adjusted prices for computer equipment fell about 11 percentage points faster than LAN equipment in 1998. The second column shows that essentially all of that difference can be attributed to differences in the semiconductor contribution: The higher semiconductor contribution in computers accounts for between 10-14 percentage points of the 10.8 percent difference in computer and LAN equipment end-use price change. If one adds in switches to the communications price index (as in the second row of the table), the higher semiconductor contribution in computers more than explains the differences in end-use prices. We conclude that differences in semiconductor input price changes, coupled with differences in semiconductor intensity, can explain almost all of the difference between rates of decline of computer and LAN equipment prices in 1998.

4. Conclusions

This paper documents a first effort at calculating industry-specific semiconductor input price indexes, and assessing the impact of changes in this high technology input price on the prices and quality improvement in equally high tech industries downstream that are attributable to price/performance improvement in semiconductors. The quality of data on semiconductor and computer prices is now acceptable for these purposes, but information on semiconductor input expenditures in all sectors, and quality-adjusted price indexes in sectors other than semiconductors, computers, and a small fraction of communications equipment remains marginal. Given these caveats, this initial analysis led us to two conclusions.

First, for 1998, changes in semiconductor input prices seem to account for somewhere between 20 to 30 percent of price declines in both consumer electronics and LAN equipment, and for 40 to 60 percent of price declines in computers. Second, in 1998, computer prices fell between 7 and 11 percentage points faster than communications equipment, depending on our measurement of communications price changes. Differences in the quantity and composition of semiconductors used in these two sectors alone would have contributed perhaps 10 to 14 percentage points to this differential. To a first approximation, then (which is all we can reasonably expect given the poor quality of the available data), we conclude that differences in the composition of semiconductor input bundles, coupled to significant differences in the relative importance of semiconductor inputs in cost, together can potentially account for the entire difference in price declines between the two sectors.

APPENDIX

1. Construction of the semiconductor input price indexes

Nominal Weights We obtained data on nominal shipments of semiconductor devices broken out by end use from a survey sponsored by the World Semiconductor Trade Statistics (WSTS) program, a cooperative venture sponsored by national semiconductor industry associations around the world. Under their auspices, the U.S.-based Semiconductor Industry Association has conducted an annual semiconductor end-use survey among U.S. users since 1984; since 1992 this survey has effectively covered all major semiconductor producers globally. The survey—administered to semiconductor producers participating in the WSTS program—asks respondents to classify their total worldwide sales by customer end-use market and geographic location. Sales numbers for non-participants in the WSTS program are imputed. The data we use cover the period 1991-99 and report nominal shipments to both North American end users and all (worldwide) users.

The annual shipments for the world market are given in table A1.

Nominal Weights for Microcomponents An unfortunate feature of the data is that before 1995, industry consumption estimates for microprocessors (MPUs), microcontrollers (MCUs) and microperipherals (MPRs) are not reported separately–instead they are lumped into one category called "MOS Micro." For this earlier period, we assume the percentage breakdown among these subcategories within user industries of "MOS Micro" prior to 1995 was the same as in 1995.

Our results are not sensitive to this assumption. Table A2 redoes table 2 in the paper employing an overall index for MOS Micro price aggregated across all user sectors over 1992-94 , in lieu of using a detailed sector-specific breakout of 1995 MOS Micro consumption as an approximation to weights for detailed (MOS MPU, MCU, MPR) MOS Micro input price indexes prior to 1995. In the worldwide indexes, input chip prices for automotive end uses still show the slowest declines, while computer chips still show the fastest– now -14% versus -31% CAGR over the period). Input prices for communications end uses still lies in between the two extremes, falling an average of -17% CAGR over the period to 27 percent of its 1992 level by 1999. The North American indexes show a similar pattern.

Interestingly, approximating sector-specific consumption bundles within MOS Micro prior to 1995 substantially widens the price decline gap between computers and other semiconductor user sectors (table2 in the text). This is because the specific type of MOS Micro chip dominating computer use of these chips (MPU) fell much faster than other MOS Micro chip types (MCU, MPR) over 1992-95; these other chips dominated consumption of MOS Micro in other sectors. The net effect of crediting MPU price declines mainly to computers, and reducing the weight of MPU declines in price indexes for other sectors, is to leave non-computer use semiconductor prices falling much less steeply over 1992-95, while semiconductors used in computers fall even faster.

Price Relatives Most of the price indexes we used for MOS devices are either taken from previous studies (Grimm(1998), Aizcorbe(2002) and Aizcorbe, Corrado and Doms (2000)) or recalculated from the sources used in those studies. Where quarterly or monthly indexes (rather than annual ones) are reported in these sources, a variant of a "superlative" procedure suggested by Diewert (2000) is used to aggregate up to an annual price relative.[14]

Table A3 summarizes features of the underlying price indexes we use for semiconductor devices. In most cases, the price measures are Fisher indexes calculated from highly detailed data. With regard to index construction, Fisher indexes are available for all but 16 percent of the market: price change for subcategories of Other MOS logic chips are measured using geometric means of price changes because only price data were available at the subcategory level.[15] With regard to the underlying data, the quality of the data is not uniform: some indexes–like microprocessors–are built from very detailed data–85 or so types of chips. At the other extreme, about 36 percent of the market–at the bottom of the table–is measured using only 43 classes of chips. As is well known, as the data become more coarse, it becomes less likely that the quality of chips in each class can be held constant over time and price declines that signal technical change become muddled with price increases that reflect increases in quality. Similarly, some indexes are built using high-frequency data (monthly or quarterly) while other use annual data. While most measures are averaged over the reported period, the prices for general purpose logic are year-end prices (the only way these data are reported).

For microcontrollers from 1996 through 1999, a synthetic Fisher ideal index based on WSTS unit values for DSPs and Aizcorbe's (2001) index for microcontrollers (excluding DSPs) over this period was constructed.

Adequate measures were not available for two types of devices. We filled in the gaps by comparing price movements for devices with missing periods with price movements in other categories when prices were available, then selecting the closest fit. For field programmable logic chips, adequate indexes are not available for 1995-99 and we assumed that prices of these devices moved like a subindex of Other MOS logic excluding it (i.e., a Fisher index based only on General Purpose Logic, Gate Array, and Standard Cell devices) over 1995-99. Indexes for microcontrollers were not available for the period before 1996. In that case, we used an average sales price available from the WSTS survey—the only available data.

Because indexes for MPUs were only available beginning in 1993, estimates in Grimm (1998) were used to extend the microprocessor index back to 1991.

Table A4 provides annual price indexes for all the devices. Two of these product classes required special treatment. We detail the methods and sources for those two indexes next.

Special Index for Microperipherals (MPR) This index assumes chip quality is proportional to the number of transistors and other electronic components contained in a chip. The index effectively measures the price per two-dimensional feature (e.g., transistor) on a MOS microperipheral (MPR) chip. The starting point was WSTS data on the value of sales, and number of units sold, over 1991-1999 for 5 classes of chips included within MOS MPR: chipsets, communications ICs, graphics ICs, mass storage ICs, voice and other ICs. Using data from Semico Research, SEMATECH has estimated the average line width per feature etched on each of these different types of chips, and the average area of each of these classes of chips. Squaring line width gives an index of the minimum size for an electronic component etched on the surface of a chip, and dividing average chip area by this index yields an estimate of the maximum number of electronic components that fit on a chip with that area. Dividing average sales price per chip by the total number of electronic components then gives us an average price per electronic component on a chip, which we interpret as a quality-adjusted price index within each of our 5 classes of MPR chips.

We then calculate WSTS revenue share data, and price relatives, for each of these 5 classes of MPR chips over the 1991-1999 period. Construction of a Fisher ideal price index for the MPR chip category is straightforward, using equation (1) in the text. As shown in table A5, the resulting Fisher index falls substantially over this period, to less than one-third of its 1991 value by 1999.

Special Index for Analog Devices We next detail the construction of the hybrid index we use for these devices. While we measure price change for the low-tech devices in this class using the available WSTS unit value data, we assume that the price change for the high-tech devices in this class parallels that of devices in the "Other MOS logic" class of chips, and average over the two indexes using Fisher weights to obtain the hybrid index.

Table A6 compares alternative assumptions to measure price change of analog devices. The measure labeled "WSTS" is constructed using the very coarse WSTS data: the index is an annual Fisher index derived from monthly average unit sales prices for between five to eleven classes of analog chips, depending on the time period. This can safely be viewed as a conservative estimate of price declines for these devices.

At the other extreme, the measure labelled "Other MOS Logic" assumes the deflator for analog devices is equal to the deflator for other MOS logic–a category of MOS semiconductor chip with price declines intermediate between the highest volume, leading edge technology used in memory and microprocessors, and the relatively mature technology used in non-MOS devices and discrete semiconductors.

The hybrid index is a Fisher index of two Fisher indexes. The index for high-tech analog devices uses the Fisher index for other MOS logic to represent price change; the index for low-tech analog devices is a Fisher index of a low-tech subset of WSTS analog product categories (shown in line 3) [16] We believe this index is likely to be a better approximation to reality.

Annual measures corresponding to the alternative cases are given in table A4.

2. Calculations for the Relative Importance of Semiconductor Inputs

Recall that we estimate semiconductors' share of variable cost in two steps. First, we pull together industry estimates of the share of semiconductor inputs in the value of *shipments* of each end use device. Then, we use Census data to translate semiconductors' share of shipments into their share of unit *variable cost*.

Table A7 pulls together a range of estimates of the semiconductor content of computers, communications equipment, and consumer electronics assembled from proprietary industry estimates and the WSTS semiconductor consumption estimates used in constructing our price indexes. The sources are denoted as follows: DQ Cons and DQ Eqp refer to Dataquest-Gartner Group, Semiconductor Product Trends in 2001, July 31, 2000; WSTS refers to the WSTS Semiconductor Industry End Use Survey, various years; and EIO stands for the Electronic Industry Outlook.

This ratio of shipments to variable cost are based on census data reported in the 1998 U.S. Annual Survey of Manufactures. We estimate the markup of shipment price over unit variable cost as shipments divided by shipments less non-labor value added (i.e., shipments/(shipments-value added+payroll)).

3. Data Sources for End-use prices

We measured computer prices using the matched-model price indexes in Aizcorbe, Corrado and Doms (2000). Although computers are relatively well measured now, quality adjustment of prices for communications equipment and consumer electronics is problematic. For communications equipment, we formed a crude measure of quality-adjusted communications equipment price change in 1998 using the available data. We started with the estimates of quality-adjusted LAN equipment prices for 1992-present that are now available from the Federal Reserve Board. For the period prior to 1996, we examined hedonic estimates of digital switch prices reported in Grimm(1996). We then used the historical ratio between quality-adjusted price changes for digital switches and quality-adjusted LAN equipment price changes over 1992-96, multiplied by LAN equipment price changes in 1998, as a crude estimate of switch price changes in 1998. Finally, we average switch and LAN equipment price changes using relative expenditure in 1998 as weights and use the resulting calculation as our measure of quality-adjusted communications equipment price change in 1998. (Note, however, that these two categories of equipment accounted for only 30 percent of communications equipment spending in 1998).[17]

To measure price change for the consumer electronics sector, We have found only one study of quality-adjusted prices for consumer electronics with a methodology that seems roughly comparable to those for computers and communications. The study pertains to consumer audio equipment only, and we can only hope that our consumer electronics prices are roughly comparable.[18]

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Footnotes

[1] There are now many studies of quality adjustment in computer prices. For an early synthesis of the literature, see Triplett (1989); more recently, see Berndt and Rappaport (2001).

[2] See, for example, Jorgenson (2001a) for one influential reassessment of the impact of IT on U.S. productivity growth.

[3] For early calculations suggesting that computer price-performance improvement was due largely to quality-adjusted price changes in electronic components used in computers, see Flamm (1989, 1999). Triplett (1996) constructs an economic framework which, with believable values, suggests that most of the improvement in computer price-performance is due to semiconductors; indeed, he has calculated that MFP for computers is modest, once the contribution of semiconductors has been removed.

[4] For studies suggesting a link between productivity growth and IT quality-adjusted price declines in the productivity speed-up of the 1990s see Oliner and Sichel (2000), Jorgenson (2001a), U.S. President, Council of Economic Advisors (2001). See Flamm (2001) for a detailed analysis of the technical and economic roots of more rapid decline in semiconductor prices, as well as an argument that the extraordinary declines in chip prices in the late 1990s must ultimately fall back to a more sustainable pace in the long-run. But note that others have expressed some skepticism on the connection between IT price-performance improvement and productivity; see Gordon (2000).

[5] The first studies of quality-adjusted prices for communications hardware (primarily for voice telephone networks) were Flamm (1989), Gordon (1990) and Grimm (1996); for semiconductor devices, the first studies were Dulberger (1993), Flamm (1993) and Norsworthy and Jang (1993).

[6] See Flamm (1989)and Gordon (1990).

[7] See Sichel (2001), Crandall (2001) and U.S. Congressional Budget Office (2001).

[8] Doms and Forman (2001) also find rates of decline for data communications and networking hardware in the1990s that are significantly smaller than those for computers over the same period.

[9] The definitions for each end use are as follows: The computer category includes mainframes, peripherals and personal computers. Communications includes telecommunications, transmission, two-way and cellular radio equipment. The remaining categories are fairly diverse. "Consumer" includes the following type of devices: entertainment, radio, TV, VCR, personal or home appliance, cameras, games, etc.; automotive represents chips used in auto entertainment, engine controls, and all other auto applications; industrial and instrument category includes lab, test, control and measurements; and chips used in government end uses include those in military & government special purchases.

[10] The robustness of these estimates to changes in the underlying assumptions is discussed in the appendix. Although the numerical results can be sensitive, the qualitative results are the same.

[11] See C. Morrison (1992) for an extended discussion of a decomposition of price change into its component elements based on variable cost function and Oliner and Sichel (2000) for a similar framework. Note that our assumption of constant returns to scale is

inessential; with non-constant returns to scale, a scale effect must also incorporated into our decomposition of price change. This decomposition is derived from cost functions and is dual to a productivity growth decomposition derived from a production function, as was used in Basu and Fernald (1997).

[12] Measurement of the value of semiconductor input cost in different industries is a notoriously weak link in coverage of statistical agencies of the manufacturing sector (see Triplett (1996) for a more extensive discussion of these problems). Note also that these cost shares are for electronic equipment produced in each end use sector—thus it is the semiconductor content of automotive electronic equipment, not the entire auto, that is being estimated.

[14] Our use of the Tornqvist-Theil index number formula given in Diewert (his formula 26) is to calculate (for annual price of a product in year 1 relative to year 0, based on monthly price data):

$$\ln P^1(p^0,p^1,s^0,s^1)=\_{m} (1/2) [s^{0,m}+s^{1,m}] \ln (p^{1,m}/p^{0,m}) ,$$

where $s^{i,m}$ is the share of expenditure on the product in question in month m in annual expenditure in year i, and subscript m refers to months. We have used this formula to construct annual price index relatives for adjoining years, then chained these to produce an index extending over the 1992-1999 period. See Diewert (2000), p. 9.

[15] The formula for a geometric mean of price change from time t-1 to time t is $I_{t,t-1} = ?_{i} (P_{i,t} / P_{i,t-1})$.

[16]Low-tech analog chips are those included in the WSTS categories for amplifiers, interface, voltage regulators and ref., and data conversion circuits; high-tech analog chips are those in the special consumer circuits, comparators and other linear devices categories.

[17]See Doms and Forman (2001), Table 1.

[18] See Kokoski,Wachrer,& Rozaklis (2000),Table 9.

Chart1

Value of Semiconductors Consumed Worldwide, by Consumption Product Class, 1999

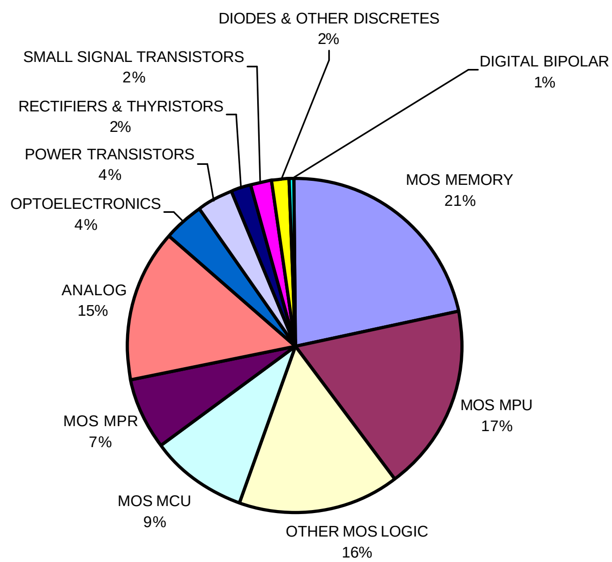


Chart 2

Share of Leading Edge Wafers in Total Silicon Area Processed, by Product,1999

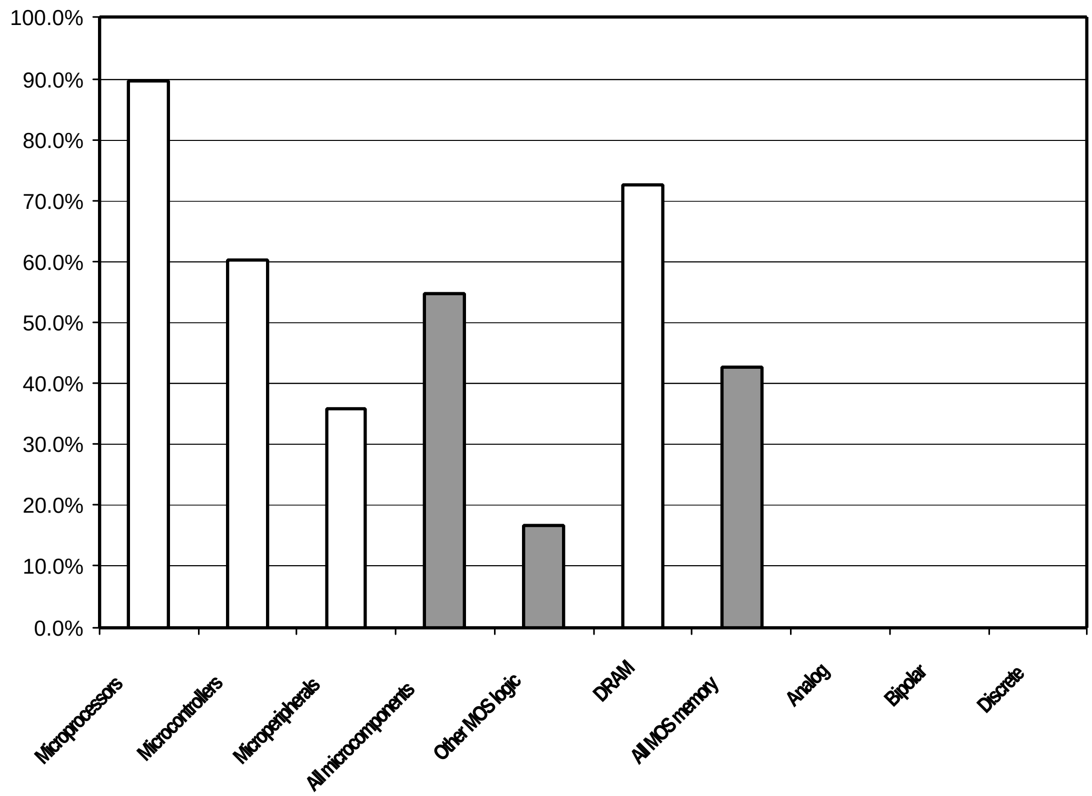


Chart 3. Value of Semiconductors Consumed Worldwide, by End Use Sector, 1999

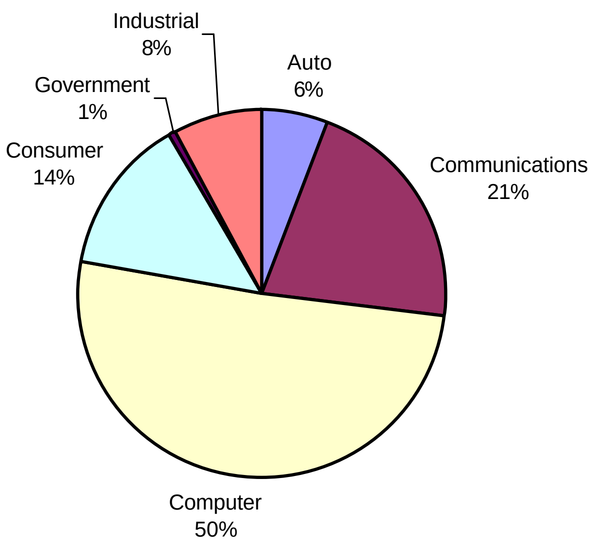
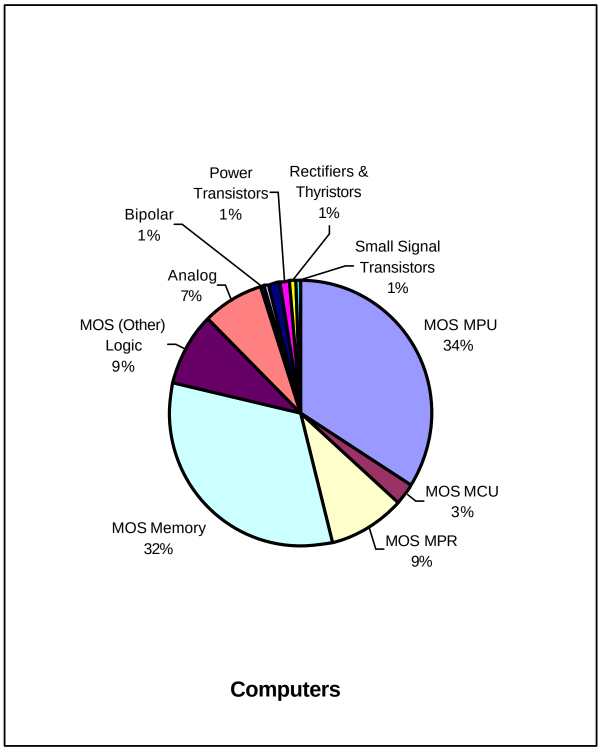


Chart 4
Semiconductors used in the Production of Computers and Communications Equipment by Product class, 1999.



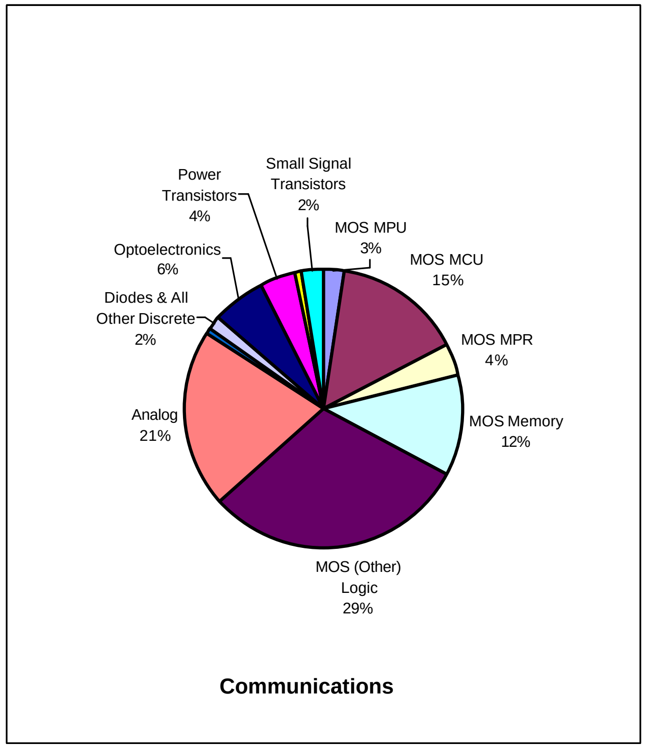


Table 1. Constant-Quality Price Change and Nominal Weights for Semiconductors

	Price Change (CAGR) 91-99	Nominal Shipments Weight, 1999	
		Computers	Communications
MOS MPU	**-52.3**	33.9%	2.5%
MOS Memory	**-30.8**	32.2%	11.7%
MOS MPR	**-14.0**	10.0%	4.0%
Other MOS Logic	**-13.2**	9.0%	30.3%
MOS MCU	**-7.5**	2.6%	14.8%
Thyristors & Rectifiers	**-7.1**	0.7%	0.9%
Power Transistors	**-5.6**	1.1%	4.2%
Small Signal Transistors	**-5.3**	0.5%	2.4%
Optoelectronics	**-3.6**	1.6%	6.0%
Diode & All Other Discrete	**-2.6**	0.5%	1.7%
Digital Bipolar	**0.6**	0.6%	0.6%
Analog (a)	**1.4 (-9.0)**	7.3%	20.8%

Source: Authors' calculations

Note: (a) The two price indexes for analog devices are referred to as WSTS and Hybrid, respectively, in what follows.

Table 2. Semiconductor Input Price Indexes, by End Use, 1992-99

Worldwide	Compound Annual Growth Rate		
	92-99	92-95	95-99
Auto	-12.35	-3.97	-18.16
Communication	-15.33	-3.33	-23.34
Computer	-32.22	-11.30	-44.60
Consumer	-13.97	-2.27	-21.82
Government	-17.30	-3.00	-26.62
Industrial	-15.36	-3.36	-23.38
North America	**Compound Annual Growth Rate**		
	92-99	92-95	95-99
Auto	-12.46	-4.64	-17.91
Communication	-15.58	-3.41	-23.69
Computer	-34.74	-13.29	-47.26
Consumer	-15.22	-2.17	-23.85
Government	-14.74	-3.37	-22.39
Industrial	-16.11	-4.27	-24.02

Source: Authors' calculations

Table 3. Derivation of Semiconductors' Cost Share and Contribution to Output Price Change

	Semiconductor Cost Share						Contribution (percentage points)	
	Price Change(a) (1)	Shipment Share (b) (2)		Shipments/ Variable Cost (c) (3)	Semi Inputs/ Variable Cost (4)=(2)x(3)		(5)=(4)x(1)	
		Low	High		Low	High	Low	High
Consumer audio	-30.4%	11%	15%	125.9%	14.0%	18.7%	-4.3%	-5.7%
Computers	-52.7%	20%	30%	150.8%	30.6%	45.1%	-16.1%	-23.8%
Communications	-31.6%	11%	19%	168.2%	18.2%	31.6%	-5.7%	-10.0%

Notes:

(a) Appendix Table A8, percent change from 1997-98.

(b) Appendix Table A7.

(c) Calculated as Shipments/(Shipments-Value Added+Payroll) using data from U.S. Census Annual Survey of Manufactures, 1998, for NAICS 3341 (Computer & peripheral equipment manufacturing), NAICS 3342 (Communications equipment manufacturing), NAICS 3343 (Audio & video equipment manufacturing).

Table 4. Semiconductors' Contribution to End Use Price Change in 1998

	End-Use Price Change (1)	Contribution of Semiconductors: Percentage points (2)		Contribution of Semiconductors: Share of End-Use Price Change (2)/(1)	
		Low	High	Low	High
Consumer audio(a)	-15.8%	-4.3%	-5.7%	26.9%	36.0%
Computers(b)	-40.3%	-16.1%	-23.8%	40.1%	59.0%
Communications					
LAN Equipment(c)	-29.5%	-5.7%	-10.0%	19.5%	33.9%
LAN Equipment & Switches(d)	-33.3%	-5.7%	-10.0%	17.3%	30.0%

Notes:

(a) Hedonic index with vintage included from Kokoski,Wachrer,& Rozaklis (2000),Table 9.

(b) Matched model Fisher for all computer systems from Aizcorbe, Corrado, & Doms (2000).

(c) Corrado (2001), p. 139.

(d) Estimated as follows:
Relative expenditure on switches, LAN equipment from Doms and Forman (2001) used as weights; weighted average of LAN equipment price change and estimated switch price change. Estimated switch price change taken as 1.258 times LAN equipment price change based on historical relationship between LAN and swtich price change over 1992-96 taken from Corrado (2001), Grimm (1996).

Table 5. Estimates of the Relative Contribution of Semiconductors to Price Change in Computers and Communications Equipment in 1998

	End-use Price Change (a) (1)	=	Semiconductor contribution (b) (2)		+	All Other Factors (1) - (2)	
Change in Computer Prices Less:			Low	High		Low	High
LAN Equipment (a)	-10.8%		-10.4%	-13.8%		-0.4%	3.0%
LAN Equipment & Switches (b)	-7.0%		-10.4%	-13.8%		3.4%	6.8%

Notes:

(a) Calculated using figures in table 4, column (1).

(b) Calculated using figures in table 4, column (2).

Table A1 Value of Semiconductors Consumed Worldwide, by Product Class, 1992-99

	1991	1992	1993	1994	1995	1996	1997	1998	1999
Diodes & All Other Discretes	1,341,463	1,290,629	1,498,533	1,747,473	2,465,981	2,189,285	2,262,636	2,144,643	2,429,508
Small Signal Transistors	1,803,269	1,783,320	1,979,948	2,432,565	3,309,019	2,884,870	2,756,933	2,374,300	2,752,609
Power Transistors	2,489,270	2,629,819	3,015,544	3,704,908	5,181,568	4,936,068	5,083,619	4,616,964	5,404,166
Rectifiers & Thristors	1,912,197	1,909,873	2,142,621	2,596,973	3,048,455	2,868,492	3,061,730	2,787,425	2,796,614
Optoelectronics	2,421,766	2,297,378	2,654,118	3,238,387	4,343,561	4,146,750	4,505,929	4,617,216	5,777,794
Digital Bipolar	3,421,608	3,147,449	3,149,852	2,773,665	2,773,878	1,925,660	1,594,019	1,099,712	990,300
Analog	8,335,914	8,728,687	10,673,019	13,585,169	16,646,353	17,043,805	19,788,937	19,072,955	22,081,701
MOS MPU	3,565,035	5,460,259	8,589,686	10,995,486	14,278,592	18,529,996	23,466,929	24,775,645	27,191,405
MOS MCU	4,851,901	5,245,160	6,560,368	8,276,384	10,735,795	11,435,438	12,622,903	12,115,824	14,083,190
MOS MPR	2,971,576	3,205,239	3,921,409	4,548,201	8,381,534	9,862,276	11,676,920	10,449,901	10,426,667
Other MOS Logic	9,260,355	9,331,793	11,857,716	15,529,061	19,781,034	20,125,581	21,047,471	18,564,413	23,158,467
MOS Memory	12,233,100	14,835,353	21,266,867	32,450,325	53,457,910	36,018,211	29,335,095	22,993,001	32,286,130
Total Semiconductor	54,607,454	59,864,958	77,309,681	101,878,593	144,403,681	131,966,433	137,203,120	125,611,999	149,378,551

Source: WSTS Survey.

Table A2. Semiconductor Input Price Indexes calculated using aggregate MOS Micro Price Index, by End Use, 1992-99.

Worldwide	Compound Annual Growth Rate		
	92-99	92-95	95-99
Auto	-13.66	-7.28	-18.16
Communication	-16.33	-5.96	-23.34
Computer	-31.33	-8.57	-44.60
Consumer	-15.14	-5.33	-21.82
Government	-17.80	-4.36	-26.62
Industrial	-15.61	-4.01	-23.38

North America	Compound Annual Growth Rate		
	92-99	92-95	95-99
Auto	-13.52	-6.92	-18.16
Communication	-16.54	-5.94	-23.69
Computer	-33.54	-9.53	-47.26
Consumer	-16.72	-6.15	-23.85
Government	-14.76	-3.90	-22.10
Industrial	-16.21	-4.52	-24.02

Source: Authors' Calculations

Table A3. Price Indexes for Individual Semiconductor Devices: Underlying Data

Type of Device	1999 shares	Index Source	Price Measure	Data. Freq.	Distinct devices	Time period
MOS						
Memory Chips	**21%**	2	Fisher	Q/Ave	84	91-99
Microprocessors	**18%**	1,3	Fisher	Q/Ave	85	92-99
Microcontrollers	**9%**	4	Fisher	M/Ave	5	91-96
		2,4	Fisher	M/A/Ave	53	96-99
Microperipherals	**6%**	4	Fisher	A/Ave	5	91-99
Logic chips	**16%**	2				
General Purpose Logic			GeoMeans	A/end	35	91-99
Gate Array			GeoMeans	A/Ave	63	91-99
Standard Cell			GeoMeans	A/Ave	56	91-99
Field Programmable Logic			GeoMeans	A/Ave	14	91-94
Other integrated circuits optoelectronics, and discrete devices	**36%**	2,4	Fisher	M/Ave	43	91-99

Sources:

1. Grimm (1997); 2. Aizcorbe (2001); 3. Aizcorbe, Corrado and Doms (2000); 4. Aizcorbe, Flamm, and Khurshid

Table A4. Annual Fisher Ideal Price Index, by Product Class, 1992-99

	91	92	93	94	95	96	97	98	99	CAGR 91-99
MOS MPU	1.52	1.00	0.69	0.47	0.19	0.071	0.033	0.010	0.0041	-52.32
MOS Memory	1.30	1.00	0.97	0.98	0.93	0.45	0.20	0.08	0.07	-30.76
MOS MPR	1.17	1.00	0.89	0.73	1.00	0.98	0.66	0.57	0.35	-13.98
Other MOS Logic	1.11	1.00	0.96	0.90	0.84	0.72	0.66	0.43	0.36	-13.16
MOS MCU	0.98	1.00	1.01	0.99	1.00	0.87	0.70	0.60	0.53	-7.48
Thyristors & Rectifiers	1.00	1.00	0.98	1.00	0.97	0.77	0.69	0.63	0.56	-7.09
Power Transistors	1.07	1.00	1.00	1.03	1.04	0.88	0.74	0.66	0.67	-5.65
Small Signal Transistors	1.05	1.00	1.04	1.05	1.06	1.00	0.82	0.70	0.68	-5.27
Optoelectronics	0.91	1.00	1.01	1.01	1.04	0.94	1.00	0.70	0.68	-3.63
Diode & All Other Discrete	0.98	1.00	0.98	1.01	1.16	1.06	0.93	0.82	0.79	-2.60
Digital Bipolar	0.87	1.00	1.08	1.12	1.08	0.93	0.73	0.71	0.92	0.57
Analog	0.95	1.00	1.07	1.16	1.23	1.27	1.18	1.09	1.06	1.40
WSTS: All analog	0.95	1.00	1.07	1.16	1.23	1.27	1.18	1.09	1.06	1.40
Low-tech	1.00	1.00	1.07	1.21	1.23	1.20	1.09	1.04	1.05	0.63
High-tech	0.92	1.00	1.07	1.13	1.24	1.30	1.18	1.07	1.02	1.22
Hybrid	1.07	1.00	1.00	1.00	0.95	0.85	0.78	0.57	0.50	-8.99
Other MOS logic	1.11	1.00	0.96	0.90	0.84	0.72	0.66	0.43	0.36	-13.16

Source: Authors' calculations.

Table A5. Price indexes for the individual classes of MPR chips.

Component Price Indexes	1991	1992	1993	1994	1995	1996	1997	1998	1999
Chipsets	118.1	100.0	100.4	80.9	102.4	124.4	79.5	76.6	42.3
Comm ICs	146.8	100.0	92.7	67.1	77.2	103.5	91.9	58.4	28.0
Graphics ICs	113.4	100.0	74.7	58.0	134.4	74.1	24.6	28.0	23.7
Mass Storage	103.7	100.0	97.4	110.4	111.2	75.0	92.9	71.8	48.0
Voice & other	99.1	100.0	83.1	72.5	35.0	44.0	43.5	35.9	22.3
Fisher Ideal Index	116.8	100.0	88.8	73.0	99.6	97.9	65.8	57.5	35.0

Source: Authors' calculations.

Table A6. Alternative Price Indexes for Analog Devices, 1992-99

	Compound Annual Growth Rate		
	91-99	**91-95**	**95-99**
WSTS: All Analog	1.40	6.85	-3.77
High Tech	1.22	7.67	-4.83
Low Tech	0.63	5.36	-3.88
Hybrid Index:	-8.99	-2.86	-14.73
Other MOS Logic	-13.16	-6.76	-19.13

Source: Authors' calculations.

Table A7. Estimates of Semiconductor Content as Percentage of Value of Product

		1998	1999	2000
Automotive	DQ Cons/DQ Eqp		18%	21%
	WSTS/EIO	16%	19%	
	WSTS/DQEqp	15%	15%	17%
Communications	DQ Cons/DQ Eqp	11%	17%	19%
	WSTS/EIO	11%	13%	
	WSTS/DQEqp		12%	16%
Computers	DQ Cons/DQ Eqp		26%	30%
	WSTS/EIO	20%	23%	
	WSTS/DQEqp	22%	24%	26%
Consumer Electronics	DQ Cons/DQ Eqp		13%	15%
	WSTS/EIO	11%	12%	
	WSTS/DQEqp	11%	11%	15%
Government	DQ Cons/DQ Eqp		4%	5%
	WSTS/EIO	2%	1%	
	WSTS/DQEqp	2%	2%	2%
Industrial	DQ Cons/DQ Eqp		8%	9%
	WSTS/EIO	8%	8%	
	WSTS/DQEqp	9%	8%	10%

Key to Sources:

Semiconductor Consumption by User Sector

DQ Cons Dataquest-Gartner Group, Semiconductor Product Trends in 2000, 7/31/2000

WSTS World Semiconductor Trade Statistics, Semiconductor Industry End-Use Survey.

Value of Equipment Production, by Industry

DQ Eqp Dataquest-Gartner Group, Semiconductor Product Trends in 2000, 7/31/2000

EIO Electronic Industry Outlook, 1998.

Table A8.
Annual Fisher Ideal Price Index, by End Use Industry, 1992-99

Worldwide	Deflator							
	92	93	94	95	96	97	98	99
Auto	1	0.96	0.92	0.89	0.72	0.59	0.45	0.40
Communication	1	0.97	0.94	0.90	0.69	0.54	0.37	0.31
Computer	1	0.91	0.83	0.70	0.39	0.22	0.10	0.07
Consumer	1	0.98	0.96	0.93	0.73	0.58	0.40	0.35
Government	1	0.98	0.96	0.91	0.65	0.48	0.32	0.26
Industrial	1	0.97	0.95	0.90	0.68	0.52	0.36	0.31
North America	**Deflator**							
	92	93	94	95	96	97	98	99
Auto	1	0.96	0.91	0.87	0.71	0.58	0.44	0.39
Communication	1	0.97	0.93	0.90	0.68	0.53	0.36	0.31
Computer	1	0.89	0.80	0.65	0.35	0.19	0.09	0.05
Consumer	1	0.98	0.95	0.94	0.70	0.53	0.37	0.31
Government	1	0.98	0.96	0.90	0.70	0.56	0.39	0.33
Industrial	1	0.96	0.93	0.88	0.67	0.51	0.35	0.29

Source: Authors' calculations.