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ABSTRACT

By any measure, price deflators for semiconductors fell at a staggering pace over much of the last decade, pulled down by steep declines in the deflator for the microprocessor (MPU) segment. These rapid price declines are typically attributed to technological innovations that lower constant-quality manufacturing costs through either increases in the quality of the devices or decreases in costs. However, Intel's dominance in the microprocessor market raises the possibility that those price declines could also reflect changes in Intel's profit margins.

This paper uses industry estimates on Intel's operations to decompose a price index for Intel's MPUs into three components: quality improvements, reductions in costs, and changes in markups. The decomposition suggests that 1) virtually all of the declines in a price index for Intel's chips can be attributed to quality increases associated with product innovation, rather than declines in the cost per chip. Of course, these increases in quality pushed down *constant-quality* costs. However, *cost per chip* did not play a role in generating the observed price declines in the MPU price index, as cost increases associated with the introduction of new, higher quality chips more than offset cost reductions associated with learning economies. With regard to markups, the sizable

decline in Intel's markups from 1993-99 only accounted for about 6 percentage points of the average 24 percent decline per quarter in a price index for Intel’s chips

Consistent with the inflection point that Jorgenson(2000) noted in the overall price index for semiconductors, the Intel price index falls faster after 1995 than in the earlier period but, again, the decomposition attributes virtually all of the inflection point to an acceleration in quality increases.

1. Introduction

By any measure, price deflators for semiconductors fell at a staggering pace over much of the last decade. As shown in the top panel of table 1, Fisher price indexes for integrated circuits—ICs, a broad class of semiconductor devices that includes logic and memory chips—fell an average of 36 percent each year from 1993 to 1999. As shown in the bottom panel, those price declines were generated primarily by sharp declines in the price index for microprocessors—MPUs, the logic chips that serve as the central processing unit in PCs.

The price deflator for ICs fell even faster in the second half of the decade, pushed down by faster declines in the MPU price index. Jorgenson (2000) noted the acceleration and hypothesized that the development and deployment of semiconductors could have been a key driver in the economy-wide resurgence in economic growth that began in the mid-1990s. Empirical work based on macroeconomic growth models supported his hypothesis by showing that the semiconductor industry accounted for nearly three-fourths of the acceleration in multifactor productivity that occurred over the 1990s.[1]

These sharp declines are typically attributed to the rapid rate of product innovation that characterizes this sector (See, for example, Triplett (2004)). Informal measures of quality change suggest that quality change is the primary driver behind the price declines typically seen for these devices (Aizcorbe, Corrado, and Doms (2000)). Indeed, the industry is credited with one of the fastest rates of product innovation and technical change within manufacturing, as chipmakers generate wave after wave of ever-more powerful chips for prices not much higher than those of existing chips.

At the same time that the quality of MPUs is increasing, manufacturers are also getting better at producing them and the attendant reductions in the manufacturing cost per chip could also have contributed to the observed declines in the price index. As is well known, the semiconductor production process is subject to important learning economies along several dimensions (See, for example, Gruber (1994) and Hatch and Mowery (1998)). Most of the empirical literature on learning by doing in the semiconductor industry has focused on memory chips—a homogeneous commodity good sold in fairly competitive markets. For MPUs, Intel's dominance of the market has generated large markups so that cost savings from learning-by-doing may not necessarily be passed along to consumers in the form of lower prices.

The presence of large markups, in and of itself, has potential implications for price measurement: while quality increases and reductions in cost per chip are associated with increases in productivity, changes in markups are not. Over the 1990s, Intel's markups shrank as increased competition from its rivals and weaker-than-expected demand for personal computers in 1995 and beyond put downward pressure on prices. This decline in Intel's markup could have potentially distorted standard price indexes because those indexes implicitly assume perfect competition.[2] So, for example, falling markups could lead one to incorrectly interpret the resulting price decline as a productivity improvement.[3] Although it is unlikely that Intel's markups fell sufficiently fast to explain much of the *absolute* price declines over the decade, those declines may, nonetheless, have had a nontrivial effect on the *acceleration* that began in 1995.

To better understand the trend and inflection point in semiconductor prices, this paper decomposes movements in the constant-quality price index into changes in the index associated with productivity growth and those associated with markups. A further decomposition of the productivity-related component into quality change—owing to rapid rates of product innovation—vs. changes in cost per chip—perhaps related to learning-by-doing—is also done. This is useful for predicting the likely effect of future developments in the industry to changes on the price index and productivity. Moreover, understanding the link between learning-by-doing—a phenomenon thought to be important for other semiconductor devices—and productivity in the MPU segment is also of interest.

The decomposition suggests that virtually all of the price declines in the Intel price index can be attributed to quality increases associated with product innovation rather than declines in cost per chip; increases in quality obviously pushed down constant-quality prices, but cost per chip do not seem to have played a role in generating the observed price declines because cost reductions associated with learning were more than offset by cost increases associated with the introduction of new, higher-quality chips. Although markups from Intel's MPU segment shrank substantially from 1993-99, those declines accounted for only about 6 percentage points of the average 24 percent per quarter decline in its price index. Similarly, changes in quality were the primary driver behind the inflection point seen in 1995.

The paper is organized as follows. Section 2 uses industry estimates of chip-level prices to show that both the absolute declines and the inflection point in the MPU price index reflect large quality increases. Section 3 uses cost estimates to explore the contributions of changes in the cost per chip and markups to the observed declines in the MPU price index. Section 4 concludes.

2. Measuring Changes in the Average Quality of Intel's MPUs

"Discussions of "quality" in price indexes often place the term in quotation marks and few authors have attempted to provide a rigorous definition."[4]

The difference between a constant-quality index and an average price series is often interpreted as an informal measure of quality both by practitioners in industry and by researchers interested in price measurement.[5] The idea is that if a price index holds quality constant and an average price series does not, then the average price can be stated as the sum of a constant-quality index and a quality measure. As in Raff and Trajtenberg (1997), the identity is:

$$(1) \qquad \text{dln (average price)} \equiv \text{dln (constant-quality price index)} + \text{dln (quality)}$$

The problem in numerically implementing this notion is that while theory tells us how to measure *constant-quality* prices, it does not tell us how to measure the *average* price series. Should it be an arithmetic average or a geometric average? Should the weights be fixed or variable? Does it matter?

Interpreting Informal Measures of Quality Change

The paradigm that comes to mind when thinking about quality change is the framework implicitly used by the Bureau of Labor Statistics (BLS) to hold quality constant when replacing one good in their basket with another. Chart 1 shows the general idea. The chart shows price profiles for two chips, with chip 2 replacing chip 1 at time t=1. The change in the price per chip from t=0 to t=2 may be stated as the product of the price changes over the life of each chip and the gap in prices of the new and exiting chip. In terms of the diagram, the change in the price per chip is the ratio of the last price for chip 2 ($P_{2,2}$) and the first price for chip 1 ($P_{1,0}$). That ratio may be written as:

$$P_{2,2} / P_{1,0} = \boldsymbol{(\, P_{2,2} / P_{2,1} \,)}\ (\, P_{2,1} / P_{1,1} \,)\ \boldsymbol{(\, P_{1,1} / P_{1,0} \,).} \tag{2}$$

This change in the price per chip could be viewed as a constant-quality price index only in the hypothetical case where the two chips are of equal quality; in that case, price per chip is all that matters. Alternatively, one can allow the chips to be of different quality and assume that any price difference at t=1 is the market’s valuation of these quality differences. In this view, one obtains a constant-quality price index by measuring price changes that occur over the life of each chip--shown in bold in (2)--and excluding the gap in the two prices at t=1. The middle term is the gap between the average price measure on the left-hand side and the matched-model index--the product of the two bold terms on the right.

Taking logs and rearranging terms, the average price change from t=0 to t=2 is the sum of three terms. The first two terms make up the constant-quality index and the third measures quality change:

$$\ln(P_{2,2} / P_{1,0}) = [\, \ln\boldsymbol{(\, P_{2,2} / P_{2,1} \,)} + \ln\boldsymbol{(\, P_{1,1} / P_{1,0} \ ]} + \ln(\, P_{2,1} / P_{1,1} \,) \tag{2’}$$

Note that the valuation of quality change is independent of any changes in the underlying costs or markups. Market prices are viewed as a signal of the markets' valuation of the different chips so that the price differentials reflect quality differentials.

This seems like a sensible way to value quality change and is, in fact, the assumption implicit in MM methods. In general, though, there are many chips that coexist in the market, and turnover is characterized by new and existing goods overlapping for some period of time. Loosely speaking, if one thinks of the logged prices in (2') as *averages*, then the matched-model index still measures price change over the lives of goods existing in both periods, but quality change is measured as a difference of (logged) means: *average* prices with entry (the change in an average price series) and *average* prices without entry (the change in the matched-model index).

A geometric mean index provides a simple example to illustrate the point. A matched-model geometric mean of price change over the period t, t-1 (in logged form-- $\ln P^{GEO}_{t,t-1}$) is an arithmetic mean of logged price relatives for the goods that exist in both periods:

$$(3) \qquad \ln I^{GEO}_{t,t-1} = \Sigma_{m\in match(t)} (\mathit{ln}\, P_{m,t} - \mathit{ln}\, P_{m,t-1}) / M_t$$

where models that exist in both periods are denoted match(t) and the number of such models at time t is denoted $M_{t.}$ To see how this index handles quality change, consider an example where a new good enters at time t. In that case, the geometric mean can be restated as a combination of two terms:[6],

$$(4) \qquad \ln I^{GEO}_{t,t-1} = \Big[\Sigma_{m\in all(t)} (\mathit{ln}\, P_{m,t}) / N_t - \Sigma_{m\in all(t-1)} (\mathit{ln}\, P_{m,t-1}) / N_{t-1} \Big]$$

$$- \Big[\big(\Sigma_{m \in all(t)} (\mathit{ln}\, P_{m,t}) / N_t - \Sigma_{m \in match(t)} (\mathit{ln}\, P_{m,t}) / M_t \big) \Big]$$

where the goods that exist at time t are indexed by $m \in all(t)$, those that exist in both periods are indexed $m \in match(t)$ and the number of all goods and matched goods sold at time t are denoted by N_t and M_t.

The first term in brackets gives the difference in the (geometric) average sales prices in the two periods. The second term compares an average sales price for time t that *includes* the new good to one that *excludes* the new good and is a measure of quality change; when the arrival of the new good raises the average sales price, it must be that the new good is viewed superior--or, of higher quality--by the market. This is the same intuition as in the simple case above, except that there quality change was measured as differences in *individual* prices whereas here it is measured as differences in *averages.* Again, the benchmark for comparison is the hypothetical case where all goods are homogeneous, in which case the price of new goods would be the same as that of existing goods and the second term in (4) would equal zero. In that view, any observed difference in the price of new and existing goods can be taken to be a measure of their quality differences. A similar expression can be derived for exiting goods.[7]

The particular functional form of the average price and quality measures depends on that of the price index. In (4), each price gets an equal weight because the functional form for the constant-quality price measure is a geometric mean. Moreover, note that for this functional form, "quality" only changes when there is turnover. This is because the weights in the index are fixed (at 1/N) and any changes in the relative importance (in terms of sales, say) of one good relative to another are not counted as quality change.

In contrast, superlative indexes do capture changes in the relative importance of goods by weighting each good's price change by its share in nominal output. For one such superlative index—the Tornquist—one can apply the same logic used above to show that the Tornquist price index captures quality changes that result from both turnover—differences in means with and without the new good—and from mix-shift among existing goods—changes in the relative importance of existing goods. The only difference is that, in the Tornquist, all measures use expenditure weights.

To see this, consider a matched-model Tornquist price index:

$$(5)\qquad \ln I^{TORN}_{t,t-1} = \Sigma_{m\in match(t)}\ \omega_{m,t}\ (\mathit{ln}\ P_{m,t} - \mathit{ln}\ P_{m,t-1})$$

where, as before, $\Sigma_{m\in match(t)}$ denotes a summation taken over goods available in both periods and each $\omega_{m,t}$ is an average of the time t-1 and time t expenditure weights: $\omega_{m,t} = \frac{1}{2}(w^{MM}{}_{mt}+w^{MM}{}_{mt-1})$, where $w^{MM}{}_{mt} = P_{mt}Q_{mt}/\Sigma_{m=match(t)}\,P_{mt}Q_{mt}$.

Again, consider the simple case where a new good enters at time t. In this decomposition, average prices are weighted geometric means with weights that either sum over all goods ($w^{ALL}{}_{mt} = P_{mt}Q_{mt}/\Sigma_{m\in all(t)}P_{mt}Q_{mt}$) or over just the matched models ($w^{MM}{}_{mt} = P_{mt}Q_{mt}/\Sigma_{m=match(t)}\,P_{mt}Q_{mt}$). One decomposition that splits out quality change from changes in average prices is:

$$(6)\qquad \ln I^{TORN}_{t,t-1} = [\ \Sigma_{m\in all(t)}\ w^{ALL}{}_{it}\ \mathit{ln}\ P_{m,t} - \Sigma_{m\in all(t-1)}\ w^{ALL}{}_{it-1}\ \mathit{ln}\ P_{m,t-1}\ ]$$

$$- [\Sigma_{m\in all(t)} \; w^{ALL}{}_{it} \; ln \; P_{m,t} \; - \; \Sigma_{m\in match(t)} \; w^{MM}{}_{it} \; ln \; P_{m,t} \;]$$

$$- [\Sigma_{m\in match(t)} \; ln \; P_{m,t} \; (w^{MM}{}_{it} - \omega_{m,t}) \;]$$

$$- [\Sigma_{m\in match(t)} \; ln \; P_{m,t-1} \; (\omega_{m,t} - w^{MM}{}_{it-1} \;) \;]$$

As before, the first term measures the difference in the average prices and the remaining terms measure quality change. The second term measures quality change associated with entry by comparing the average prices with and without the new good; it strips out any changes in the average price that arise from the entry of the new (higher-quality) good. In the absence of entry, all goods are matched in both periods and the term equals zero.

The last two terms capture changes in the quality measure that occur as the relative importances of goods change over time. These terms strip out any changes in average price that arises from changes in the composition of expenditures. For example, suppose all the underlying prices are unchanged from time t-1 to time t but that expenditures shift owing to changes in the market's perception of the relative quality of goods. The last two terms will capture this as a change in quality by changing the weights associated with each good's price.

Note that if goods' expenditure shares are equal in both periods, then $\omega_{m,t}=w^{MM}{}_{it}=w^{MM}{}_{it-1}$ and these two terms equal zero. Also, note that if there is no turnover and goods' relative importances are constant, then the Tornquist index reduces to a difference in (weighted) average prices—the first term.

Intel Price Data and Calculations

The decomposition in (6) is done using data on Intel's MPU pricing that were obtained from MicroDesign Resources (MDR)—the industry's primary source for data on Intel's operations. The data are quarterly observations on prices, unit shipments, and revenues for Intel's microprocessors at a high level of product detail. MDR estimates prices by taking Intel's published list prices and making any needed adjustments for volume discounts. They also estimate unit shipments and revenue data using Intel's 10K reports and the World Semiconductor Trade Statistics data published by the Semiconductor Industry Association (see Aizcorbe, Corrado and Doms(2000)) for a fuller description of the data).

Chart 2 uses price profiles for Intel's desktop chips introduced from 1993 to 1998 to illustrate two features of these profiles that are characteristic of microprocessors and other semiconductors.[8] First, there is a high degree of turnover in this segment as new, faster chips are brought to the market. Second, prices fall steeply over the life of each chip; prices typically start at between \$600 to \$1000 at introduction--substantially higher than the prices of existing chips. By the time the chip exits the market, its price has fallen to under \$100. The steepness of these profiles could reflect demand- or supply-driven forces. On the demand side, the profiles are consistent with the view that users are initially willing to pay high prices for new chips but as the introduction of the new (better) chip nears, they are less willing to do so and prices of the incumbent chips fall.[9] On the supply side, these profiles are consistent with the view that prices over the life of the chip are pulled down by declining costs as firms find ways to produce each chip at lower cost.

Because most price indexes are essentially functions of weighted averages of price change, the steepness of the slopes for these contours will translate into rapidly declining price indexes. As seen in the first column of table 2, the chained, matched-model Tornquist index for Intel's chips falls sharply over this period: at an average rate of 24.4 percent per quarter.[10] In contrast, changes in the average price—the second column—show little movement; falling only 2.1 percent per quarter.[11] Apparently, the average price series says more about the distribution of prices over time than it says about declines in prices over the life of each chip. Intuitively, it is relatively flat because the effect of declines in prices over the life of each chip on average price is undone when the next chip enters the market at the same high introductory price.

This large gap between declines in the price index and those in average prices implies that virtually all of the declines in the price index stem from increases in the quality of chips; as tabulated in the last column, 22.3 percentage points of the 24.4 percent average decline in the Tornquist price index reflect increases in quality change.

The last two rows of the table provide averages of price change in the pre- and post-1995 period. The first column verifies the inflection point noted by Jorgenson: the declines in the price index accelerated from an average quarterly decline of 17 percent over 1993-1995 to about 30 percent in 1996-1999. As seen in the last column, virtually all of the acceleration is accounted for by increases in measured quality. Average prices did fall faster in the second half of the decade but explain only 3 percentage points of the acceleration in the Tornquist index.

3. Measuring Changes in the Costs Per Chip

"In general, Intel's prices are several times the manufacturing cost of the chips, so that cost has little influence on their price."[12]

The changes in average prices calculated above can be decomposed into contributions from changes in the cost per chip vs. those in the markup:

$$\text{(7)} \quad \text{dln (average price)} \equiv \text{dln (cost per chip)} + \text{dln(price/cost per chip)}$$

While average prices changed little over this period, there may have been offsetting changes in costs and markups that have different implications for movements in the index. This section quantifies the contributions of costs and markups to changes in average prices to assess any distortions caused by changes in markups and to explore the role that learning economies might have played over this period.

In terms of the earlier decomposition, the first term in (6) may be broken out as follows:

$$\begin{aligned}
&[\ \Sigma_{m\in all(t)}\ w^{ALL}{}_{it}\ \mathit{ln}\ P_{m,t}\ -\ \Sigma_{m\in all(t-1)}\ w^{ALL}{}_{it-1}\ \mathit{ln}\ P_{m,t-1}\ ] = \\
\text{(8)}\quad &[\ \Sigma_{m\in all(t)}\ w^{ALL}{}_{it}\ \mathit{ln}\ AC_{m,t}\ -\ \Sigma_{m\in all(t-1)}\ w^{ALL}{}_{it-1}\ \mathit{ln}\ AC_{m,t-1}\ ] \\
&\quad +\ [\ \Sigma_{m\in all(t)}\ w^{ALL}{}_{it}\ \mathit{ln}\ (P_{m,t}/AC_{m,t})\ -\ \Sigma_{m\in all(t-1)}\ w^{ALL}{}_{it-1}\ \mathit{ln}\ (P_{m,t-1}/AC_{m,t-1})]
\end{aligned}$$

The first term measures changes in the average cost per chip and the second measures changes in the markup. This decomposition allows one to isolate any potentially distorting effects of increased competition in MPU markets over the 1990s on the MPU price index and assess the potential importance of learning by doing on average costs and, hence, the price index.

Manufacturing Costs and Learning

The cost structure and manufacturing process for semiconductors is extremely complex.[13] The process involves taking a silicon wafer of fixed size, etching chips—initially called "die"—on this wafer, and eventually separating out the individual die and packaging them for sale. The manufacturing cost per wafer is constant, so that anything that increases the number of usable die on a wafer reduces the average cost per usable die. An obvious way to reduce the cost per die is by increasing the size of the wafer upon which the chips are etched, but this actually occurs only infrequently.

More commonly, firms reduce average cost by reducing the size of the die by either reducing the size of each feature on a chip— i.e., etching smaller transistors —or by reducing the spaces between them. Reductions in the size of features is made possible when there are advances in the equipment used to etch the chips and, thus, requires investment in new equipment. Reductions in the gap between features occurs with learning as firms gain familiarity with the production of a new die and find ways to etch these features closer together (i.e., learning). This requires less investment because it only requires changing the masks that are used to etch the chips (not entirely replacing the equipment).

A final way that firms lower the average cost per usable die is by increasing the *yield* of production during the ramp-up of a new die. The complexity of the manufacturing process is such that the *early months* of production of a new die are marked by high defect rates that hold down yields—defined as the ratio of usable chips to all chips. Within a few months of launching production, yields stabilize at about 90 percent and the average cost of production bottoms out. [14]

Most of the available work on cost and pricing of semiconductor devices is for devices in the memory segment – DRAM chips in particular. For those devices, learning is an important driver of costs and, because that segment is fairly competitive, of prices. In those studies (See Flamm (1989) and Irwin and Klenow (1994), for example), show that price contours for DRAM chips are shaped much like those for MPUs shown in Chart 2 and that learning economies are an important determinant of those contours. As discussed below, learning plays a lesser role in determining the shape of price contours for MPUs.[15]

Industry Estimates for Intel's Costs

Data on cost per chip were obtained from MDR—the same source as the price data. Their cost estimates include labor and material costs plus depreciation of the equipment and part of the building,[16] but do not include an adjustment for the design of the chip or other R&D costs. Thus, the cost concept is closer to variable cost than total cost, and the implied markup could be pure profit or normal returns to R&D and chip design.[17]

As seen in the last row of table 3, the revenue and cost data imply large markups for Intel that declined over this period from nearly 90 percent in 1993 to 73 percent by 1999. The largest declines occurred in 1995-96--when Intel was reportedly under intense competition from its rivals--and again in 1998--when the recession in Asia began to affect world demand for electronic goods.

Cost over the Life of the Chip

An important feature of the MDR estimates is that costs are estimated at "maturity." MDR collects the data somewhere between the "sixth and twelfth month after the release of a new processor, when defect rates are approaching or have reached maturity. Costs will be higher than that during the first few months of production."[18]

The timing of MDR's cost estimates for these pioneer chips does not allow one to say much about increased yields that could pull down costs over the lives of those chips. Nonetheless, one can argue that cost declines associated with increases in yields cannot explain the shape of the price contours over the life of a chip. Because costs are typically very low relative to price. Whereas prices typically fall from about $750-1000 to about $100 over the life of the chip, cost per chip at maturity ranges $50-100. Given this wide gulf between price and cost per chip, even if increased yields reduced costs to one-fourth of their original levels—from, say, $200 to $50—that would still only explain a fraction of the observed price declines. This gap between price and average cost has important implications for empirical studies in the learning-by-doing literature. There, learning economies are typically estimated using average prices as a proxy for average costs. This requires either that markups be constant over the life of the chip or that any changes in markups be small. Although this assumption makes sense in the more-competitive segments in the semiconductor industry (e.g., memory chips), it is clearly at odds with the empirical evidence for MPUs.

It is also unlikely that this type of learning will have a large impact on the price index. Numerically, the Tornquist weights price declines using expenditure weights. Because the declines in average cost early in a chip's life coincide with low yields (low output levels), these changes in costs carry a low weight in the index and, thus, the numerical effect of this type of learning on the price index is likely to be small. Moreover, as explained below, the decline in costs from learning only affect a small number of chips—the pioneering chips that introduce a new die—so that the effect on an index over all chips is likely to be small.

Costs across chips

The distinction between "die" and "chip" is important for our purposes. Although "chip" is the relevant concept from a demand perspective—consumers view chips with different attributes as distinct goods—the relevant concept from a cost perspective is the "die." This is illustrated in chart 3, where the MDR estimates of cost per chip are given for several of Intel's chips that were on the market beginning in 1993, arranged by chip family and in rough order of introduction; the older 486 chips are grouped on the left; the Pentium I chips are in the middle and the Pentium II chips are on the right.

As may be seen, improving attributes—like the speed of the chip—does not always increase the cost per chip. This is because chips of different speeds are often cut from the same wafer and, therefore, cost the same to produce. Once a wafer is etched, the individual die are tested for speed. The ubiquitous presence of defects is such that only some die will test at a high speed and can be sold as a high-speed chip. The others are "binned" together with chips that test at lower speeds and are sold as such. But, because the cost per chip is a function of the number of chips on a wafer—not on the speed of each chip—cost is the same for the high- and low-speed chips.

Chart 3 also shows the effect of die shrinks—one type of learning discussed above: cost per chip declines with the introduction of new, smaller die within each chip family—as occurred with the 75, 120, and 166 Mhz Pentium I chips. These cost declines associated with learning are large: manufacturing cost of the last Pentium I chip was less than one-half of the cost of the first Pentium I chip.

Finally, costs increase discretely with the introduction of new chip families as the learning curve begins anew: for example, the first Pentium II chip costs more than twice what the last Pentium I chip costs.

Over this period, the introduction of new chip families was such that these increases in costs more than offset declines in costs from the learning that occurs within chip families. As seen in the middle column of table 4, cost per chip actually increased 3.7 percentage points over 1993-1999, with the largest cost increases occurring with the introduction of the Pentium I (in 1994) and the Pentium II (in 1997).

This increase in costs coincided with declines in Intel's markup that contributed about 6 percentage points to the 24.4 average quarterly decline in the MPU price index. Looking ahead, to the extent that changes in competitive conditions have stabilized, all else held equal, one can expect a price index for Intel's chips to fall a bit slower in the future than in the 1990s. The net effect of the increase in costs and the decline in markups was a small decline in the average price (column 1).

With regard to the inflection point, as seen in the last two rows of the table, cost per chip rose less fast in the latter part of the 1990s and contributed about 3 percentage points to the decline in the overall price index. The decline in markups was the same in the early and latter parts of the decade and, thus, does not explain any of the inflection point.

4. Summary

This paper provides an assessment of the relative importance of technological progress and markups in generating the observed declines in price indexes for microprocessors over the 1993-99 period. Industry estimates on Intel's price, cost, and shipments of microprocessor chips at a highly disaggregate level were used to establish that product innovation and the attendant increases in quality was the primary driver of the steep price declines seen in price indexes for Intel's chips over 1993-99 and of the inflection point that occurred in 1995.

Although the cost data confirm the importance of learning economies in driving down costs per chip, the data also show large cost increases associated with the introduction of new chips. Over the 1990s, the rate at which new chip families were introduced was such that the latter effect dominated and cost per chip increased. At the same time, Intel's markup declines, contributing about 6 percentage points to the 24 percent average quarterly decline in the price index. However, markups changed about the same before and after 1995 and, thus, do not appear to have played a role in generating the inflection point in 1995.

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Table 1. Chained Fisher Price Indexes for Integrated Circuits, 1993-2000

Annual Percent Changes

	1993	1994	1995	1996	1997	1998	1999
ICs	-9.34	-14.33	-36.3	-45.54	-44.27	-55.29	-49.83
Memory chips	-4.57	0.7	-9.62	-38.04	-43.7	-49.05	-17.58
DRAM	2.64	7.56	0.59	-47.16	-58.72	-61.87	-16.5
Other	-8.99	-4.78	-22.12	-23.28	-26.19	-37.26	-22.04
Logic chips	-18.79	-25.81	-53.82	-59.16	-51.42	-64.34	-61.98
MPU	**-26.07**	**-32.94**	**-63.51**	**-66.98**	**-53.6**	**-70.53**	**-69.12**
Other	-4.1	-2.36	-6.43	-35.26	-42.17	-28.33	-23.96
Other	7.86	5.62	1.9	-4.26	-11.67	-6.41	1.97

Contributions:

Memory chips							
DRAM	0.35	1.58	0.14	-5.71	-5.35	-4.91	-1.98
Other	-1.84	-0.64	-3.98	-2.73	-2.71	-2.98	-2.12
Logic chips							
MPU	-17.55	-20.61	-43.23	-42.7	-33.69	-45.49	-47.99
Other	-1.13	-0.3	-1.34	-5.56	-6.11	-3.87	-4.12
Other	2.13	0.92	0.42	-0.8	-1.94	-0.81	0.27

Source: Author's Calculations

Table 2. Decomposition of Tornquist Price Index for MPUs
(Average quarterly percent change)

	Tornquist Price Index	Weighted Geometric Mean	Tornquist Quality Index
	(1)	(2)	(1)-(2)
1993	-7.4	-4.2	3.3
1994	-14.4	3.0	17.4
1995	-26.9	-0.6	26.3
1996	-22.8	-3.7	19.1
1997	-27.1	4.8	31.9
1998	-37.7	-6.3	31.4
1999	-30.2	-8.1	22.0
1993-99	-24.4	-2.1	22.3
1993-95	-17.1	-0.3	16.8
1996-99	-29.3	-3.3	26.0

Source: Author's calculations based on proprietary data from MDR.

Table 3. Revenue, Manufacturing Costs and Implied Margin for Intel's Microprocessors.

	1993	1994	1995	1996	1997	1998	1999
Revenue	6.8	8.8	12.0	14.9	19.9	22.4	25.0
Manufacturing Cost	0.8	1.2	2.2	3.5	4.8	6.2	6.8
Implied Margin	6.0	7.6	9.8	11.4	15.1	16.2	18.2
Margin/Revenue	88.2	86.4	81.7	76.5	75.9	72.3	72.8

Source: MicroDesign Resources

Table 4. Contributions to Changes in Average Price From Cost per Chip and Markups
(average quarterly percent change)

	Average Price	Contribution from: Cost per Chip	Markup
	(1)	(2)	(3)-(2)
1993	-4.2	3.3	-7.4
1994	3.0	9.8	-6.8
1995	-0.6	3.0	-3.6
1996	-3.7	-2.1	-1.6
1997	4.8	8.3	-3.5
1998	-6.3	2.2	-8.5
1999	-8.1	1.5	-9.6
1993-99	-2.1	3.7	-5.8
1993-95	-0.3	5.5	-5.8
1996-99	-3.3	2.5	-5.8

Chart 1. Simple Example of Quality Measurement

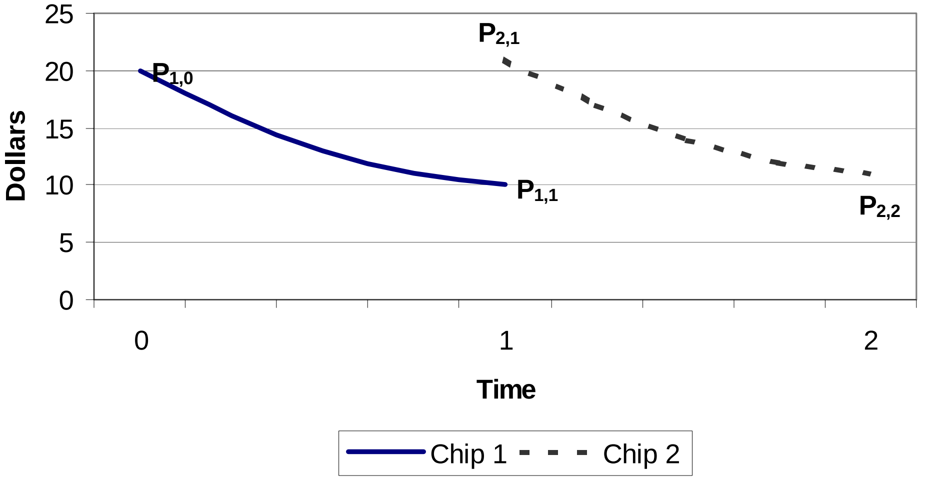


Chart 2. Price Contours for Intel's Pentium I MPUs

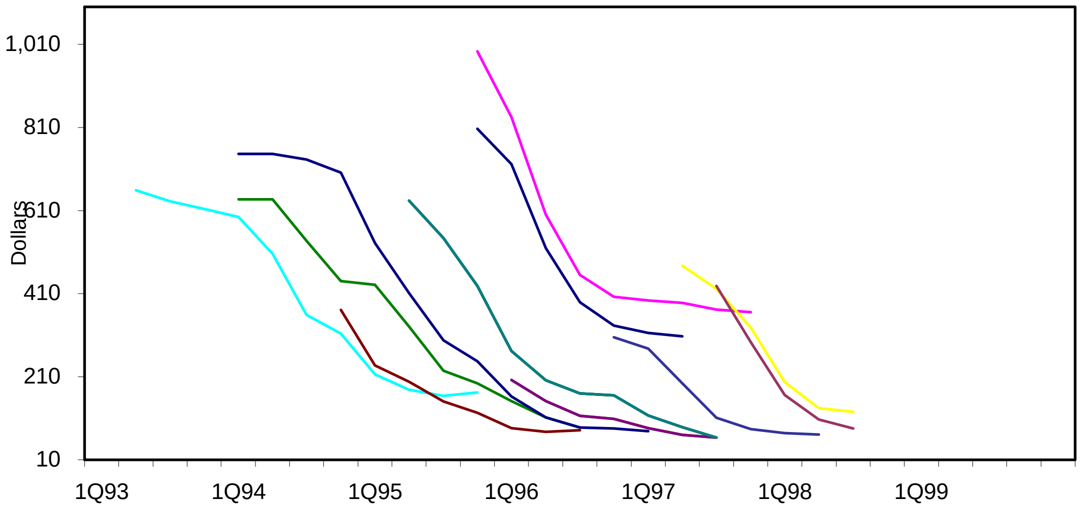
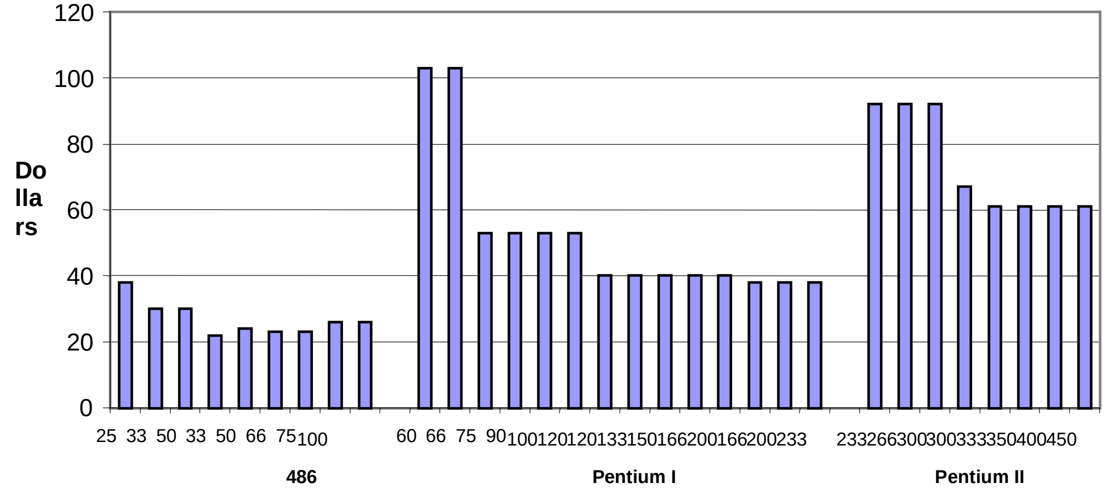


Chart 3. Cost per Chip at Maturity by Speed of Chip
For Selected Intel MPUs



Footnotes

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[1] See, for example, Triplett (1998), Jorgenson (2000), Oliner and Sichel (2000), Jorgenson and Stiroh (2000), McKinsey (2001) and Gordon (2001).

[2] This issue is not relevant for the calculation of an *input* price index, because the actual price paid (including any markup) is precisely what the input price index measures and that is what matters for the productivity of downstream industries. However, use of an *output* price in measuring productivity for the semiconductor industry could be problematic. Under perfect competition, an output "price" index can be used to measure productivity because it tracks changes in (unmeasured) marginal costs; when firms have market power, it may not. See Jorgenson and Griliches (1967), Diewert (1983) and Diewert (1999) for the theoretical foundations underlying these productivity measures.

[3] The importance of market structure for output and productivity measurement has been studied in many different contexts. In the empirical micro literature, Denny, Fuss and Waverman (1981) and Morrison (1992) econometrically estimate multiproduct cost functions to remove the influence of markups in productivity measures. Elsewhere, Diewert (1983, 1999) suggests that markups be handled in the same way that excise taxes are in productivity measurement. In the macro literature, Hall (1988), Domowitz, Hubbard and Peterson (1988), and Basu and Fernald (1997) expand the Solow growth model to account for the presence of markups. Finally, Anderson, dePalma and Thisse (1992) and Feenstra (1995) examine the effect of markups on price indexes in the context of specific functional forms and Berry, Levinson and Pakes (1995) and Pakes(2001) study the effect of markups on hedonic regressions.

[4] Greenlees (1999).

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[5] In industry, the issue of "quality" usually comes up in trying to explain changes in average sales prices—the data that are typically reported by trade associations. So, for example, changes in average sales prices are often explained as resulting from "mix-shift"—a change in the composition of goods of varying quality. Sometimes—as is the case for the average sales price of automobiles—the gap between average sales prices and a constant-quality price index—like the CPI—is used as a measure of quality improvements. In the academic literature, Hulten (1997) has studied the issue from a theoretical perspective. In the empirical literature, the issue typically comes up in the context of examining biases in the CPI. Reinsdorf (1993) used average sales prices for homogeneous goods as a check on potential biases in the CPI: the check being that if quality is increasing, then average sales prices should rise faster than constant-quality indexes like the CPI. Raff and Trajtenberg(1996) use this notion in the context of the early years of the American automobile. More recently, Bils and Klenow (2001) use this identity in the context of a structural model to identify the degree to which BLS methods adequately control for quality change.

[6] To see this, add and subtract two (geometric) means: one for *all* N logged prices at time t and one for all prices at time t-1. Rearranging the expression gives (3).

[7] Silver(2005) works out the more general case that allows simultaneous entry and exit.

[8] See Flamm(1996) and Irwin and Klenow(1994) for similar profiles for DRAM memory chips.

[9] An alternative explanation is that, facing heterogeneous consumers, Intel practices intertemporal price discrimination, starting prices at a high level to sell to those willing to

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pay a high price for the new chip and incrementally lowering price to sell to other segments.

[10] The percent changes reported in here do not line up with those reported in ACD(2000). The measures here are calculated as *averages* of the quarter-to-quarter price changes while those in ACD(2000) are reported as *compound annual growth rates*. While both measures give similar qualitative results, the former is more intuitive in this context.

[11] This average price is the first term in (6); calculations using a simple unweighted geometric mean give very similar results.

[12] Gwennap and Thomsen (1998), P. 67

[13] See Hatch and Mowery (1998) and Flamm (2003) for a fuller description of the manufacturing process.

[14] However, it's not clear that all learning economies should be viewed as "technological progress." Lessons learned over a long span of time--like how to make faster chips--are clearly technical change. But, the increase in yields that occurs every time a new chip is introduced may best be viewed as a form of increasing returns or an adjustment cost like the kind faced by automakers when a changes at a new model year require a ramp-up to full production volumes.

[15] The cost structures for MPUs and DRAMs are fairly similar and so some of the sources for learning economies are common to both. One important difference in the two is that DRAM chips are fairly simple – they store data – and the storage capability of the chip is such that if you want more storage you can simply buy more chips (rather than buy a bigger memory chip). Perhaps this is why DRAM producers have focused on using

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technological advances to lower costs rather than to increase the storage capability per chip.

In contrast, an MPU chip is different in that each computer has only one MPU – you want a faster computer you must purchase a new MPU. Not surprisingly, technological advances that allow Intel the option of reducing the cost per chip vs. increase the quality of the chip typically increase quality. Thus, learning in the MPU segment often leads to increases in quality rather than decreases in costs.

[16] MDR uses a four-year straight-line depreciation for the cost of equipment and clean room. Gwennap and Thomsen (1998), P. 68.

[17] Use of variable costs–rather than total costs—is consistent with a short-run view of production, where once the firm incurs these set-up costs (R&D and plant and equipment investment), these costs are sunk and the relevant cost concepts (marginal and average) are based on variable costs. Flamm (1996) uses a similar concept of marginal cost in his model of semiconductor production; Danzon (2000) also takes this view when discussing the cost structure for pharmaceuticals—another industry characterized by large setup costs.

[18] Gwennap and Thomsen (1998), P. 74.