

Research Spotlight

Technological Progress in the Microprocessor Industry

By Unni Pillai

PRODUCTIVITY in the U.S. economy picked up in the mid-1990s after two decades of sluggish growth. Many studies have found that productivity growth in information technology (IT)-producing industries (computers and communications) accounted for a sizeable portion of the productivity improvements in the aggregate economy (see Jorgenson 2001; Oliner and Sichel 2000). The surge in productivity in IT-producing industries was accompanied by an increase in the rate at which quality-adjusted prices declined for semiconductor chips, which are intermediate components used in computers and communication devices. Among the numerous semiconductor chips used in the IT industry, the acceleration in price declines was most pronounced for microprocessor chips, which form the nerve centre of modern desktop and laptop computers (see Aizcorbe 2005). These findings suggest that an increase in the rate of technological progress in the microprocessor industry might have driven down the quality-adjusted prices of microprocessors and of the upstream computer and communication products and thus played a central role in the pickup of aggregate productivity.

While the acceleration in quality-adjusted price declines in the microprocessor industry could have been caused by an increase in the rate of technological progress in the industry, it could also have resulted from other nontechnology-related factors, for example, an increase in competition in the industry (see Aizcorbe, Oliner, and Sichel 2006). An increase in the rate of growth of a purely technological variable would corroborate the evidence of a technological acceleration gathered from quality-adjusted prices. Such a corroboration is made in my recent study “A Model of Technological Progress in the Microprocessor Indus-

try” (see Pillai 2009), which looks at changes in microprocessor performance, a purely technological variable used among computer scientists and industry people to measure computing power. The data for performance of microprocessors is available from Standard Performance Evaluation Corporation, a not-for-profit organization that includes academics and leading computer companies. Chart 1 plots the performance of microprocessors produced by Intel and AMD during 1971–2008.

Each point in chart 1 corresponds to a microprocessor produced by Intel or AMD; the x-axis shows the date on which the microprocessor was first sold, and the y-axis shows the performance of the microprocessor. The acceleration in growth rates of performance in phase II (1990–2000) and the subsequent slowdown in phase III (2001–2008) is evident. The data in chart 1 show that the increase in the rate of quality-adjusted price declines obtained in other studies was not caused by changes in prices alone. There was some underlying technological shift in the microprocessor industry, which shows up in a purely technological measure like performance. The pattern of acceleration and slowdown occurred for both Intel and AMD, which together occupy almost all of the microprocessor market. The goal of my study was to provide a technology-centered explanation of the acceleration and slowdown (Pillai 2009).

Technological progress in microprocessors (and other semiconductor chips) has been made possible by continuous decrease in the size of the transistor, the basic electronic component in semiconductor chips. Smaller transistors are faster. Moreover, if transistors are smaller, then more of them can be put in a given area. Hence, a decrease in transistor size allows microprocessor firms, like Intel and AMD, to use more transistors in their microprocessors and to develop more sophisticated microprocessor designs (microarchitecture) that have higher performance. This continual increase in the number of transistors per chip was first predicted by Gordon Moore, a cofounder of Intel.

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Moore predicted in 1975 that the number of transistors in cutting edge semiconductor chips would double every 2 years, a prediction that has roughly held true (chart 2).

The development of new technology to make smaller transistors is a complex task. Semiconductor manufacturing involves a combination of chemical, mechanical, thermal, and optical processes, some of the more important ones being lithography, deposition, clean, and etch. The ability to make smaller transistors requires innovations in all these different processes. The research and development (R&D) required for these innovations has been undertaken by a group of companies different from companies like In-

tel and AMD who manufacture chips. For example, the lithography market is currently dominated by three companies—ASML, Nikon, and Canon—and the deposition market is dominated by Applied Materials and Tokyo Electron. These firms embody their innovations in new vintages of capital equipment. Intel and AMD repeatedly purchase newer vintages of capital equipment from the equipment companies and use them in their manufacturing plants to make faster microprocessors, with the smaller transistors made possible by the new vintage of equipment. Chart 3 shows the adoption of new capital equipment by Intel and AMD; the date of adoption of the vintage is shown on the x-axis, and transistor sizes are shown on the y-axis

Chart 1. Acceleration and Slowdown in Growth of Microprocessors Performance

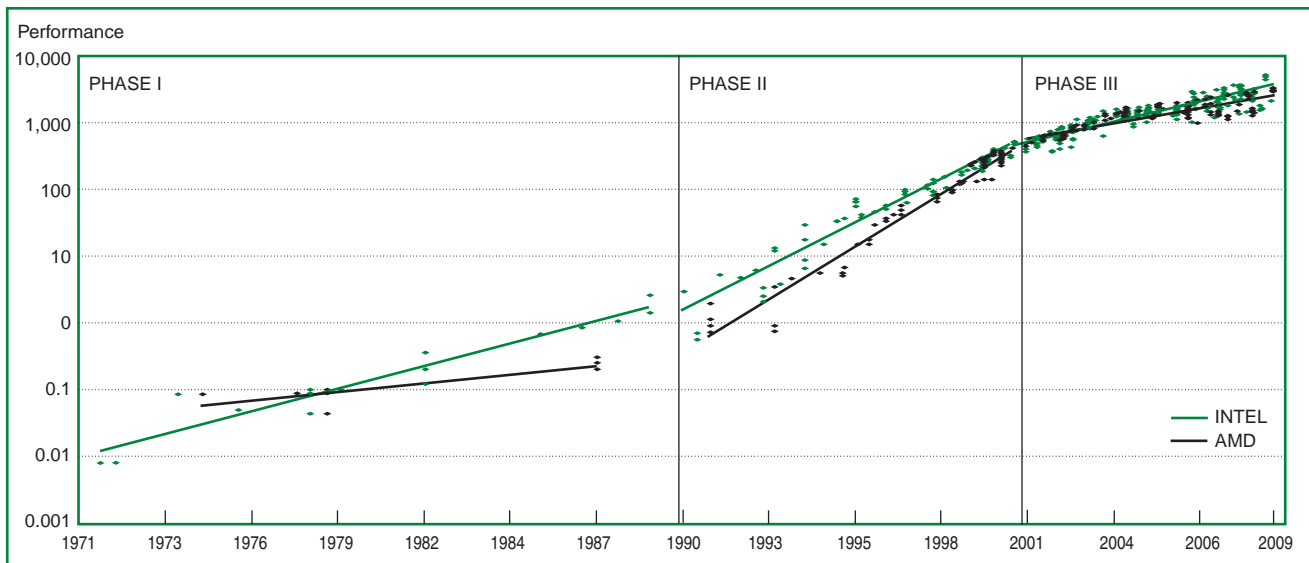
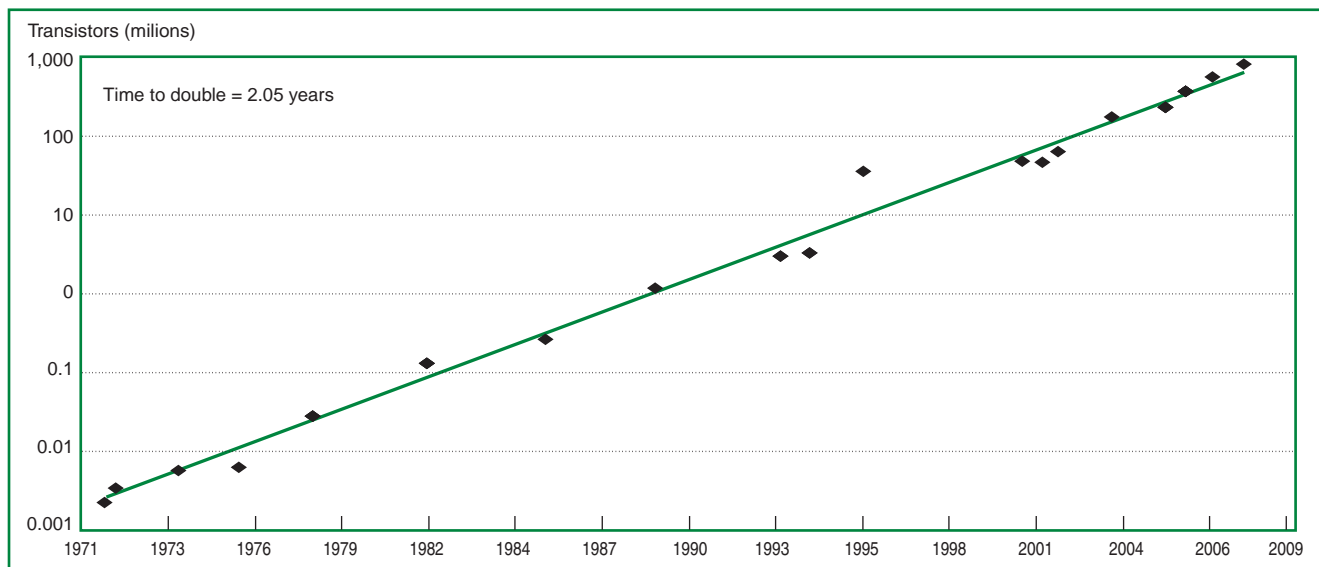


Chart 2. Moore's Law



(measured in microns, which is a millionth of a meter). The names of the lithography process used in each vintage are shown on the graph.

Chart 3 shows that Intel has adopted 14 vintages during 1971–2008. Before 1990, the average interval between adoptions was 4.3 years, which decreased to 2.08 years after 1990. Intel was adopting new vintages at shorter time intervals during the period after 1990, implying that the semiconductor equipment firms were innovating at a faster rate after 1990. The decrease in the intervals between vintages (technology node cycles) after 1990 has been noted by many others in the semiconductor industry.

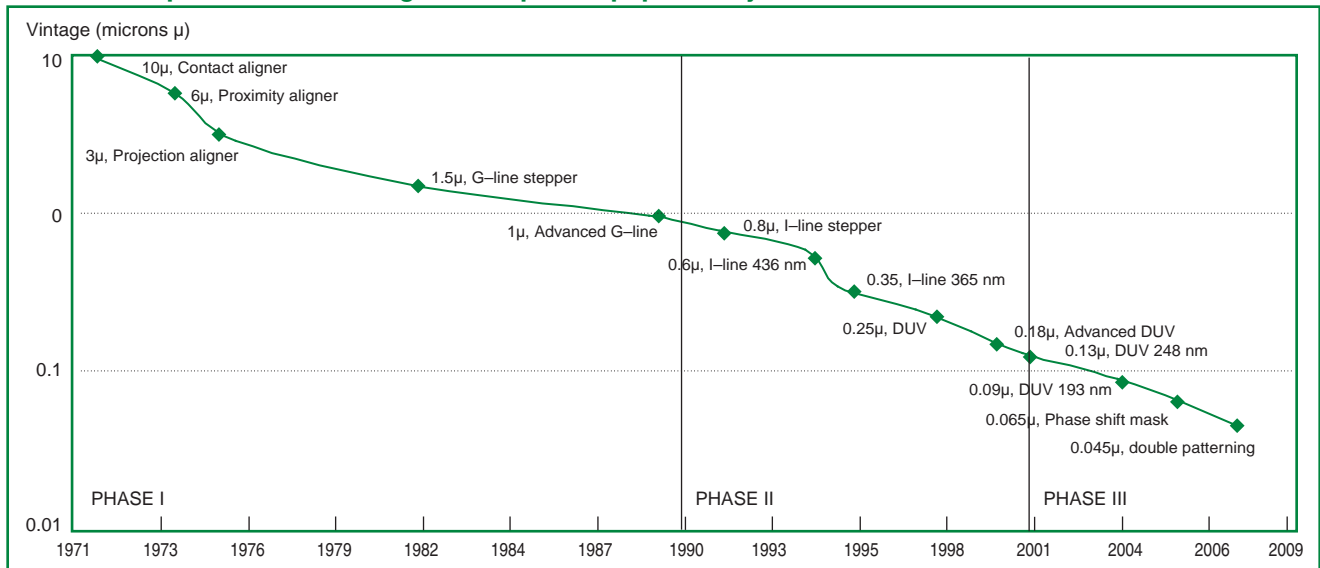
A proximate explanation for the acceleration is that an increase in the innovation rate in the semiconductor equipment industry allowed microprocessor firms Intel and AMD to reduce the time lag between new vintage adoptions. This caused the increase in the growth rates in performance seen in chart 1. But this explanation raises another question: how did the semiconductor equipment firms manage to innovate faster after 1990? One possible explanation is that the increase in innovation rate was the result of activities undertaken by SEMATECH, a consortium of semiconductor companies that was established in the United States in 1988 in response to increasing competition from Japan. Since its establishment, SEMATECH has worked with semiconductor equipment companies to accelerate the development of new vintages of capital equipment. Although initially established as a consortium of U.S. companies, SEMATECH expanded to include non-U.S. members and became an international consortium. Coincident with SEMATECH’s efforts, the semiconductor industry also established the Inter-

national Technology Roadmap for Semiconductors (ITRS), a consensus plan listing the industry’s forecast for the next 15 years of progression to newer vintages and the obstacles faced and possible solutions to overcome these problems. These national and global efforts improved the coordination among the disparate semiconductor chip manufacturers and equipment makers and could have led to the more rapid development of new vintages of semiconductor capital equipment.

Competing with this supply side explanation is a plausible demand side explanation of the acceleration. The acceleration in microprocessor performance in the 1990s coincided with the IT boom fueled by the expansion of the Internet. The newfound uses of faster computers—for example, in online video and multimedia applications—might have made it profitable for companies like Intel to undertake investments that would increase computing performance at a faster rate than before. In this explanation, the exogenous demand shock fueled by the Internet boom led to the acceleration in growth of performance.

Some support for the technology-based explanation comes from the R&D data for semiconductor equipment companies. The North American Industry Classification System (NAICS) classifies the semiconductor equipment manufacturing industry under a separate six-digit code with the name “Semiconductor Machinery Manufacturing” (NAICS code 333295). The R&D expenditures of publicly listed companies in NAICS code 333295 are available from the COMPUSTAT database. Although the data for North American companies are available for all the years of interest (1971–2008), the data for the rest of the world are available only from 1989 onwards. The finding that

Chart 3. Adoption of New Vintages of Capital Equipment by Intel



emerges from these data is that the average annual growth rate of R&D in the industry was lower during 1990–2008 than during 1971–89. The average annual R&D growth rates are listed in table 1. The first row lists the average annual growth rate of R&D for U.S. companies only, while the second row shows the growth rates for the set including U.S. and foreign firms.

Table 1. R&D Growth Rates in the Semiconductor Machinery Manufacturing
[Percent, average annual rates]

	1971–89	1990–2008
U.S. companies.....	25.9	19.6
U.S. and foreign companies.....	25.9	22.1

As can be seen from table 1, the R&D growth rates were lower during 1990–2008 than in 1971–89. Thus, even as the innovation rates in the semiconductor equipment industry increased during 1990–2008, R&D growth rates in the industry decreased. The observation that R&D growth rates in the semiconductor equipment industry have decreased has been documented in many other sources as well, most notably in Hutcheson (2005). The simultaneous occurrence of increases in innovation rates and decreases in growth rates of R&D in the semiconductor equipment industry lends indirect support to the technology-based explanation: that coordination activities undertaken in the semiconductor industry by SEMATECH, ITRS, and other R&D organizations enhanced the R&D capabilities of equipment firms, leading to faster transitions to newer vintages.

While the acceleration in microprocessor performance could be traced back to the increase in innovation rates in the semiconductor equipment industry and faster adoptions of new vintages by microprocessor firms, a similar story cannot explain the slowdown after 2000. The average period between adoptions since 2000 has remained roughly 2 years, the same as the average interval in 1990–2000. However, many studies have pointed to a different explanation for the slowdown: the slowdown was caused by problems related to microprocessor design, where new architectures that can speed up execution were not developed. In the beginning of the current decade, Intel hit a well-known problem: its cutting edge microprocessors began generating a lot more heat than could be handled by the cooling technologies at hand. To avoid overheating its microprocessors, Intel was forced to abandon the design trend that it had followed in the past and shifted to what became known as the multicore design. The essential idea behind the multicore design is to

have many processors working in parallel to increase performance. This approach, however, has well-known limitations, and current software technology is not developed enough to fully take advantage of these parallel processors (see Patterson 2010). This shift in Intel's microprocessor design led to the slowdown in growth in microprocessor performance seen in chart 1.

A competing explanation is that microprocessor performance slowed because the consumer demand for processing power was saturated. Consumer focus had shifted from faster desktops and laptops to smaller networked devices like netbooks, smartphones, and electronic readers. The microprocessor companies chose to decrease the rate of improving the performance because the additional profits they would have obtained did not justify the costs involved in continuing to increase performance at the same rates as in 1990–2000. In the first explanation, microprocessor firms hit a problem that they were not able to solve; whereas in the second explanation, it just was not profitable to continue on the same technological path as before. Further research is needed to understand which of these two explanations is responsible for the slowdown. If the first were true, then it would imply that the microprocessor industry would revert back to its accelerated path of technological progress once the current design problems are solved; whereas if the second were true, then it would imply that the current rate of technological progress would continue into the future.

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