Has Moore's Law Been Suspended or Repealed? An Empirical Economic Analysis of the Pace of Innovation in Semiconductors

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Extended Abstract [A New Dataset is Currently Being Constructed and Analyzed, Paper Not Yet Written]

An important economics literature (Oliner and Sichel, 2000; Jorgenson, 2001; Jorgenson, Ho, and Stiroh, 2005) credited the marked acceleration of U.S. productivity growth in the U.S. in the late 1990s to the impacts of information technology investments on the economy, which in turn were fed by technological advances in microelectronics, upstream. This literature utilized data on quality-adjusted price declines for semiconductors, and downstream, semiconductor-using information technology (computers, communications equipment), and traced through their impacts on output and productivity in the larger U.S. economy using a standard economic growth accounting framework.

This literature highlighted the fact that the late 1990s were a period of unusually rapid technological progress in the semiconductor components responsible for a considerable portion of technological improvement in information technology. Estimates suggest, for example, that from 40 to 60 percent of the decline in quality-adjusted prices for computers around this time was attributable to improvements in price-performance for semiconductors going into computers. Similarly, a rough estimate suggests that from 20 to 30 percent of declines in quality-adjusted communications equipment prices was attributable to improved semiconductors used in building this equipment.

This paper explores whether the more rapid pace of technical progress in microelectronics in the late 1990s, attributable to technological innovation in manufacturing, and to other factors, has come and gone—whether the rate of innovation has declined significantly in semiconductors— and in particular, in microprocessors, an important product with a high intrinsic economic value. Microprocessors are the largest single semiconductor input, in terms of value, in personal computers, and are the technological core of all computers, big and small.

Has the rate of innovation in the semiconductor industry really declined substantially, and if so, why? Why is it that some of the metrics measuring semiconductor innovation constructed by some economists appear to be in apparent contradiction with the current consensus among engineers and technologists involved in the semiconductor industry? What are the causes and the possible implications for the broader economy? The answers to these questions are much less obvious than might seem evident in the raw numbers. Furthermore, if semiconductor innovation played such a critical role in lowering information technology cost, and, indirectly, increasing productivity in the U.S. economy, in the 1990s, is it possible that a decline in the pace of semiconductor innovation is playing an instrumental role in currently measured lower rates of productivity improvement in the U.S.?

To answer this question, I begin by surveying the current "semiconductor industry consensus" about slowing technical progress in semiconductors described in engineering journals and the semiconductor trade press, and the types of empirical evidence that is mustered in these outlets to support this view. I then turn to analysis of microeconomic data—detailed data on prices, and characteristics, of semiconductors. Unfortunately, public data on semiconductor prices is quite poor, and has been getting

worse over time, due in no small part to industrial consolidation and increased concentration in the semiconductor manufacturing industry. Using one new dataset I have constructed on retail pricing for microprocessors ("retail boxed" microprocessors constitute about 20% of the microprocessor market, with pricing that is substantially more visible than the highly confidential negotiated prices paid by the largest computer makers), I test whether the pace of innovation in semiconductors has slowed in recent years. Preliminary analysis of a variety of measures—matched model price indexes, statistically estimated hedonic price indexes—suggests that the slowdown in technological innovation in semiconductors is in fact real.

Preview Draft Section: **Measuring Quality-Adjusted Prices for Microprocessors**

I begin by noting that official government statistics show a tremendous slowdown in the rate at which microprocessor prices have been falling, as well as a significant attenuation in the rate at which prices of the desktop and laptop PCs that make use of these processors have declined. The U.S. Producer Price Indexes for microprocessors, laptop computers, and desktop computers show annual (January-to-January) changes in microprocessor prices steadily falling from 60-70 percent rates during the "golden age" of the late 1990s and early 2000s, to a low of 2.5 percent for the year ending in January 2013. A parallel fall in price declines for laptop and desktop computers seems also to have occurred, from peak annual decline rates of 40%, in the late 1990s, to rates mainly in the 10-20% range in the last several years.

The Bureau of Labor Statistics describes its methodology for constructing computer price indexes as a hedonic method,[1] but is somewhat opaque about its methodology in constructing its microprocessor price series (there is no published methodology describing precisely how these numbers are constructed). It is believed that these are matched model indexes based on some weighted selection of products appearing on Intel list price sheets (the same data source I utilize below),[2] but this is not entirely clear.

There is also some evidence that the BLS may have employed variety of different methodologies for measuring its microprocessor price indexes over the 1995-2014 periods.[3]

As an alternative to the BLS measure, I have constructed alternative price indexes for Intel desktop microprocessors, tracing the contours of change over time in microprocessor prices using a unique, highly detailed data set I have collected over the last two decades. Since the mid-1990s, Intel has periodically published, or posted on the web, current list prices for its microprocessor product line, in 1000-unit trays. These list prices are available at a very disaggregated level of detail, distinguishing between similar models manufactured with different packaging, for example, and are typically updated

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[1] See U.S. Bureau of Labor Statistics, Producer Price Index Program, "Hedonic Models in the Producer Price Index (PPI)," June 2011, available at www.bls.gov/ppi/ppicomqa.htm .

[2] Based on a brief conversation with BLS officials, Cambridge, MA, July 2014.

[3] The BLS web site shows three different "commodity" price indexes (as opposed to its single semiconductor industry price index) for microprocessors over this period. The current microprocessor "commodity" price index is based in December 2007, but is only reported on a monthly basis from September 2009 through the present. There are also two discontinued microprocessor commodity price indexes, one based in December 2004, and running through June 2005, and another based in December 2000 and running from 1995 through December 2004. One inference that might be drawn is that the BLS changed its methodology for measuring microprocessor prices three times during the period we are discussing.

every 4 to 8 weeks—though price updates have sometimes come at much shorter or longer intervals.[4] By combining these detailed prices with detailed attributes of different processor models, it is possible to construct a very rich data set relating processor prices to processor characteristics, over time.

This permits one to construct both "matched model" price indexes, the traditional means by which government statistical agencies measure industrial prices, and so-called "hedonic" price indexes, which relate processor prices to processor characteristics. It is now well understood in the price index literature that there is a close relationship between matched model indexes and hedonic price indexes.

My Intel dataset permits measuring differences in processor characteristics down to individual models of processors, controlling for such things as processor speed, clock multiplier, bus speed, differing amounts of level 1 ("L1"), level 2 ("L2"), and level 3 ("L3") cache memory, architectural changes, and particular new processor features and instructions. The latter have become particularly important recently—since mid-2004, Intel has dropped processor clock speed as the principle characteristic used to differentiate processors in its marketing, and introduced more complex "processor model number" systems that distinguish between very small and arguably minor differences between processors that proliferated with more recent product introductions.

Price Indexes for Intel Desktop Processors [Very Preliminary Results, Now Being Extended with Additional Data and AMD Processor Prices]

For comparison purposes, I begin by constructing a matched model price index for Intel desktop processors. Since I do not have sales or shipment data at the individual processor model level, I weight each observed model equally, by taking the geometric mean of price relatives for adjoining periods in which the models are observed.[5] A price index based on the simple geometric mean of individual product price relatives (sometimes called a Jevons price index), is chained across pairs of adjoining time periods, and depicted in Figure 1. It has the same qualitative behavior as the official government producer price index for microprocessors, falling at rates exceeding 60% in the late 1990s, and slowing to a decline rate under 10% since 2009. This geometric mean matched model index actually falls a little more slowly than the official PPI in recent years, which may be attributable to the fact that the geometric mean index weights all models equally, while the PPI probably uses a subset of the data, with some weighting scheme for models drawn (and replaced periodically) from subsets of processor types. The PPI also uses fixed weights from some base period to weight these price changes, while my geometric mean matched model index chains adjoining paired comparisons of models, and therefore implicitly allows weights given to different models over pairs of adjoining time periods to evolve over time.

The adjoining pairs of periods over which this regression was run were chosen to overlap. The time dummy variables in the above regression were used to construct an index of adjoining period price levels; the overlapping time period was used to link these period-to-period (on average, roughly 8-9 months per year with reported list prices) indexes into a longer chained price index. Note that typical power consumption for a processor (TDP, thermal design power) was generally unavailable for Intel

[4] My data initially (over the 1995-1998 period) made use of compilations of this data collected by others and posted on the web; since 1998-99, most of this data was collected and archived directly off the Intel web site.

[5] Since there occasionally were multiple price sheets issued within a single month, I have averaged prices by model by month. Since Intel did not issue new prices sheets on a monthly basis, "adjoining time periods" means contiguous monthly observations.

processors released prior to late 1998. I therefore estimated two versions of a hedonic index, one with TDP as a characteristic, and one without. TDP is statistically significant when it is available, and therefore the hedonic price index including TDP is the preferred index.

Figure 1 shows the price indexes produced using the above methods. The slowing of declines in price in 2004 and 2005 is quite apparent, followed by a temporary resumption of a somewhat faster rate of decline after 2006, followed by a marked and much more extreme slowdown after 2009.

The first four columns in Table 1 compare my estimated hedonic and matched model price indexes and the BLS PPIs. As expected, matched model index price declines are often close, but generally decline more slowly than those measured by the hedonic price index based on the same data. My estimates over comparable time periods are quite similar to the matched model index results of Aizcorbe, Corrado, and Doms, and to the producer price indexes. Prior to 2004, my geometric mean matched model and the PPI move quite closely, with my hedonic indexes showing a modestly higher rate of decline, as expected. From 2004 through 2006, both my geomean and hedonic price indexes decline much more slowly than the PPIs, and from 2006 through 2009 my geomean falls at about the same rate as the PPI, and my hedonic index declines more rapidly. From 2009 to 2010 both my geomean and hedonic fall more slowly than the PPI. Finally, from 2010 through 2014, both my geomean and hedonic indexes again fall more slowly than the PPI, but all three sets of declines are in the low single digits.

Table 1

Annualized Compound Rates of Change in Microprocessor Price Indexes

		Compound Annualized Decline Rate						
		Intel Tray Price				**Producer Price**		**Retail**
		Hedonic, no TDP	**Hedonic with TDP**	GeoMean Matched Mocel		Microprocessor PPI		GeoMean Matched Model
1998m9-2001m10		-68.3%	**-73.0%**	-65.0%		-57.5%		
2001m10-2004m2		-50.5%	**-50.1%**	-48.2%		-46.6%		-34.0%
2004m2-2006m1		-14.4%	**-13.8%**	-10.7%		-25.2%		-11.1%
2006m1-2009m1		-42.1%	**-36.9%**	-31.5%		-29.0%		-24.2%
2009m1-2010m11		-13.7%	**-13.6%**	-6.2%		-22.7%		-11.3%
2010m11-2014m7		-2.7%	**-2.9%**	-2.2%		-3.7%		

Source: Author's dataset and calculations, except Microprocessor PPI, from BLS.

I have also constructed a geometric mean, chained monthly price index based on retail prices for processors, using data from a commercial web site that reported the lowest price for a particular processor model across a selection of internet-based retailers, over the period from 2001 through 2010. These prices are actually a relatively small subset of the much larger set of list prices for all Intel processors, and presumably represent the models that were most popular in the retail marketplace. The final column of Table 1 reports changes in this retail price index for equivalent time periods. Generally,

the pattern over time is similar (steepest declines over 2001-2004 and 2006-2009, slower declines over 2004-2006 and 2009-2010).

To summarize these results, then, though there are substantial differences in the magnitude of declines across different time periods, data sources, all of the various types of price indexes constructed concur in showing substantially higher rates of decline in microprocessor price prior to 2004, a stop-and-start pattern after 2004, and a dramatically lower rate of decline since 2010.

Taken at face value, this creates a new puzzle. Even if the rate of innovation has slowed in microprocessor-specific technologies, if the underlying innovation in semiconductor manufacturing technology has continued at the late 1990s pace (i.e., a new technology node every two years and roughly constant wafer processing costs in the long run), then manufacturing costs would continue to decline at a 30 percent annual rate, and the rates of decline in processor price that are being measured now fall well short of that mark. Either the rate of innovation in semiconductor manufacturing must also have declined, or the declining manufacturing costs are no longer being passed along to consumers to the same extent, or both. The semiconductor industry and engineering consensus seems to be that the pace of innovation in semiconductor manufacturing has slowed markedly.

Is the Slowdown Real?

One recent study (Byrne, Oliner and Sichel, 2014) has questioned whether the Intel posted list prices that are being used by all analysts of microprocessor pricing trends are in fact real prices, and raise the possibility that the post-2004 slowdown is a spurious artifact of changes in Intel pricing practices.[6] Their argument is that "[b]y 2006, the company had moved to a business model that featured more active management of its product offerings below the [technological] frontier…by setting list prices that were relatively stable over a chip's life cycle, Intel may have been attempting to extract more revenue from less price-sensitive buyers while offering discounts on a case-by-case basis."[7] Arguing that new products get little discount from the posted list price, while older products are heavily discounted from list, they argue that a hedonic price index based only on newly introduced products is the correct measure of quality-adjusted price trends for Intel microprocessors. Throwing away most of their sample of Intel products, and keeping only newly introduced models, they run an annual hedonic price model over pairs of years, and find quality-adjusted prices declining at the same rate in 2000-08 as in 2008-12, with a 39 percent annual rate of decline.[8] This is vastly higher than any of the rates shown in Table 2 for the equivalent time periods.

While the observation that Intel seems to have lowered its advertised list prices much less frequently after 2006 than before 2006 certainly seems true, based on the public Intel price list data, the assertions that actual transaction prices for recently introduced chips are not significantly discounted from list, while transaction prices for older chips after 2006 are heavily discounted, with a discount that increases with age, is essentially unobservable and untestable, since no data on Intel transaction prices for its wholesale sales are publicly available. Indeed, evidence produced in the AMD-Intel antitrust

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[6] D.M. Byrne, S.D. Oliner, and D.E. Sichel, "How fast are semiconductor prices falling,," AEI Economic Policy Working Paper 2014-06, July 2014, available at www.aei.org/publication/how-fast-are-semiconductor-prices-falling/ .

[7] Ibid., pp. 8.

[8] Ibid, Table 7, p. 34. Note that, with very much smaller sample sizes, the researchers use only two processor characteristics—performance on a single software benchmark, and power draw—in their hedonic regression.

investigation seems to show that even new chips sold to large customers were heavily discounted from list prices prior to 2006, at times with conditional rebates that were not publicly reported by Intel or its customers.[9]

Also arguing against this claim is the behavior of the BLS computer prices displayed earlier. Changes in BLS producer price indexes for computers, constructed using hedonic methods, seem to reflect the decelerating declines in list price indexes for Intel microprocessors, before and after 2006, as would be expected given the significant role of microprocessor price in computer cost.

Finally, there is the behavior of retail prices to consider. Retail prices in the electronics industry are linked to wholesale prices, directly and indirectly. Most directly, the very largest retailers can purchase boxed processors directly from Intel, or like smaller retailers, from distributors. (Approximately 20% of Intel processors in recent years, by volume, were sold directly as boxed processors, primarily to small computer makers and electronic retailers.[10]) Computer original equipment manufacturers (OEMs), electronics system manufacturers, and electronic parts distributors also can purchase processors directly from Intel, and resell excess inventories to other distributors, resellers, and retailers, and these show up on the retail market labeled as "OEM package" (vs. "Retail Box" packaging). These products are sold by retailers and brokers, and have the great virtue of having a price that is advertised publicly and directly observable in the marketplace. (The retail data use in constructing my matched model price index include both OEM and retail packaged chips sold by internet retailers.) The retail data used in Table 1 seem to clearly point to a deceleration in microprocessor price declines after 2004.

If one presumes that retail transaction prices (which are observable in the market), at least in the long run, should have some stable relationship to wholesale producer transactional prices (which are not directly observable; because of the direct and indirect linkages between retail and wholesale markets, and the impact of arbitrage and competitive market forces in distribution channels), then one would expect to observe a systematic change in the relationship between observed prices in the retail market, and Intel list prices after 2006. This is testable using observational data.

I explored the possibility that there was some detectable change in the relationship between Intel list (posted wholesale) prices and observed retail prices after 2006 by constructing a panel of a total 1580 monthly observations on average retail and posted list price covering 163 distinct Intel desktop processor models sold by Internet retailers over the years 2000 through 2010.[11] The fixed effects

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[9] See European Commission, "Non-confidential Version of the Commission Decision of 13 May 2008, COMP/37.990 Intel," available at http://ec.europa.eu/competition/antitrust/cases/dec_docs/37990/37990_3581_18.pdf .

[10] "Although it sells microprocessors directly to the largest computer manufacturers, such as Dell, Hewlett Packard, and Lenovo, its Channel Supply Demand Operations (CSDO) organization is responsible for satisfying the branded boxed CPU demands of Intel's vast customer network of distributors, resellers, dealers, and local integrators. Intel's boxed processor shipment volume represents approximately 20 percent of its total CPU shipments…Processors ship from CW1 to one of four CW2 "boxing" sites, which kit the processors with cooling solutions (e.g., fan, heat sink) and place them in retail boxes and distribution containers. Such boxing sites are typically subcontracted companies that ship the boxed products to nearby Intel CW3 finished-goods warehouses where they are used to fulfill customer orders. Channel customers range in size and need; they are mostly low-volume computer manufacturers and electronics retailers." B.Wieland, P. Mastrantonio, S. P. Willems, and K. G. Kempf, "Optimizing Inventory Levels Within Intel's Channel Supply Demand Operations," *Interfaces*, Vol. 42, No. 6, Nov–Dec 2012, pp. 517–18.

[11] My retail price data actually end in January 2011.

regression model (permitting a particular low-end Celeron model, for example, to be related to Intel list price with a different retail margin than a high end i7 model) that I estimated specified that the log of retail price for model i in month t was given by

$$(3)\ \ln(R_{it}) = a_i + b\ln(Iit) + c\,Age_{it} + d\,OEM_{it} + After2006 + e\,After2006 \times \ln(Iit) + f\,After2006 \times Age_{it} + u_{it},$$

with R_{it} an observation on average retail price for model i in month t; Iit the average posted Intel list price in a month in which list price had been posted at least once; Age_{it} the number of elapsed months since the month the model's price had been first posted on a published Intel price sheet; After2006 a binary indicator variable with value 1 in 2006 and thereafter, zero before; OEM a binary indicator for whether the product sold was the retail boxed version, or the bare chip in OEM packaging; and u_{it} a random disturbance term. If the Byrne, Sichel, and Oliner assumption is correct, and post-2006 transaction prices contain age discounts from Intel list price that pre-2006 prices did not, we would expect to find a statistically significant shift coefficient on the interaction of After2006 and Age.

Figure 2 shows the results of estimating this model.[12] The After2006 shift variable, and all of its interactions, including the interaction with processor model Age, are close to zero and statistically insignificant individually, and jointly.[13]

Interestingly, there does seem to be small but statistically significant age effect, with retail price declining by about .58 percent for every additional month after the product is first sold by Intel. But this relationship holds throughout the 2000-2010 period, and we cannot reject the hypothesis that there was no change in 2006 and after. The model also suggests that on average, products were sold by retailers in OEM packaging at a 5 percent discount. The elasticity of retail price with respect to a decline in Intel list price was about -.77, i.e., a ten percent decline in list price was associated with about a 7.7% decline in retail price.[14]

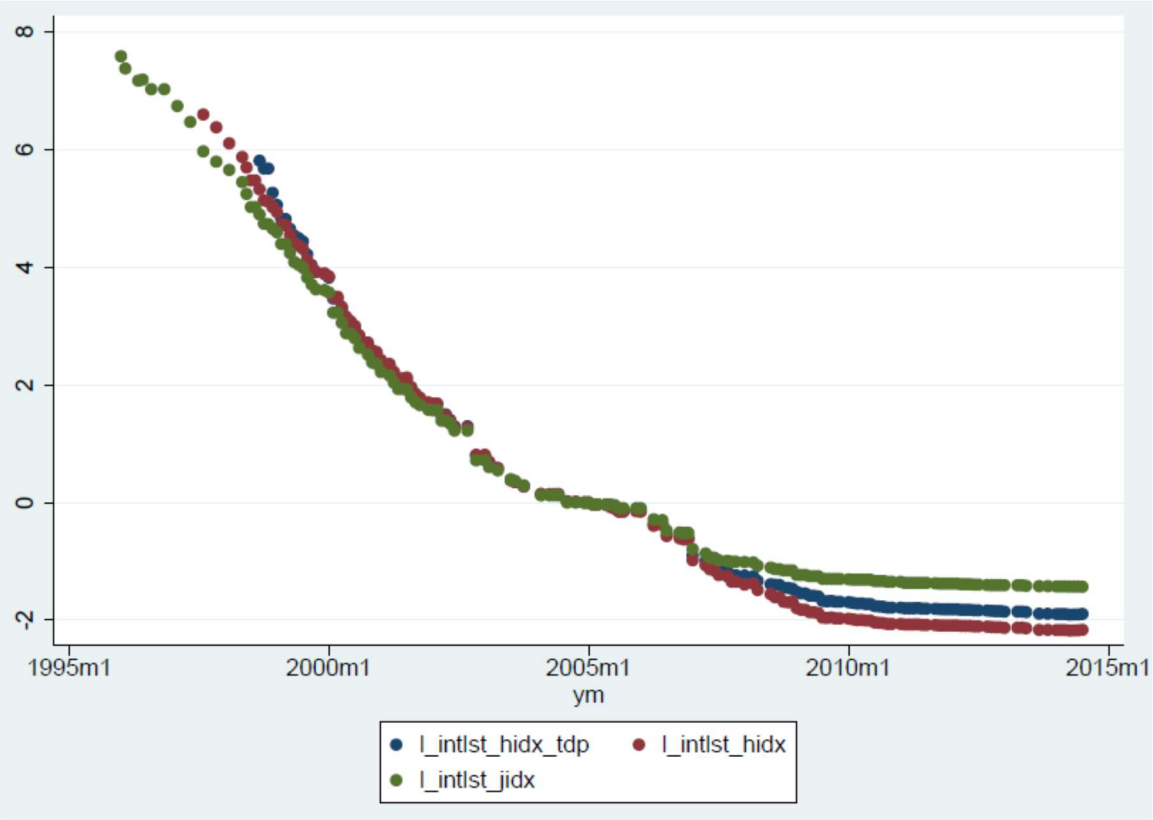
Based on the only evidence on actual transaction prices that is publicly available, i.e., advertised retail prices from Internet-based vendors, then, we find no evidence to support the suggestion that there was some structural change after 2006 in the relationship between Intel list price and retail market prices. Of course, this does not directly prove that there was no change in the relationship between Intel list prices and (unobserved) discounted OEM contract prices for processors, but it argues against the assumption that this must have been the case.

Even more to the point, is there direct evidence of the technological slowdown implied by the price indexes displayed in Table 1? That is the question that will be considered in final section of this study.

[12] Robust standard errors clustered on processor model are shown in Figure 8.
[13] The Wald F(3,162) test statistic for the joint hypothesis that all After2006 terms were zero was .82, the p-value .49.
[14] Very similar results are produced if a model that is linear in price, rather than the logarithm of price, is used.

Figure 1

Geomean Matched Model and Hedonic Price Indexes for Intel Desktop Processors



Green: Geometric Mean Matched Model Index

Blue: Hedonic Index with Thermal Design Power (TDP) as included characteristic

Brown: Hedonic Index without TDP as included characteristic

Figure 2

Fixed Effects Model of Log Retail Price For Intel Desktop Processors

	(Full Model)	(Constrained Model)
	lp_ret	lp_ret
lp_tray [log Intel Tray Price]	0.763***	0.768***
	(15.37)	(17.93)
oem	-0.0497***	-0.0496***
	(-6.70)	(-6.77)
age	-0.00676***	-0.00582***
	(-3.70)	(-4.91)
1.aft2006	0.0204	
	(0.13)	
1.aft2006#age	0.00162	
	(0.83)	
1.aft2006#lp_tray	-0.0108	
	(-0.39)	
_cons	1.347***	1.303***
	(4.87)	(5.55)
N	1580	1580
R-sq	0.987	0.987
adj. R-sq	0.986	0.986

t statistics in parentheses
* p<0.05, ** p<0.01, *** p<0.001