Economic Benefits from Technological Innovation in Microelectronics

Kenneth Flamm

University of Texas at Austin

November 2010

ROUGH DRAFT

COMMENTS ONLY

In many respects, microelectronics is the most visible technology area in which sustained, decades of Federal investments in science and technology have had clearly significant impacts on the U.S. economy. Government investments in this area, historically, were influential in the early technological development of the industry (Tilton, 1971; Levin, 1982; Flamm, 1985, 1996), seem also to have played a significant role in the revitalization and restructuring of the U.S. semiconductor industry in the 1990s (Macher, Mowery, and Hodges, 1998; Browning and Shetler, 2000; Flamm and Wang, 2003; Carayannis and Alexander, 2004), and have continued to influence the trajectory of technological innovation in specific areas where government and industry interests intersect.

Why Do We Care About Semiconductors?

An important recent economics literature (Oliner and Sichel, 2000; Jorgenson, 2001; Jorgenson, Ho, and Stiroh, 2005) has 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 are credited in large part to technological advances in microelectronics, upstream. This literature utilizes data on quality-adjusted price declines for semiconductors, and downstream, semiconductor-using information technology (computers, communications equipment), and traces through their impacts on output and productivity in the larger U.S. economy using a standard economic growth accounting framework.[1] The research implicitly interprets the extraordinary declines in quality-adjusted price measured in semiconductors and IT as primarily reflecting technological change, without actually identifying the specific innovations that led to these price declines in microelectronics and IT. Therefore, at some very high level, these studies measure economic benefits of technological innovation in microelectronics, without actually identifying any specific innovations responsible for these benefits.[2]

---

[1] These growth accounting studies do not measure what economists typically use as a measure of social benefit resulting from an investment that ultimately lowers prices to final consumers, consumer's surplus (the excess of cumulative consumer willingness to pay over price charged for what is consumed). In a competitive industry, where prices are ultimately competed down toward average costs in the long run, one would expect the bulk of the social return from investment in technical innovation to show up as consumer's surplus. A study that attempts to measure the consumer's surplus created by declining semiconductor prices is Flamm (1997), which compares semiconductor price declines to the impact of 19th century railroad transport cost declines, and concludes (p. 32) that "the microelectronics revolution has had from two to four times the relative impact on the U.S. economy that the railroad had over comparable time periods."

Analzying welfare gains downstream from semiconductors, Greenwood and Kopecky (2010) estimate that the development and improvements to the personal computer increased consumer welfare by between 2 and 14 percent of total personal consumption expenditure.

[2] There has been some argument that these studies overstate the contribution of information technology to the U.S. productivity growth resurgence. For example, Feenstra, Reinsdorf, and Slaughter, 2008, argue that about 20% of the increase in productivity actually flowed

Taking the next step, and directly connecting technical advances in microelectronics to the extraordinary price declines seen in downstream information technology (which in turn drive the productivity growth analyzed in these studies) is difficult but not impossible. Using a microeconomic cost theory framework, Aizcorbe, Flamm, and Khurshid (2007), for example, estimate that 40 to 60 percent of the decline in quality-adjusted price for personal computers in 1998 was due to declines in price for the semiconductors contained within these computers.

But the existing literature is relatively silent on what is causing the breathtaking price declines in semiconductors. Since the prices of labor and material inputs going into semiconductors are not declining at rates remotely close to those being measured in semiconductors, it has been uncontroversial to assert that the price declines are primarily and overwhelmingly the result of rapid and continuing technical innovation in the design and manufacture of semiconductors. In this sector, at least, a quality-adjusted price index also functions as an index of technological innovation.

Stylized Facts About Innovation in Semiconductors

Record-breaking rates of technological innovation. Over the last two decades, a substantial body of economic research has shown that semiconductor prices have been declining at truly extraordinary rates. (Dulberger, 1993; Flamm, 1993; Grimm, 1995; Flamm, 1997; Aizcorbe, 2002; Aizcorbe, Corrado, and Doms, 2003; Aizcorbe, Oliner, and Sichel, 2006; Flamm, 2007). The basic facts are these: from the mid-1970s to the mid 1990s, an aggregate price index for semiconductors declines at a rate of about 20 percent annually. In the late 1990s, there was a dramatic acceleration in rates of decline in semiconductor prices, and the aggregate rate of price decline hit almost 30 percent annually, averaged across all products. Leading edge semiconductors (memory and microprocessors) had rates of price decline that were 50 to 100 percent greater than the weighted averages for all products.

---

from mismeasured declines in prices of imported goods, and tariff reductions. Those familiar with data for these sectors understand the generally poor quality of government-collected statistics on computer, communications equipment, and semiconductor manufacturing, sales, and trade. Indeed, recent efforts by government statistical agencies to improve their price indexes for these products have often relied on data collected by private consulting firms, rather than official government surveys. On the other hand, the same message-- of IT investment leading to significant productivity improvements—has been replicated in careful industry-level studies (e.g., Bartel, Ichniowski, and Shaw, 2007; Casolaro and Gobbi, 2007; Motohashi, 2007), as well as in studies of other economies outside of the U.S. (Eicher and Rohn, 2007; Jorgenson and Vu, 2007; van Ark, O'Mahony, and Timmer, 2008; Inklaar, Timmer, and Van Ark, 2008). Thus, putting aside continuing concerns about high tech sector data quality, the linkage between IT investment and productivity growth seems well established.

These rates of price decline are off the charts. Even in computers, often the poster child for sustained technological innovation, measured price declines have typically been at the low end of this range (i.e., 20-30 percent annual declines).

Substantial variation over time in rates of innovation. From the mid-1970s to the mid-1990s, the two leading edge products accounting for the biggest chunk of the semiconductor market (both were invented in the early 1970s)-- memory chips (specifically, dynamic random access memory, DRAM), and microprocessors-- saw prices fall at a much faster rates, exceeding 28% annually for DRAM, near 30% annual declines for microprocessors (Flamm, 1997; Aizcorbe, Oliner, and Sichel, 2006).[3] Beginning in the mid-1990s, DRAM prices begin to fall at a rate approaching 48% annually, while rates of price decline in microprocessors exceed 60% annually. (Aizcorbe, Oliner, and Sichel, 2006; Flamm, 2007). Most recently, rates of decline have slackened somewhat, and seem closer to historical averages prior to the mid-1990s surge. (See Table 1.)

Links between policy, organizational, and institutional changes and innovative behavior. Responding in large measure to the perceived success of Japan's government-subsidized cooperative industrial research projects of the late 1970s (particularly the so-called "VLSI projects", credited with stimulating innovation in the Japanese semiconductor industry (Flamm, 1996)), the U.S. Congress passed the National Cooperative Research and Production Act in 1984, and created limited relief from antitrust sanctions for research and development joint ventures registering with the U.S. government. (Link and Bauer, 1987) Over the years, electrical, computer, and electronics companies have been the industrial sector making the most frequent use of these provisions—accounting for at least 17% of such registrations over 1985-94, and almost 30% of the registrations over 1994-2003. (Link, 1996, p. 621; National Science Board, 2006, appendix table 4-36) Perhaps the highest profile such R&D joint venture was the U.S. semiconductor industry's SEMATECH research joint venture, started up over 1987-88.

A second example of changes in semiconductor industry innovation behavior stimulated by institutional and policy factors was the visible increase in patents filed by semiconductor producers after the creation of a "pro-patent" Central Appellate Court for the Federal Circuit (CAFC) in 1982. In an industry which previously been among the least reliant on patents to protect technological advantages, there was an upsurge in patents relative to R&D expenditure after the 1980s (Hall and Ziedonis, 2001). Interestingly, this strengthening of patents seems to

[3] Flamm (1997).

have led primarily to a rise in the probability of semiconductor firms being the target of patent lawsuits filed by parties *outside* the industry, not in litigation amongst semiconductor firms—a mutual détente within the industry seems to have been the outcome of this patent "arms race" (Hall and Ziedonis, 2007).

A final, and particularly important example of how innovation outcomes can be associated with institutional and organizational changes, is connected to the creation of the International Technology Roadmap for Semiconductor (ITRS). In the mid-1990s, US semiconductor R&D consortium SEMATECH adopted a strategic plan intended to accelerate the introduction of new generations of semiconductor manufacturing technology. SEMATECH's intention was to reduce this time from 3 years to 2 years. In the late 1990s, this U.S. national roadmap evolved into a global roadmapping effort (the International Technology Roadmap for Semiconductors, ITRS), involving the semiconductor industries of the US, Japan, Europe, Korea, and Taiwan (Flamm, 2009). Whether this closer coordination among specialized suppliers of equipment and materials, and their users in the semiconductor industry, brokered through the ITRS, is entirely responsible for accelerated innovation in the industry may be debated, but one thing that is clear is that the industry did collectively shift to a new innovation cycle, reducing it to two years between new technology generations, or "technology nodes", for the last 15 years. (See Figure 2)

The creation of the International Technology Roadmap for Semiconductors (ITRS) was a unique event-- in no other global high technology industry do all major equipment and materials producers, and their semiconductor-producing customers, worldwide, invest significant resources in coordinating investments setting the direction and pace for introduction of new manufacturing technologies. Also, since the 1990s, there has been a surge in new semiconductor R&D consortia activity. Some have been purely private enterprises (IBM's "common platform" semiconductor manufacturing technology consortia comes to mind) while others have also benefitted from government subsidies (IMEC, in Flanders).[4]

The substantial variation over time in the rate of innovation, plus the apparent correlation of institutional and organizational arrangements with innovation rates, mean that there is some hope of disentangling the factors accounting for changes in the pace of

[4] IBM's "common platform" partners are currently Samsung and Globalfoundries; previously they also included Sony, Infineon, Chartered, and Toshiba. See Flamm(2009). Sony, Infineon have since greatly reduced the scope of their semiconductor manufacturing activities, while Chartered was acquired by Globalfoundries.

innovation over time. Studies of innovation in semiconductors are of interest because of the intrinsic economic importance of this industry, and because the methods used and lessons learned may be applicable to other sectors.

Inside the Black Box: Structural Models of Technological Innovation in Semiconductors

One can argue there are two basic empirical approaches to modeling the impact of technology investments on technological innovation. One approach views technology as a "black box"—innovation inputs, like R&D expenditure, or R&D effort by scientists and engineers, go into one end of the box, and innovative outputs pop out the other end, after unknown time lags.[5] "Black box" studies use statistical methods to tease out how variation in amounts of inputs, or different types of innovative inputs, affects measures of innovative output, in order to calculate a variety of effects of interest: the average private or social economic return from stuffing an additional input—engineers or funding—into the input hopper, and the range of variation in average economic returns across different types of inputs, industries, and characteristics of the "black boxes" (types of research performers, organizational structures, input quality). The most sophisticated such studies worry about the endogeneity of innovative inputs, that is, that observed inputs are likely to be influenced by realized returns, or be correlated with other unmeasured determinants of economic return. There are also many problems with measuring both inputs and outputs to innovation in these studies, and even the modest sample sizes needed for minimal statistical precision typically require pooling many heterogeneous entities with relatively few controls for heterogeneity.[6]

---

[5] The unknown time lags are a serious issue, because annual variation in R&D expenditures (or staffing) within organizations over time is relatively small. The high degree of collinearity between any year's R&D and previous year's R&D spending is the reason researchers often instead construct a "knowledge capital" stock variable, which effectively allows them to simply add up lagged R&D expenditures (reduced by an assumed depreciation rate) into a single aggregated R&D measure.

[6] Measuring both inputs and outputs is difficult, but metrics for innovative output are particularly hard to define. Counts of patents and publications are often used, but patents and publications don't directly measure innovation, or the economic value of an innovation, and in many cases may even best be viewed as an input to, and not an output from, what ultimately ends up as an economically valuable industrial innovation. Further, it is known that most patents (and publications) are worthless economically, and the role of patenting and publishing as complements to the development of economically valuable innovations is highly variable across industries. Citation-weighted patents and publications are often used to define a more meaningful metric of important patents and publications, but these still are complements to new industrial technology, and do not directly measure or define either an important innovation or its economic value.

The alternative approach might be called a "structural" model of innovation. The top is peeled off the black box in this approach, and a model of how technical parameters, derived from engineering, technical, or scientific analysis, affect economically meaningful outcomes (costs, product characteristics) is provided. An economic description of suppliers, and market demand, is also specified. Technological innovation can then be defined as the process leading to alteration of technical parameters embedded in the model, and the social returns to innovation calculated by comparing benefits to both consumers and producers, with the value of all investments, both private and public, in altering the technical parameters. (Figure 1)

The advantage of a structural model over the black box approach is that it allows the economic impact of a single technical innovation to be predicted. Statistical methods may be used to characterize demand and supply within an industry, but these are ultimately combined with a technological model that interacts these economic descriptions with technical parameters. The economic impact of the innovation is calculated by simulating the impact on model outcomes of altered technical parameters. The disadvantage of a techno-economic structural model is that it may require a considerable investment by the researcher in peeling back the black box within a specific product and industry, in order to integrate a parameterized technical description based on scientific literature, of the product and production process, with economic descriptions of supply and demand.

Interestingly, seminal empirical economic studies of the value of technological innovation (Griliches (1958), and Mansfield (1977)) were arguably structural models, identifying and tracing through the impacts of specific innovations on cost or product characteristics, and measuring benefits to producers and consumers from a technical change by solving the model. The "black box" approach, which probably accounts for more of the current literature on economic effects of innovation, came later.[7]

Semiconductor technology innovation lends itself very naturally to a structural modeling approach. The ITRS roadmap can be viewed—and utilized—as the core of a technical parameterization of semiconductor manufacturing technology directly related to economic concepts. Semiconductor technologists conceptualize technological change in their industry as being characterized by new generations of manufacturing processes--"technology nodes". Each new generation of manufacturing equipment (at the new technology node) is described by the

[7] It might be argued that this was a form of "endogenous" technical change, driven by ever cheaper statistical computing power and the growing number of large, computerized historical data sets available to researchers.

minimum width of the smallest feature that can accurately be created on an electronic device engraved on a silicon wafer (e.g.," the 90 nm technology node"). Historically, the advent of a new generation of semiconductor processing equipment has been characterized by the capability to manufacture electronic devices with minimum feature widths that are 30 percent smaller than the minimum width of a feature created using the previous generation of processing equipment.[8]

We can think of the elapsed time between each generation of new (30% reduction in critical feature size, F) technology node as characterizing an underlying "rate of innovation" in semiconductor manufacturing technology. If we crunch the numbers using the assumption that-- as was historically the case from the mid-1970s to the mid 1990s-- that a new technology node (a 30% reduction in F) was introduced every 3 years, while processing cost per area of silicon remained roughly constant, the net result would a 21 percent annual decline in manufacturing costs for some given assemblage of electronic components on a chip. (Flamm, 2003, 2004). This almost exactly matches the historical rate of decline for an aggregate price index for semiconductors (though significantly below the rate of price decline for the highest tech leading edge products, DRAMs and microprocessors)! Conversely, if these stylized facts are correct, the fact that quality-adjusted DRAMs and microprocessors were declining at a roughly 50 percent faster rate during the pre-1995 decades must be due to something other than changes in manufacturing costs due to the adoption of new technology nodes.

Figure 2 showed that beginning in the mid-1990s, new technology nodes began to be introduced at a faster pace in the industry-- every 2 years, rather than every three years. Crunching these numbers, while continuing to assume that costs per area of processed silicon remain roughly constant over a decade or more, would lead us to predict that the decline in manufacturing cost per electronic component would ratchet up from 21 percent annually, to 29 percent annually. Again, this is close to the observed decline rate for an aggregate price index for all semiconductors in the late 1990s. Thus, an increase in the rate of technological innovation in semiconductor manufacturing in the late 1990s explains much, but not all, of the observed acceleration in rates of price decline for semiconductors.[9]

---

[8] Since the area of a rectangular electronic device created with these minimum feature sizes would be approximately halved (since .7 x .7 equals .49 of the area previously required) when this new equipment arrived, the net effect would be a halving of the silicon area needed per manufactured electronic device.

[9] See Flamm 2003, 2004; Aizcorbe, Oliner, and Sichel, 2006.

If all the industry was doing was shrinking device sizes on a planar surface, then the manufacturing cost story we just told would be the complete story. But, in fact, the semiconductor industry was also incorporating other types of innovations into the design of its products. In memory chips, for example, design innovations adopted in the late 1980s enabled manufacturers to replace flat, planar storage capacitors with three-dimensional "stacked" or "trench" capacitors, allowing arrays of memory cells (the electronic circuitry capable of storing a binary "bit" of data) to occupy a smaller footprint on a silicon wafer manufactured at any given critical feature size, F. The 1990s were a period in which rapid progress was made in new circuit designs for memory cells, which shrank the areal footprint for a memory cell from a multiple of 16 to 22 times F^2 in 1995, to 10 times F^2 in 1998. Reducing the required area for electronic components by 50 percent over three years, with constant processing costs per area, is equivalent to about a 21 percent annual decline in manufacturing cost per device. Thus, by adding this effect to the impact of the acceleration in the introduction of new technology nodes, we have pretty much accounted for most of the increase in the rate of decline in DRAM prices in the late 1990s.[10]

The even larger "excess" price decline for microprocessors in the late 1990s (when quality-adjusted prices were declining at even faster 60%+ annual rates) requires more detailed explanation. I have elsewhere argued that these declines reflect the rapid introduction of a large existing stock of computer architectural and design features into microprocessor designs in the late 1990s.[11] A subsequent reduction in the rate of price decline for microprocessors, in this interpretation, is related to the rapid incorporation and exhaustion of the stock of "low hanging fruit" computer architectural innovations developed over 30 years of mainframe and supercomputer architectural development, that could be easily and quickly adapted for use in microprocessors in the late 1990s.[12]

The point of this simplified description of technological innovation in semiconductor manufacturing is that the impacts of particular innovations, or sets of complementary innovations, can be connected directly to effects on circuit element cost. Using this framework,

---

[10] The story is actually somewhat more complicated, because the memory cell area of a DRAM typically accounts for only half of the area of a DRAM chip. The remainder of the DRAM chip is peripheral circuitry. See Flamm, 2010, for a fuller discussion.

[11] Flamm, 2007, sketches out the details of this analysis.

[12] A very interesting study by Pillai, 2007, comes to the same conclusion based on different evidence.

we can (a) construct an analytical framework that accounts systematically for the significant historical variation over time in rates of decline for quality-adjusted semiconductor prices visible in Table (1), in terms of the adoption or diffusion of specific technical innovations, (b) evaluate the potential economic effects of specific technological goals using an explicit analytical framework, and (c) potentially, use these evaluations to assist in evaluating real world technology investment decisions.

A "micro-microeconomics" of technological innovation, then, seems feasible. We could, for example, compare the economic impact of a research project that accelerates the adoption of a new manufacturing technology node by a year, with the gain from a proposed new circuit structure that promised to shrink device size by 50%, and ask which potentially has the greater economic return. While the above describes semiconductor manufacturing, structural models of the impact of specific technical innovations on solar electric energy production costs, or vaccine manufacturing, etc., are likely to be just as useful and relevant.

Connecting the Dots

Clearly, a detailed exploration of the interaction between technological developments and industrial economics can yield significant insights into the specific, detailed determinants of the pace of technological progress in an economically important high tech sector, and offer a framework for evaluating the potential economic payoff from funding technology projects that propose specific technical goals. More detailed research into "connecting the dots" between specific technology investments, and specific economic benefits, might also produce useful insights into what types of technical, institutional, and organizational characteristics of research projects yielded the highest probabilities of producing large economic benefits. Both types of studies could be of substantial interest to Federal S&T agencies as they consider how to allocate scarce funding resources.

Recent studies have taken a variety of approaches to tracing through the links between specific technological innovations in microelectronics, and economic benefits produced by these innovations. The first of these approaches, using survey-based cost-benefit analysis of technology investment projects, superficially resembles a structural model of technical innovation, insofar as benefits from a technology investment are calculated, then compared to estimates of the costs of those investments. However, rather than relying on an explicit model of product demand, and a supply and cost structure that is explicitly linked to technical parameters that are altered, and a new equilibrium outcome computed (as in Griliches (1958) or Mansfield (1977)), producer responses on surveys or questionnaires are used as the basis for

estimates of benefits from the technical change. By definition, then, an important component of social return in high tech (consumer surplus created by lower product prices resulting from technical change) is omitted, and these studies can at best only estimate private returns.

Some of this literature has focused explicitly on the semiconductor industry. Link, Teece, and Finan (1996), for example, estimate the returns to an early sample of R&D projects undertaken by SEMATECH, by surveying SEMATECH member companies on the economic benefits received from these projects. Combining these estimated benefits with project costs supplied by SEMATECH administrators, they calculated internal rates of return. While their specific empirical results are of limited interest,[13] their methodology illustrates a number of common pitfalls in using cost-benefit analysis for technology program evaluation.

It is useful to briefly consider the goals and purposes of a study like this. The intent, clearly, is to ask questions like: Was the portfolio of projects undertaken by SEMATECH, overall, a worthwhile investment from the view point of its members? From the social perspective, taking into account the costs of SEMATECH's government subsidy, did it provide a good return? Would the investment have been undertaken absent the government subsidy?

Simply measuring the retrospective return on any single project would be uninteresting, since a low or even negative return on any single project would be an expected outcome even if the program as a whole were highly successful, if it were funding long-range, risky projects with substantial risk. Similarly, a very high rate of return on a clearly successful project is equally unenlightening.[14] What would be more useful is a forward-looking modeling framework that successfully measures the historical economic impact of selected technical innovations, and thus validated, could then be used to measure the potential payoffs to new innovations, for comparison with their potential costs.

Furthermore, even a completely unsuccessful R&D project, that created no positive stream of returns, and so had a net negative return when analyzed as a standalone project, might actually have a positive return if viewed in a broader context. The information gleaned

---

[13] Note that this study was undertaken early in the history of SEMATECH, and looked at projects started during a tumultuous period of substantial internal debate about the kinds of projects SEMATECH should be undertaking. A new CEO took over in 1991, and in 1993 reorganized much of its agenda around support for the goal of shortening the period between technology nodes from 3 to 2 years.

[14] As Griliches (back in 1958, p. 426) put it, "Does it really make sense to calculate the rate of return on a successful 'oil well'?"

from a failure could stimulate others to avoid making investments that would not succeed, or guide resources into other technology projects in technology areas with a higher probability of success. It is even possible that an entire commercially unsuccessful **program** of multiple technology project investments might have a net negative return when considered in isolation, but that information about what doesn't work might have substantial positive value in guiding further R&D investments by organizations with access to this information. Indeed, the "loser" technology program might even yield a net positive return when these other avoided R&D failures are taken into account. These kinds of informational spillovers are famously difficult to detect or measure, and for this reason we are entitled to be a little skeptical about the utility of retrospective modeling of economic returns, when used for research program evaluation. Should a negative commercial return on a recently ended nuclear fusion program convince us that we would have been better off simply not doing it? Will a failure not help us better design the next technology investment in the fusion energy area?

Another difficulty frequently found in this type of study that is that the basis for estimating benefits from projects was a survey instrument asking companies for an estimate of the monetary value of benefits received.[15] Since company accounting systems are not be set up to model "what-if" questions, such evaluations implicitly involve the survey respondent somehow doing their own model of the impact of the technology on prices and costs faced by the firm, and comparing an actual outcome with the hypothetical scenario of no new technology available. Such survey responses may not make it clear whether those sampled actually are sharing the same common assumptions about the effect of not using the new technology on key technical parameters, or the extent to which those effects are felt throughout the industry, or implicit assumptions about effects on market demands and competitor's supplies. The respondent's (mental?) modeling process, unfortunately, is not explicit, so it is unclear to what extent the response relies on, say, higher costs felt across the industry being passed on to consumers in the form of higher prices, or, alternatively, simply absorbed by the company in diminished profit margins, or felt in both higher prices and lower operating margins.

Another strand in the use of cost-benefit analysis to model the economic effects of technological innovation is associated with the National Institute of Standards and Technology

[15] In the Link, Teece, and Finan study, company representatives were asked their opinions "about the economic state of the company in the absence of the research project. Benefit data were derived by comparing these responses to the current economic state of the company" (p. 742).

(NIST), which has a long record of sponsoring external cost-benefit studies of both intramural R&D projects (funded by external budgets, or by NIST's own budget), and extramural R&D projects administered by NIST (like NIST's Advanced Technology Program (ATP)).[16] These studies have played an important role in stimulating recent interest in this area, by collecting substantial data on firms and technologies involved in these programs, and enlisting outside consultants and academic economists in an effort to analyze the impacts of its programs on innovation, and resulting economic benefits. However, the varied approaches taken by the authors of these studies, using different assumptions and methodologies, make it difficult to arrive at any robust conclusion about what these studies show, exactly, aside from producing generally high internal rates of return and benefit-cost ratios.[17] Table 2 shows a summary list of such NIST-sponsored evaluation studies related to semiconductor technology.

While the methodological variety in the NIST ATP evaluation studies does not facilitate cross-study comparisons of results, it did serve to stimulate useful and interesting work on measuring knowledge spillovers, one of the most difficult and thorny issues for research on economic benefits from innovation. Studies by Fogarty, Sinha, and Jaffe (2006), and Watkins and Schile (2006) are notable for their focus on challenges to measurement of benefits posed by spillovers, and their studies of how they might be directly measured. In addition, the NSF's SciSIP research program is currently funding two projects which address the issue of diffusion of innovations, and spillovers, in the semiconductor industry.[18]

A second approach might be described as structural models applied to case studies, where a researcher uses technical and engineering data to build an economic simulation model of production cost with and without the use of a specific innovation. Adding to that the relationship between cost and price, and demand, then allows the private (benefits appropriated by the innovating firms) or social (taking into account benefits to users or consumers not captured by the innovators) returns to be estimated.

---

[16] For useful surveys of some of the issues faced in these studies, see Tassey (2003), Powell (2006).

[17] As Tassey (2003) notes, if we take 50% as a 'hurdle rate' for social return based on studies of private sector social returns by Mansfield, et al (1977), Tewksbury et al,(1980), and Griliches (1988, 1995), we would conclude that returns on these projects generally exceed that hurdle rate.

[18] Those two projects are Flamm, "Modeling Innovation Chains Using Case-Based Econometrics: Nano-electronics and Biotechnology Applications," NSF Award 830389, and Klepper, "Clusters, Heritage and the Microfoundations of Spillovers - Lessons from Semi-Conductors," NSF Award 965451.

One recent example of a systematic approach to measuring benefits (in this case, cost savings to semiconductor producers) and costs from a technical innovation in semiconductors is NIST's commissioned study on the costs and benefits from investments in measurement technology in the semiconductor industry (NIST, 2007).[19] In this study, interviews are not used to elicit estimated benefits, but rather to solicit estimates of technical parameters related to cost savings, which are then utilized in a modeling framework to arrive at benefits estimates. Another is Watkins and Schlie (2006), which estimates benefits to both producers and consumers created by NIST investments in semiconductor-based photonic technology in a specific firm, as well as identifying indirect spillovers to other firms. Pillai (2007) analyzes empirical data tracking technological change in semiconductor lithography, and links it to observed rates of quality-adjusted price change in microprocessors. Flamm (2010) estimates the private value of a hypothetical one year acceleration in the adoption of a $6F^2$ memory cell design in DRAMs to be about 16% of annual sales of DRAMs for DRAM producer Samsung in 2005 using a techno-economic simulation model. These studies are all most useful in that they contribute to understanding the channels through which economic impacts of the innovation are felt, by to some extent lifting the cover off the black box.

A third approach takes more disaggregated patent, bibliometric, or R&D funding data than is usually available, and estimates a “black box” model of the impact of these more highly disaggregated innovative inputs on output, or market value, or firm profits. Early examples are the Megna and Klock (1993) and Shane and Klock (1997) studies of the impact of R&D and patent counts on semiconductor firm market value. Another example of this approach is Deng (2006), studying the relative impact of external backward and forward patent citations on the market valuation of U.S. semiconductor firms, as measures of knowledge spillovers to and from other firms. Deng finds that externally cited patents may contribute to market value as much as half of the firm’s own R&D investments.

Similarly, Chin, Lee, Chi, and Anandarajan (2006), examining the impact of patent citations, and spillovers from R&D performed by other firms on Taiwanese semiconductor firm valuation, find that firms with more highly cited patents have higher market valuations. In addition, they find firms’ market value is positively related to R&D performed by other firms, indicating that spillovers are significant. They also disaggregate semiconductor producers by

[19] The study finds an internal rate of return of 67% on all R&D investments in measurement technology and standards in the semiconductor industry. Note that this excludes any consumer's surplus beyond the estimated cost savings (which might ultimately be passed on to consumers in competitive market segments).

position in the industry value chain (i.e., front-end fabrication, back-end assembly and test, design only), and find effects that vary greatly by industry segment. But note that, as in all studies using patent citation measures as control variables, it is not reasonable to interpret estimated coefficients in these models as causal effects.[20] Also, these studies do not generally provide useful information about what specific innovations are generating observed economic impacts.

However, there have been studies that break these innovation input indicators into distinct technological or scientific categories, which permits analysis of what categories of innovations, or technical and scientific areas, have generated different levels of economic impact, on average. Yu (2006) studied the effect of process R&D on a single semiconductor firm's manufacturing costs; Chesbrough and Liang (2008) analyzed the returns to internal and external contract R&D investment, as separate categories, using firm level data for the Chinese semiconductor industry. Torero (2001) analyzes the effect of patenting and scientist stocks on startup behavior in Silicon Valley and Route 128 semiconductor companies.

A fourth approach uses direct indicators of innovation adoption (for example, one might imagine using product "tear downs", as in Chuma (2008)), to trace the diffusion of specific innovations across firms, and exploit differences in the timing of adoption of specific innovations by different firms to directly estimate the effects of technological innovation on firm market value or economic performance. These are essentially "black box" models of the private economic impacts of innovation investments, but advance the field by utilizing direct measures of adoption of innovations in order to estimate private returns to adoption of specific technological innovations. Lou, Lee, Gong, and Lin (2010) examine the effects of technical innovation (distribution of semiconductor production capacity by technology node, indexed by the critical feature size, F, discussed earlier) on the market value of U.S. semiconductor companies, and find a positive impact.

A fifth approach involves so-called "event studies" of the impact of announcements of specific research projects, results, or innovative new product introductions on stock market value. This permits another type of estimate of private benefit from a specific technological

[20] For example, it is not sensible to argue that an increase in externally cited patents itself causes an increase in market value for the firm. If it did, any firm could increase its market value by simply increasing the number of external patents it cited whenever it filed a new patent application of its own! The point is that the external patent cites are really a proxy for something else that we are not measuring directly. Similar arguments apply to the interpretation of other patent citation indicators.

innovation. Austin (1993) first applied this sort of model to analyze the effect of biotech patenting on biotechnology firm valuations. Examples of this approach applied to product categories that include semiconductors include Sood and Tellis (2009), who look at the impact of innovation announcements on stock market prices. They distinguish between "setup" (alliances, funding, expansions), development (prototypes, patents, product pre-announcements), and marketing (product launches) announcements, and find that development announcements seem to have the greatest effects.

Along similar lines, Raghu, Woo, Mohan, and Rao (2008), apply the event study methodology to patent infringement litigation announcements rather than patent announcements per se, while Wang, Chiu, Chen, Yu, and Lin (2009), looked at the announcement effect of patent applications on Taiwanese electronics companies' stock prices. In a related but somewhat different sphere, Hughes, Lenway, and Rayburn (1997) analyze the impact of US trade policy action announcements on U.S. semiconductor firm stock prices. Unfortunately, these studies provide little insight into the reasons—the why and how—of different particular events creating different economic impacts on firms.

Conclusions and Implications for U.S. Science Agencies

The modern empirical economic analysis of technological innovation began roughly 50 years ago, in the late 1950s, with detailed studies of the institutional, technical, and economic details of the process through which particular innovations made their economic impact felt. The early pioneers built structural models of the sectors in which the innovations occurred, and directly linked technological developments to shifts in industrial supply and demand for affected products. These early studies required a great deal of researcher investment in sector-specific data and analysis, but also produced great insights into the process of innovation in the sector studied, and a definitive understanding of the nature and impact of scientific research and technological innovation in that particular sector. For example, Zvi Griliches' pioneering studies of the development and diffusion of hybrid corn continue to guide our understanding of agricultural innovation, the rationale for federal research investments, and the mechanism through which the federal investment in agricultural research generated great economic returns for this nation.

The continuing explosion in inexpensive computing power, the proliferation of large scale economic databases, and the computerization of journals and patent data, has shifted the center of gravity for empirical research on innovation to the statistical harvesting of empirical regularities across broad swatches of sectors and industries. Social scientists have turned to the

readily and increasingly available computerized data that our information society now provides on certain measured correlates of innovation—patents, scientific publications, and their citations, data "scraped" off of public web sites—and have set about developing statistical models and data mining techniques to unleash that cheap computer power on these vast new databases. That effort is clearly paying off, particularly in methods and models that trace out linkages and pathways between different research performers, their innovative outputs, and commercial technology-intensive products.

But at the same time, much useful insight can still be had only by investigating what is going on inside the "black box," and these large-scale, data-driven methods do not usually provide visibility into how it is, precisely, that a new concept or idea ends up having a large economic impact. One of the lessons of this review is that much can be learned from studying the process of innovation in a particular sector in greater detail. The first part of this essay was intended to point out that we really now know quite a bit about the mechanics of how those staggeringly high rates of price decline in semiconductors came about, and can even predict the economic consequences of changes in a few key technical parameters that are central to this very important industry.

We may even be approaching the point where we can usefully provide a first-order approximate evaluation of the economic merits of alternative research programs that propose to alter one or another of these key technical parameters in the semiconductor industry. To some extent this may be unique to the semiconductor industry, where a huge amount of public information is being continually updated through the ITRS roadmapping process. Indeed, the apparent success of the ITRS in ratcheting up the rate of technological innovation in semiconductors suggests that this is an experience that may be worth studying by other industrial sectors with large numbers of participants and complex technical coordination problems. For example, could a public-private technology roadmapping partnership help the U.S. better define a technology strategy that meets its national energy policy goals? These sorts of questions seem worth exploring.

How does all this relate to U.S. science agencies? Historically, much of the economic research on innovation funded by some of these agencies has been concerned primarily with retrospective program evaluation, and intended to demonstrate relevance and earn political support. This is certainly understandable, given the recent and sometimes contentious history of the post-war public-private partnership that is the U.S. R&D system. But an equally valuable

goal would be for research on technological innovation to provide insight to policymakers on what kinds of research projects are likely to provide the greatest social return to the nation.

Insights about how to best predict the economic impact of research projects, based on the organizational, institutional, and technical details of the project, can improve the efficiency of the national research investment. Rather than primarily looking backward, a valuable thrust for economic research on innovation would be to invest in economic methods that look forward, that seek to peek inside the black box, in order to provide sound advice on maximizing the economic return on public technology investments.

References:

A. Aizcorbe, “Price Measures for Semiconductor Devices,” Finance and Economics Discussion Series 2002-13, (Board of Governors, Federal Reserve System: Washington), 2002.

A. Aizcorbe, K. Flamm, and A. Khurshid, “The Role of Semiconductor Inputs in IT Hardware Price Decline: Computers versus Communications,” in E.R. Berndt and C.R. Hulten, Ed., **Hard to Measure Goods and Services**, (Chicago and NBER: Chicago, 2007).

A. Aizcorbe, S. Oliner, and D. Sichel, “Shifting Trends in Semiconductor Prices and the Pace of Technological Progress,” Finance and Economics Discussion Series 2006-44, (Board of Governors, Federal Reserve System: Washington), 2006.

D. Austin, “An Event Study Approach to Measuring Innovative Output: The Case of Biotechnology,” **American Economic Review** 83, 1993.

A. Bartel, C. Ichniwoski, and K. Shaw, “How Does Information Technology Affect Productivity? Plant-Level Comparison of Product Innovation, Process Improvement, and Worker Skills,” **Quarterly Journal of Economics**, November 2007.

L.D. Browning and J.C. Shetler, **Sematech: Saving the U.S. Semiconductor Industry**, (Texas A&M: College Station), 2000.

E. Carayannis and J. Alexander, “Strategy, Structure and Performance Issues of Pre-competitive R&D Consortia: Insights and Lessons Learned from SEMATECH,” **IEEE Transactions On Engineering Management**, VOL. 51, NO. 2, May 2004.

L. Casolaro and G. Gobbi, “Information Technology and Productivity Changes in the Banking Industry,” **Economic Notes by Banca Monte dei Paschi di Siena SpA**, vol. 36, no. 1-2007.

H. Chesbrough and F. H. Liang, “Return to R&D Investment and Spillovers in the Chinese Semiconductor Industry: A Tale of Two Segments,”2008, presented at 2008 Industry Studies Conference.

C. L. Chin, P. Lee, H.Y. Chi, and A. Anandarajan, “Patent Citation, R&D Spillover, and Tobin’s Q: Evidence from Taiwan Semiconductor Industry,” **Review of Quantitative Finance and Accounting**, 26, 2006.

H. Chuma, “Increasing complexity and limits of organization in the microlithography industry: Implications for science-based industries, **Research Policy**, 35(3), 2006.

H. Chuma and N. Hashimoto, “Moore’s Law, Increasing Complexity, and the Limits of Organization: The Modern Significance of Japanese Chipmakers’ DRAM Business,” RIETI Discussion Paper Series 08-E-001, Tokyo, 2008.

Y. Deng, “The value of knowledge spillovers in the U.S semiconductor industry,” **International Journal of Industrial Organization**, 26(4), 2008.

M. Doms, A. Aizcorbe, and C. Corrado, “When do matched-model and hedonic techniques yield similar measures?,” Working Papers in Applied Economic Theory 2003-14, (Federal Reserve Bank of San Francisco: San Francisco), 2003.

E. Dulberger, “Sources of Price Decline in Computer Processors: Selected Electronic Components,” in M. Foss, M. Manser, and A. Young, Ed., **Price Measurements and Their Uses**, (NBER: Chicago), 1993.

T. Eicher and O. Roehn, “Sources of the German Productivity Demise: Tracing the Effects of Industry-Level Information and Communication Technology Investment,” **German Economic Review** 8(2), 2007.

R. C. Feenstra, M. B. Reinsdorf, and M. J. Slaughter, “Effects of Terms of Trade Gains and Tariff Changes on the Measurement of U.S. Productivity Growth,” December 2008.

K. Flamm, “Economic Impacts of International R&D Coordination: SEMATECH and the International Technology Roadmap,” in S.Nagaoka, M. Kondo, K. Flamm, and . Wessner, Ed., **21st Century Innovation Systems for Japan and the United States: Lessons from a Decade of Change**, (NRC: Washington, DC), 2009.

K. Flamm, “How Does the Timing of Technical Innovation Affect Semiconductor Manufacturing Profitability?,” University of Texas at Austin, 2010.

K. Flamm, “Internationalization in Semiconductors,” in J. Grunwald and K. Flamm, **The Global Factory**, (Brookings Institution: Washington), 1985.

K. Flamm, “Measurement of DRAM Prices: Technology and Market Structure,” in M. Foss, M. Manser, and A. Young, Ed., **Price Measurements and Their Uses**, (NBER: Chicago), 1993.

K. Flamm, **Mismanaged Trade? Strategic Policy and the Semiconductor Industry**, (Brookings Institution: Washington), 1996.

K. Flamm, **More for Less: The Economic Impact of Semiconductors**, (Semiconductor Industry Association: San Jose), 1997.

K. Flamm, “Moore's law and the economics of semiconductor price trends,” **International Journal of Technology, Policy and Management**, 3(2), 2003.

K. Flamm and Q. Wang, “SEMATECH Revisited: Assessing Consortium Impacts on Semiconductor Industry R&D,” in C. Wessner, Ed., **Securing the Future: Regional and National Programs to Support the Semiconductor Industry**, (National Academies Press: Washington), 2003.

K. Flamm, “The Impact of DRAM Design Innovation on Manufacturing Profitability,” **Future Fab International**, 35, 2010.

K. Flamm, “The Microeconomics of Microprocessor Innovation,” (2007).

M.S. Fogarty, A. K. Sinha, and A. B. Jaffee, **ATP and the U.S. Innovation System: A Methodology for Identifying Enabling R&D Spillover Networks**, GCR 06-895, (NIST: Washington), 2006.

J. Greenwood and K. Kopecky, “Measuring the Welfare Gain From Personal Computers: A Macroeconomic Approach,” NBER Working Paper 13592, revised version (Cambridge: 2010).

Z. Griliches, “Research Costs and Social Returns: Hybrid Corn and Related Innovations,” **Journal of Political Economy**, 66(5), 1958.

Z. Griliches, “Productivity Puzzles and R&D: Another Non-explanation,” **Journal of Economic Perspectives**, 2, 1988.

Z. Griliches, “R&D and productivity: econometric results and measurement issues,” in: Stoneman, P. (Ed.), **Handbook of the Economics of Innovation and Technological Change**, (Blackwell: Oxford, U.K.), 1995.

B. Grimm, “Quality-Adjusted Price Indexes for Some Metal Oxide Semiconductor Integrated Circuits,” (U.S. Dept. of Commerce: Washington), 1995.

B. Hall and R. Ziedonis, "The patent paradox revisited: an empirical study of patenting in the U.S. semiconductor industry, 1979–1995," **RAND Journal of Economics**, 32(1), 2001.

B. Hall and R. Ziedonis, "An Empirical Analysis of Patent Litigation in the Semiconductor Industry," paper presented to the AEA annual meeting, Chicago, IL, 2007.

D.W. Jorgenson, "Information Technology and the U.S. Economy," **American Economic Review**, 91(1), 2001.

D.W. Jorgenson, M. Ho, and K. Stiroh, "Growth of U.S Industries and Investments in Information Technology and Higher Education," in C. Corrado, C. Hulten, and D. Sichel, Ed., **Measuring Capital in a New Economy**, (Chicago and NBER: Chicago), 2005.

D. W. Jorgenson and K. Vu, "Information Technology and the World Growth Resurgence," **German Economic Review** 8(2), 2007.

R.C. Levin,"The Semiconductor Industry," in Nelson, Ed., **Government and Technical Progress**, (Pergamon: New York), 1982.

A.N. Link and L.L. Bauer, "An economic analysis of cooperative research," **Technovation**, 6(4), 1987.

A.N. Link, D. J. Teece, and W.F. Finan, "Estimating the Benefits from Collaboration: The Case of SEMATECH," **Review of Industrial Organization**, 11, 1996.

C. C. Lou, T. P. Lee, S. C. Gong, and S. L Lin, "Effects of technical innovation on market value of the U.S. semiconductor industry," **Technological Forecasting & Social Change**, forthcoming, 2010.

J. T. Macher, D. C. Mowery, and D. A. Hodges. "Reversal of fortune? The recovery of the U.S. semiconductor industry. **California Management Review**, 41(1), Fall, 1998.

E. Mansfield, J. Rapoport, A. Romeo, S. Wagner, and G. Beardsley, "Social and Private Rates of Return from Industrial Innovations," **Quarterly Journal of Economics**, 91(5), 1977.

P. Megna and M. Klock. "The Impact of Intangible Capital on Tobin's Q in the Semiconductor Industry," **American Economic Review**, 83, 1993.

K. Motohashi, "Firm-level analysis of information network use and productivity in Japan," **Journal of the Japanese and International Economies**, vol. 21, 2007.

National Science Board, **Science and Engineering Indicators 2006, vol. 2**, (NSF: Arlington, VA), 2006.

S. D. Oliner and D. E. Sichel, "The Resurgence of Growth in the Late 1990s: Is Information Technology the Story?" **Journal of Economic Perspectives**, 14(4), 2000.

U.S. Pillai, "The Economics of Technological Advancement in Microprocessors," 2007.

T.S. Raghu, W. Woo, H.R. Rao, and S. Mohan, "Market Reaction to Patent Infringement Litigations in the Information Technology Industry," **Information Systems Frontiers**, 10(1), 2008.

H. Shane & Klock, M., "The Relation Between Patent Citations and Tobin's Q in the Semiconductor Industry," **Review of Quantitative Finance and Accounting**, 9 (2), 1997.

A. Sood and G.J. Tellis, "Do Innovations Really Pay Off? Total Stock Market Returns to Innovation," **Marketing Science**, 28(3), 2009.

J. Tewksbury, M. Crandall, W. Crane [1980], "Measuring the Societal Benefits of Innovation", **Science**, 209, 1980.

J. Tilton, **International Diffusion of Technology: The Case of Semiconductors**, (Brookings Institution: Washington), 1971.

M. Torero, "Analyzing the Spillover Mechanism on the Semiconductor Industry in the Silicon Valley and Route 128," 2000, presented at Econometric Society World Congress 2000.

Y. H. Wang, W.T. Chiu, J.C. Chen, S. T. Yu, Y. H. Lin, "Announcement Effect Of Patent Application: Evidence From Taiwan Listed Electronics Industries," **Proceedings of Business And Information**, http://bai2009.org, 6(1), 2009

T.A. Watkins and T. W. Schile, **Direct and Spillover Effects of ATP-Funded Photonics Technologies**, GCR 06-893, (NIST: Washington), 2006.

S.H. Yu, "An Empirical Investigation of Process Innovation and Learning in Semiconductor Manufacturing: A Life-Cycle Perspective," 2006, presented at American Accounting Association, Management Accounting Section, Midyear Meeting, 2007.

Table 1

Quality-Adjusted Price Decline Rates, Annualized

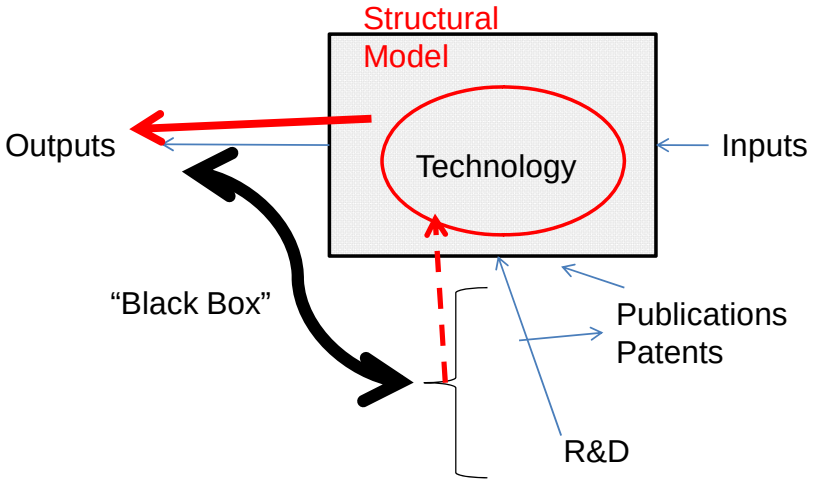
	Processors		
CAGR	All Computer	Desktop	Mobile
93:1-96:1	-44.0%	-44.0%	
96:1-00:1	-67.0%	-68.2%	-70.2%
00:1-04:1	-53.5%	-61.6%	-59.4%
04:1-07:4	-22.2%	-31.6%	-16.6%

	DRAM	Flash
92:1-96:1	-3.1%	-20.9%
96:1-00:1	-46.4%	-27.1%
00:1-04:1	-42.9%	-28.4%
04:1-07:3	-28.9%	-36.8%

Source: Author's calculations, using industrial production price indexes constructed by Federal Reserve, Board of Governors.

Figure 1

Structural Model vs. "Black Box" Model of Economic Impact



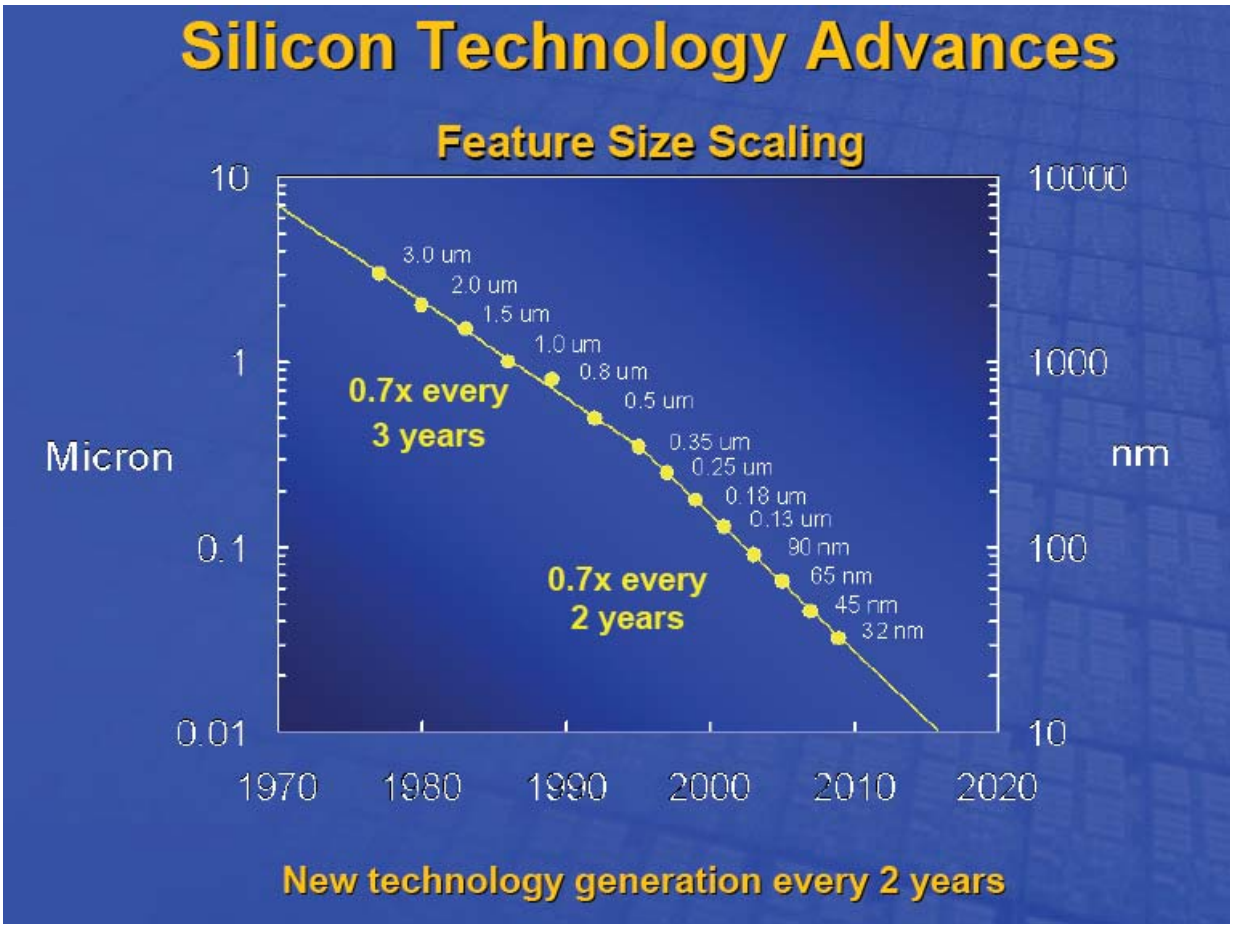


Figure 2

Source: Intel, reported in Bill Holt, "Facing the Hot Chip Challenge (Again)," presented at Hot Chips 17, Stanford University, August 2005.

	NIST Economic Impact Studies in Semiconductor Technology Area Since 1995		
	Intramural Research	Internal Rate	Benefit-Cost
Year	Project Title	Output	of Return	Ratio
1999	IGBT semiconductors	design automation software	76%	23
2001	Josephson voltage standard	standard reference material	877%	5
2008	Superfilling models & techniques	research models & techniques	79%	6
2008	Low-K materials characterization	materials characterization	N/A	9
	Sectoral Research Study		
2007	Semiconductor Measurement	metrology, materials, software	N/A	3.3
	ATP Program		
2006	Displaytech	FLCOS IC-based displays	33%	N/A
Sources: Available at http://www.nist.gov/director/planning/studies.cfm.			
	http://www.nist.gov/director/planning/planning.cfm		
	http://www.atp.nist.gov/eao/gcr06-893.pdf		

Table 2