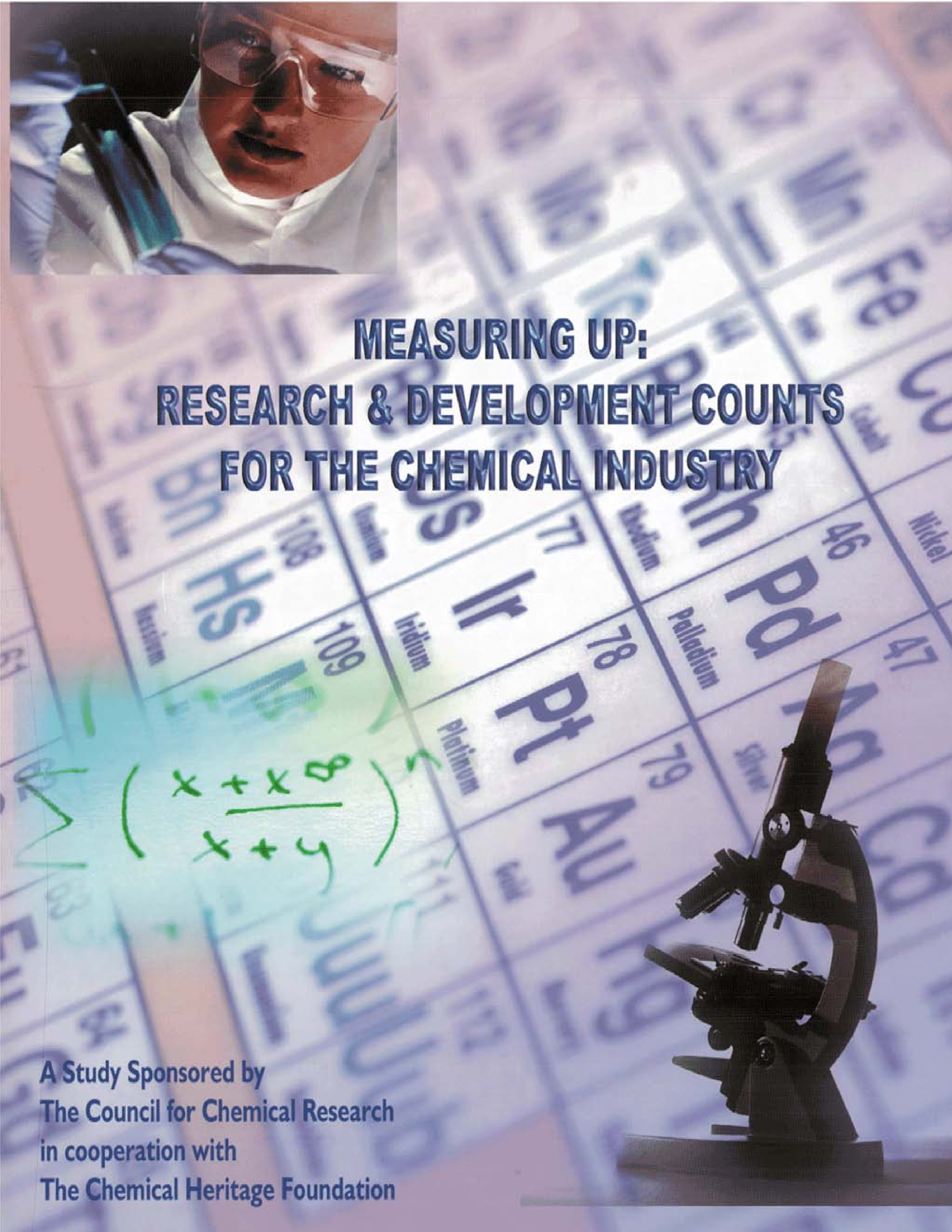

MEASURING UP: RESEARCH & DEVELOPMENT COUNTS FOR THE CHEMICAL INDUSTRY

A Study Sponsored by
The Council for Chemical Research
in cooperation with
The Chemical Heritage Foundation

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INTRODUCTION

In a world that is increasingly driven and imprinted by science and technology, there is a growing need for incisive methodologies to measure the value of research and development to industrial innovation and productivity.

The chemical industry has been, and continues to be, one of the major building blocks of the U.S. economy. It is the top U.S. exporter, with more than $68 billion in exports in 1998. Chemicals contribute the largest trade surplus of any non-defense related sector of our economy, over $13 billion. The U.S. chemical industry, valued at $419 billion, represents 10 percent of all U.S. manufacturing.

This study was undertaken to measure the impact, and thus the return or payoff, of chemical research and development. Although macroeconomic studies have addressed and documented the contributions of R&D to the nation's general economic growth, this study attempts to direct the question to a specific field of research: chemical research.

New methodologies, assessment tools, and approaches were used to more effectively quantify the contributions of chemical research. In turn, these findings will aid government, academia, and industry itself to better measure the future contributions of chemical research. The study results will help determine the size and scope of future R&D investments. Additional innovative methodologies will be required to further explore and refine these measurements in this still developing field.

Each of the three principal investigators addressed a different piece of this complex problem. The study presents the results from three separate perspectives, each derived with a different methodology.

Note:
The definition of the chemical industry for the purposes of this study does not include pharmaceuticals.

Key Study Accomplishments

- The development of a measurement that can quantify the impact of chemical R&D.

- A methodology to show linkages between chemical literature citings and science innovation.

Study Findings

- Every dollar invested in chemical R&D today produces $2 in operating income over six years; Add to that the time-value associated with money (inflation), and the return on a dollar R&D for chemical companies is 17 percent after taxes

- The chemical industry out-performed the S&P 500 Index until 1995; since 1995 the industry has been consistently behind the S&P

- The chemical industry's share of total U.S. R&D has declined from 11 percent in 1956 to 8 percent in 2002

- Twentieth century economic growth came largely through increases in knowledge-capital, especially education and R&D

- The chemical industry falls slightly below the national average in R&D investment as a percentage of sales (large companies are slightly above average)

- The industry still appears to be holding strong in the face of growing globalization

- Predictability of government funding is more important to industry than the actual level of funding

- Chemical patents show an increasing link to scientific papers

- Chemical technologies show roughly six science references per patent, the high end of the range

- A very high percentage of science links come from papers generated by academic researchers receiving public funding

- Science links in patents favor national origin, i.e. U.S. patents are likely to cite U.S. science papers

- This domestic science linkage in U.S. patents highlights the need for a broad domestic science base to spur technological development and innovation

The Study Team

Dr. David Sicilia, a historian who teaches at the University of Maryland, presents the historical overview of the chemical industry and the evolution of its research, particularly since World War II.

Dr. Baruch Lev, Professor of Finance at New York University, and **Dr. David Aboody**, Assistant Professor at the University of California-Los Angeles, take a traditional econometric approach in which they correlate the inputs, or investments made by firms, to the outputs, or returns that a firm gains.

Dr. Francis Narin, President of C.H.I. Research, Inc., and **Dr. Michael Albert**, Vice President of C.H.I. Research, Inc., employ a bibliometric methodology, quantitatively studying publications, the collaborations they reveal, the impact they have as measured through citations, and the depiction of boundary changes in fields under scrutiny.

Dr. Ashish Arora is a Professor of Economics and Public Policy at Carnegie Mellon University. He served as "converger," facilitator, and moderator for the study team.

Study Contributors

ABB Lummus Global Inc.
Air Products & Chemicals, Inc.
Bayer Corporation
Brigham Young University
The Council for Chemical Research
Degussa Corporation
The Dow Chemical Company
Dow Corning Corporation
E.I. DuPont de Nemours & Co.
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Georgia Institute of Technology
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Purdue University
Texas Tech University
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U.S. Environmental Protection Agency

EXECUTIVE SUMMARY

David Sicilia and the Historical Perspective

The chemical industry, by all measures, is a mature industry, David Sicilia characterizes it as the "quintessential American enterprise of the 20th century." As an industry, it exemplifies the century's key business trends: diversification, conglomeration, and an increasing reliance on science-based technological developments.

Modern R&D, the institutionalized effort to control the pace and direction of technological development, is also a product of the 20th century. Among Thomas Edison's West Orange facilities there was an invention factory, a chemical R&D lab where Edison attempted to routinize the invention process.

Chemical companies were among the very early industrial pioneers in building R&D facilities and performing routine research. Among them were firms still familiar and dominant today, such as DuPont, Dow, and General Chemical.

The Chemical Industry Evolves and Matures through Two World Wars

David Sicilia characterizes World War I as a "chemists' war." America was cut off from Germany, the leading producer of dyestuffs and pharmaceuticals, and was consequently forced to rely on its own resources. This resulted in boosted production of heretofore imported chemical intermediates. It also pushed the nation and the chemical producers toward greater reliance on their own domestic R&D.

R&D activity across the nation burgeoned in the period between World War I and World War II. The chemical industry was well represented in this expansion. Despite the economic downturn of the Great Depression, the chemical industry produced revolutionary new products, among them neoprene and polyester.

Following World War II, the federal government began investing heavily in big science, primarily R&D targeted to meet the nation's Cold War needs. The federal government soon led in research funding as a torrent of federal dollars flowed to research universities and defense contractors. Heavy concentration on military R&D was rationalized by its potential for spillover applications in the domestic economy.

The primary recipients of government defense funding were in fields such as electrical and electronics equipment, aerospace, and nuclear energy. Sicilia explains, "While large numbers of chemists were employed in those fields, the chemical sector as a whole did not benefit as much as several others from the federal government's heavy Cold War spending. . . . these other industries had kind of a Marshall Plan whereas the chemical industry was rather left to be more self-reliant."

The Age of Global Competition: 1974-2000

Postwar economic expansion began to disappear. The first oil shock in 1973 triggered alarming reverberations throughout the U.S. economy. Chemical enterprises were not spared. At the same time, the nation faced increasing global competition, especially from Germany and Japan. The situation was aggravated by a dramatic rise in costs for performing R&D, coupled with lengthened timeframes for results.

To emerge from these difficulties, the chemical industry developed a new strategy. By forming links with complementary enterprises and with major research universities, performance has improved impressively since the 1970s, exports have risen, and world market share for the industry has been maintained. Sicilia notes, "Chemical industries have been one of the few so-called high tech industries that have actually held up well in the face of increasing global competition."

Investors and Performers in U.S. R&D

In the last half of the 20th century, federal funding of R&D can be characterized as inconstant, subject to frequent change. (*See Sources of Funding for U.S. R&D*

1955-1998, page 13.)

It is significant to note that for the same period industry spending on R&D, even adjusted for inflation, indicates a continuously upward trend. And in 1994, industry spending actually surpassed government investment in R&D. That gap continues to widen.

Sicilia argues that even more significant than the level of government R&D funding is its predictability. He states. “Business has performed better when policy has changed slowly or remained stable. . . . Unpredictability is most injurious to long-term endeavors such as strategic planning and fundamental research.” Thus, the stability of industry’s R&D funding on its own behalf counts for far more than just the dollars invested. Great value accrues to industry from the predictable environment that stable funding can create.

The Chemical Industry’s Share of Total U.S. R&D

The chemical industry’s share of total U.S. R&D has declined from 11 percent in 1956 to 8 percent in 1992 (last year comprehensive data was reported to NSF). (*See U.S. Chemical Industry R&D as a Percentage of Total U.S. R&D 1956-1992, page 15.*)

To assess the industry’s decline in the nation’s total manufacturing R&D picture, Sicilia asked if, during this period, the chemical industry was growing faster or slower than the manufacturing sector as a whole. It turns out that the total volume of manufacturing grew threefold but the total output of chemicals and allied products grew approximately fivefold. The chemical industry was growing at a faster pace than manufacturing as a whole but its share of investment in R&D was slipping. Sicilia suggests that this poses a problem for the industry because technological innovation has always been a powerful “engine of economic growth.”

Challenges in Measuring Impact of R&D to Economic Growth

There are complex challenges in quantifying R&D and knowledge generation to arrive at a measurable value of their input. In following the guiding principle of the input/output measurement, the inputs—land, labor, and capital—are correlated with the outputs to distinguish or segregate the increase in productivity that cannot be attributed to increased inputs. Sicilia notes that. “Economists affectionately refer to this inexplicable gain as the residual.”

By examining historical data, one can observe the increasing size and importance of the “residual” to the economy. (*See Measuring the Productivity Residual, page 15*) Between 1840 and 1860, the residual pales in significance to growth from new labor and capital, and is also less than the contribution of new land. But between 1870 and 1930, we see the residual begin to transform the growth equation. While labor and capital remain roughly the same, the residual has jumped slightly more than 10 percent, while the contribution of new land has diminished appreciably. The postwar period between 1940 and 1990 shows the residual eclipsing all other inputs, even labor, meaning that the economy has become considerably more productive. Land is at zero because no appreciable *new* land has been added.

Sicilia points out that, “economic historians are unified in their opinion that the 20th century [generated] economic growth that came largely through the addition of increases in knowledge-capital, particularly education and research and development.” Ashish Arora confirms this by citing Nobelist Robert Solow’s estimation that 80 percent of the growth in U.S. labor productivity—output per worker—between 1904 and 1949 was due to technical change. More precisely, 80 percent of this growth could not be accounted for by increases in the amount of capital per worker and was a “residual,” Although the residual is not entirely due to investments in R&D, most economists currently agree that R&D, investments in education, and other aspects of knowledge generation are clearly at the core of the residual.

As the role of R&D becomes clearer, its contribution takes on more power and prominence.

A dilemma yet to be addressed is that current studies can calculate what it costs to produce something versus what it sells for, but none of the measurements identify a value to give to the improved quality of an item produced over time, e.g. television sets.

As the science of measuring R&D value to firms has become more sophisticated, we can see from Ashish Arora’s diagram (*See Measuring the Payoff from Research, page 10*) that a firm’s totality of R&D is a composite of diverse inputs. These include publicly financed R&D from universities and government labs, spillovers from domestic and foreign firms, and technological and scientific advantages (such as advanced catalytics, which can provide more flexibility in developing chemical processes). Moreover, the payoff from this R&D accrues not only to the firm, but also to others in the industry and elsewhere.

Arora further notes that the payoff from R&D depends upon other factors and investments in production, sales, and marketing. The interaction and interdependence of these various inputs to create growth is still poorly understood. Their combination has a chemistry of its own that cannot as yet be measured despite the fact that we can observe that output is at a higher rate. From the science of learning, we know that as we absorb new knowledge and practice skills these inputs restructure the brain, resulting in increased capability. The various elements that make up the residual seem to be doing something similar.

Baruch Lev and the Econometric Approach

Research and development conducted by corporations, universities, and national labs has according, to Lev, in large measure accounted for the chemical industry's consistent prowess. Today, the industry produces more than 70,000 different chemical substances generated by over a century of intensive R&D.

According to Ashish Arora, Baruch Lev's objective is to measure the private rate of return on R&D. In other words, this section is not expressly concerned with measuring the social payoff to investments in R&D. Instead, his focus is squarely on the private returns chemical firms are able to capture from their own R&D investments.

Arora also states that, "Lev uses an econometric model, with operating income as the output (measure of the payoff), and investments in physical capital and R&D as the inputs. Thus, he is measuring the private return to private investments in R&D."

Employing this econometric approach, Lev shows that although R&D is largely responsible for the historical growth and success of the chemical industry, chemicals have been somewhat subdued or on a plateau in investments for innovation since the 1990s. Thus Lev's study constitutes an empirical assessment of the overall productivity of chemical R&D.

The R&D intensity (R&D expenditures as a percentage of sales) in the chemical industry can be described as moderate. This is explained partly by the fact that the chemical industry as a whole is portrayed as a "swing" industry. Companies vary across a broad spectrum, with some leaning toward high knowledge assets while others can be categorized in the low knowledge assets echelon. Viewed in totality, the chemical industry is just slightly below the national average of companies with R&D expenditures. It lags behind such innovative sectors as pharmaceuticals, software, and computers. Despite this midrange position, one should not ignore the fact that the average R&D intensity of chemical companies in this study increased from 2.47 percent in 1980 to 4.70 percent in 1999. According to Lev, this is "a robust increase."

It is complex, at best, to attach accurate value to knowledge assets (intangibles) clue to the high-risk nature of the assets and because they are not traded in organized markets. In addition, outmoded accounting rules deny them the status of "assets" portrayed on corporate balance sheets. Intangible assets are the major missing asset from the traditional balance sheet.

Nevertheless, Lev shows in Figure 1 (page 19) the median values of intangible capital in 1998 for 19 industries. The chemical industry is situated in the middle group. A different perspective of intangible value and contribution is portrayed in Figure 2 (page 21) showing the growth rate of intangibles-driven earnings by industry over the 1990s. Of the 26 industries listed, the chemical industry falls into the high-end of the lower 1/3 of the total list, with an annual intangible-earnings growth rate of 8.2 percent.

For comparison, computers, in the high knowledge earnings group, show an annual growth rate of 19.4 percent. So, in intangible capital, chemical companies rank in the middle (Fig. 1) but in the growth of intangible assets contributing to overall corporate performance in the 1990s, they are in the low rate-of-growth group (Fig. 2).

There are also significant correlations between a company's R&D intensity and its return on R&D. According to Lev, ". . . estimates indicate a large difference between the returns on R&D of the high and low R&D intensity companies, roughly 40 to 20 percent, respectively." Additionally, the pattern of benefits differs. The high intensity group reaps the benefits of their R&D over a substantially longer period than the low intensity group. This suggests the existence of substantial economies of scale in chemical R&D.

Lev has also shown the value of spending R&D dollars today as opposed to tomorrow. The results are quite significant, revealing that a dollar R&D contribution in the chemical industry on average increases the same year's operating income by almost 37.2 cents and next year's operating income by 43.9 cents. The impact of a dollar R&D on operating income in the following two years is 40.7 cents and 31.6 cents, respectively. Further impact diminishes after seven years.

On average, an R&D dollar increases current and future operating income by $1.94. Add to that the time-value associated with money (inflation), and the return on a dollar R&D for chemical companies is 26.6 percent. For comparison purposes, this is less than the software industry's 29.3 percent (Figure 2).

The chemical industry's post-tax return on R&D is 17 percent and is considerably higher than chemical companies' average cost of capital, roughly 8 percent. The difference between the industry's 17 percent return and its 8 percent cost of capital is, in Lev's words, ". . . a very powerful engine of growth."

A comparison of the chemical industry to the S&P 500, an index of the 500 largest U.S. companies, provides additional perspective. (*See Figure 3, page 27 and Table 3, page 28.*) The chemical industry outperformed the Index until 1995. Since then, the industry has been consistently behind the S&P. Lev attributes this to the surge of the U.S. economy, particularly in new technology. Chemical companies are doing fine according to Lev, but they have not experienced this kind of surge. From 1995 to the end of 2000, the S&P 500 was mainly propelled by technology and science-based (e.g. pharmaceutical and biotechnology) stocks.

Lev summarizes, "The favorable capital market performance of chemical companies (up to 1994) thus indicates that the high return on R&D indeed contributed to corporate value and growth. This contribution, however, was constrained by the fact that the total investment in R&D by chemical companies is modest (Fig. 1).

In conclusion, he explains that the chemical industry is doing quite well, but its engine for growth is much like a Volkswagen beetle engine in a Ford explorer SUV. "It is a terrific engine, but it is relatively small . . . is it powerful enough to somehow elevate [and] transform the entire industry?" That remains a critical question for the chemical industry.

Lev does not foresee massive changes in chemical R&D budgets in the near future, although he suggests that his findings, ". . . indicate the desirability of modest (e.g., 15-20 percent) increases in R&D budgets, perhaps over several years. It seems reasonable to expect that the return on such modest R&D increases will be in the range of the estimated returns—well above cost of capital."

Further, he does not dismiss the importance of scalability, a term he defines as doing much more with what you have. "Finding new uses with ingenuity, finding additional customers, alliances . . . if the objective is really to move forward, to surge forward with those who are now leading the economy."

Arora reminds us that chemicals is an enabling technology in many industries. Therefore, the benefits of chemical research are also captured by these industries in the form of lower prices and higher quality of chemical inputs purchased.

Francis Narin and the Bibliometric Methodology

Some of the benefits of chemical R&D flow directly as new knowledge. Patent citations provide one way of tracking this flow of knowledge. By the same token, chemical R&D draws upon publicly funded scientific research. Ashish Arora points out, "members of a scientific community at universities and even in corporate labs are expected to disseminate their findings to the community at large by publishing their research. Others are then free to draw upon these with no recompense other than an acknowledgement through cita tion."

All of Narin's analyses are based on the U.S. Patent System and the patents granted within that system to both U.S. and foreign inventors. The number of patents gives an indication of the technological size of the chemical enterprise, while citation properties of patents denote the quality of U.S. chemical patents and their impact.

Three citation markers are employed throughout Narin's work to examine and make a qualitative judgment of these properties: the Current Impact Index (CII) for patents, their science linkage, and their Technology Cycle Time (TCT).

The number of chemical patents is growing, albeit somewhat slowly. The United States still holds the majority of U.S. chemical patents. The distribution of domestic chemical patents for the past twenty years shows that 52 percent are American-invented, while Japanese and German-invented patents in the U.S. system respectively hold 18 and 12 percent of the total distribution.

The classification that tracks the impact of patents, the CII shows good news for chemical patents. The CII provides a normalized measure of the impact that an earlier set of patents is having on technology appearing in the current year. It is described by Narin as "a patent citation indicator, which looks back from the current year at the previous five years of a set of granted U.S. patents." The CII shows how frequently certain patents have been cited from patents granted in the current year. Narin further states that, "It is based on the well-established idea that the more highly cited a set of patents is, the more technological impact it is likely to have." Since the average for all U.S. patents depicts a 1.0 CII, a set of patents with a CII of 1.1 is cited ten percent more than would be expected for the current year.

The impact of American-invented chemical patents is increasing, with its CII rising from 1.05 in 1986 to 1.2 in 1999. Narin suggests that this is probably due to the technological renaissance the U.S. has experienced in the past decade. He further explains that, "while U.S. information technology patents appear particularly highly cited compared to foreign-invented patents, U.S. chemicals, electronics, and life sciences are all doing quite well." These reasonably high domestic citation rates reinforce the belief that they are high quality technology.

Meanwhile, the Japanese impact, having dominated the U.S. in the late 1980s, has fallen dramatically, almost to the level of third ranking Germany. (*See Impact of U.S.-Invented Chemicals Patents is Increasing, page 38*.) Narin is quick to point out that this drop is not only confined to chemical patents in the case of Japan.

Further, Narin finds that chemicals, as well as life sciences, are science-driven technologies. They show an increasing link to scientific papers, in addition to other patents. By counting the number of times a patent cites to scientific papers or similar research publications, science linkage can show us how close a given set of patents is to fundamental scientific research. Narin explains that, "Science linkage is strongest in very advanced areas of biotechnology such as genetic engineering, and virtually zero in the older mechanical technologies." Chemical technologies show roughly six science references per patent, and Narin indicates that this is toward the high end of the range.

As a whole, the chemical industry is a strong second in science linkage behind life sciences, and a high percentage of the linkages come from papers that are generated by academic researchers receiving public funding. For domestic chemical industry patents from 1993 and 1994, 18 percent of their science came from industry itself. The other approximately 80 percent was split between public science and foreign science, which happens to be roughly 75 percent public as well.

Narin also indicates an important distinction between chemical patents invented inside versus outside the United States. He shows that science linkage has always been higher in U.S.-invented patents but has dramatically increased in the last five years, some five times greater than the average German- or Japanese-invented patent, (*See Science Linkage for U.S.-Invented Chemicals Patents is Higher than for Competitors, p. 38*.)

Science links in patents also show a strong tendency toward national origin. German patents tend to cite German science papers, as other countries link to their own research papers. This, according to Narin, indicates that a domestic science base is quite important to domestic technology development and innovation.

Narin found that this trend is mirrored in the U.S. not only on a national basis, but astoundingly, at a state level as well. Companies are disproportionately prone to cite papers that have been written in their own backyards, so to speak. It would be easy to then conclude that the papers themselves might not be of the highest quality since location seems to be a strong factor of linkage. However, this is not the case.

In fact, a chemistry paper that is in the top 1 percent of total cited chemistry papers is six to seven times as likely to be cited in a patent as a paper randomly picked. Therefore, there is a geographical link, if you will, between the sources of top-tier chemistry papers and the companies who cite these papers.

It should be noted that there is also a high degree of specialization in these patents, meaning that a chemical patent tends to cite other chemical patents as opposed to patents from other fields.

The third citation marker for patents, Technology Cycle Time or TCT, is calculated as the median age of patents cited on the front page of a U.S. patent document. This measure is used to determine the speed of innovation in a company or industry. The cycle time is slowing down for U.S.-invented chemical patents, from a bit more than eight years in 1980 to around ten years in 1999.

Narin suggests that this is not necessarily a bad trend: rather, it shows that chemical patents are still building on strong established science. However, this realization might explain the lack of economic surge in the chemical industry that is mostly sparked by brand new technology, as shown in Lev's econometric work.

In addition, as noted earlier, the number of chemical patents is an indicator of the technological size of the chemical enterprise, and perhaps its prowess. Thus it is important to note that twenty years ago, in 1980, there were about 5800 U.S.-invented chemical U.S. patents, which represented 16 percent of all U.S.-invented U.S. patents. But though these patents grew to 8200 in 1999, patenting in other fields had mushroomed, leaving the chemical patents' percentage of the whole much smaller.

Narin's documentation indicates that all U.S.-invented patents grew from 37,200 in 1980 to 83,600 in 1999, evidencing a decrease in the chemical patent share of the total from the earlier 16 percent to only 10 percent in 1999.

In examining other industry sector patent behavior over the same period, Narin tells us that the decrease in chemical patent share corresponds to appreciable increases in U.S. patent share for both information technology and for the life sciences. The figures are quite dramatic. In 1980, IT had less than 10 percent of patent share but by 1999 that had rocketed to close to 24 percent. In life science patents, the 1980 share was 8 percent, jumping to 14 in 1999. (*See Information Technology Share is Increasing the Most, page 35*.)

Narin shows that the citation rates of the domestic chemical industry are still flourishing, while not necessarily at the accelerated rates of life sciences (due to the high scientific intensity of genomic research). Further, he has uncovered a substantial link between geographic hotbeds of scientific breakthroughs and their respective knowledge spillovers into the chemical industry. This connection directly validates the usefulness and need of further publicly funded academic research.

Comments

So what can we surmise from all of this about the U.S. chemical industry and the value of its R&D? Chemicals have been one of the few high-tech industries to maintain resilience and a strong competitive edge despite the increasing trend of all markets toward globalization. This is testament to the industry's cognizance of national and international trends as well as its adaptability.

With economic growth in the 20th century coming largely from knowledge-generation, especially education and R&D, the chemical industry can be rated high, but not highest. For example, in the chemical industry, the before-tax contribution of R&D to future operating income is 26.6 percent. As a comparison, this is slightly lower than the software industry's 29.3 percent.

Despite this, the future does not portend great changes in chemical company R&D budgets, so one key to further productivity improvements could come from scalability. Any large industry surges will necessitate more ingenious use of current level R&D budgets, intensified efforts to attract new customers, and renewed initiative to form more alliances. However, Baruch Lev recommends modest increases of 15 to 20 percent in R&D budgets over a several year period. This is based on his findings that R&D returns are considerably higher than the chemical industry's cost of capital and should remain so in the future.

Collectively, the chemical industry is a strong second in the science linkage of its patents, just behind life sciences. Chemical patent science linkage has grown dramatically in the last five years, but the Technology Cycle Time of chemical patents has slowed from roughly eight years to ten years in the last decade. Also, the chemical patents' share of all U.S.-invented patents has fallen as other industries in the new economy, such as information technologies and life sciences, have come to the forefront.

For the most part, the chemical industry seems to be doing quite well, due in large part to consistent support of R&D. There is every indication that future progress and productivity gains in the chemical industry will be strongly connected to its ability to maintain a steadfast commitment to reliable R&D support. This has proven to be one of, if not the, most significant factors in the industry's productivity growth. This study is strong validation of the inherent value of research and development to continued growth of the industry.

In the larger picture for America, this study indicates that the nation has a strong and well-distributed science base. Public as well as private sector research contributes to industry's productivity gains. With this foundation, the domestic economy in general and the nation's core industries, including the chemical industry, are in a much stronger position to survive the rigors of future global economic development.

STUDY TEAM REPORTS

Introduction
by Ashish Arora

Technological Advance and Economic Growth

Measuring the payoff from investments in research is a difficult and challenging undertaking. This despite the widely held belief that it is precisely such investments that are responsible for a great deal, perhaps even the bulk, of economic growth. Vannevar Bush had earlier articulated the same thesis more boldly: “Basic research leads to new knowledge. It provides scientific capital. It creates the fund from which the practical applications of knowledge must be drawn. Today it is truer than ever that basic research is the pacemaker of technological progress” (Bush. 1945: 19).

Even critics of this bold assertion acknowledge that the creation of new knowledge is the basis for productivity increase and economic growth. Economists, notably Moses Abramovitz (1956) and Robert Solow (1957) provided a more formal and quantitative, albeit incomplete, scaffolding for the idea that economic growth derived from sustained increases in productivity. Using different approaches, these researchers showed that growth of material inputs, primarily capital and labor, accounted for only a small fraction of the growth in the national output of the U.S. Solow (1957) estimated that 80 percent of the growth in U.S. labor productivity—output per worker—between 1904 and 1949 was due to technical change. More precisely, 80 percent of this growth could not be accounted for by increases in the amount of capital per worker and was a “residual.” This residual was due to unknown causes: in Solow’s view, to technical progress, an interpretation Abramovitz agreed with, although he cautiously dubbed it “a measure of our ignorance.”

Research that followed tried to reduce the extent of our ignorance by measuring investments in R&D, and by developing better measures of the improvements in labor, capital, and other inputs. Introducing measures for input quality did reduce the “residual,” but a substantial portion of growth in total economic output remained unexplained. More recent theoretical literature (Romer 1986) has put technical change back at the heart of economic growth by recognizing that firms invest in R&D with an eye to the profits that such investments are expected to generate. Obtaining convincing empirical evidence has been more difficult, for reasons that I discuss in some detail below.

From Research to Economic Payoff

Reducing the extent of our ignorance has been a long, arduous, and highly incomplete journey for economists, historians, and other social scientists. There are many different sources of inputs into research and many different beneficiaries. The process through which knowledge is translated into useful goods and services and improved living standards is extraordinarily complex. It is cumulative, building on what is already known, and often there are long lags between the creation of new knowledge and its economic application.

R&D expenditures are the conventional way in which economists and others measure investments in R&D. However, research projects differ. The payoff from basic research, which aims to understand the fundamental nature of phenomena, is often realized in ways that are very different from research aimed at solving a concrete problem. The distinction between applied and basic research is not easy even for those involved, and well nigh impossible for outsiders.

Moreover, “diffusion” of knowledge takes time and requires complementary investments. For instance, the economic payoffs from the massive investments in information technology since the 1960s were two decades in the coming.[1] History teaches us that we ought not to have been surprised by the long lag. Paul David’s now justly famous paper on the long delays in the productivity benefits from the massive investments in electrification pointed out some of the reasons (David, 1990). For instance, technical breakthroughs in electrical generation and in electrical machinery had to await the substantial investments in an electricity network and grid.

Private and Social Payoffs, and Knowledge Spillovers

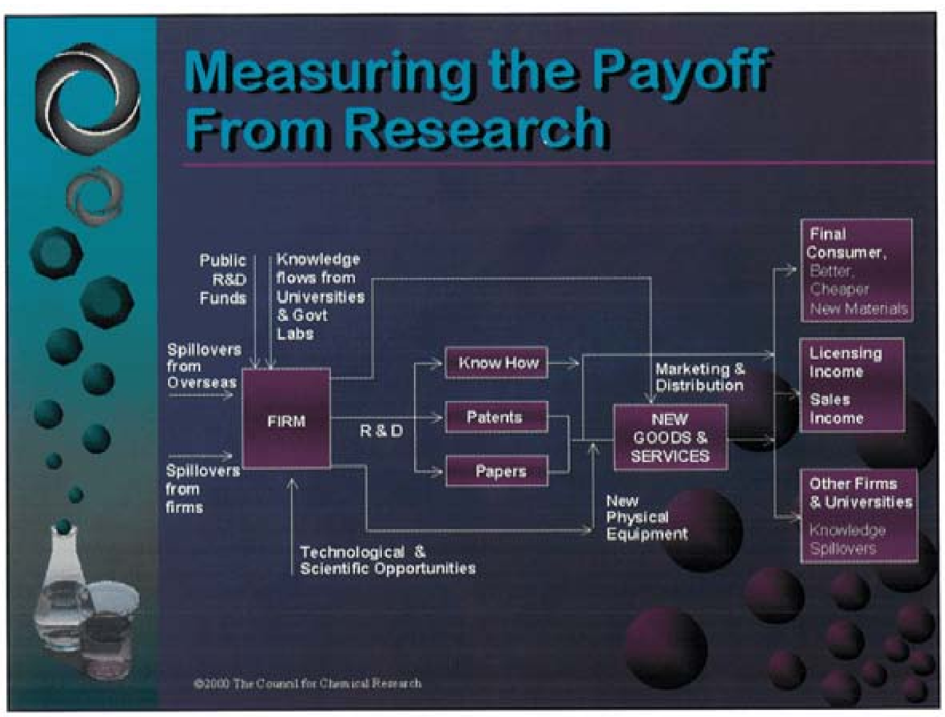
The important message from the historical record, therefore, is that measuring the payoff from research faces a number of challenges. The first challenge is immediate. Not only are there long lags between when the R&D investments are made and when the impacts are felt, but the length of these lags is unknown and may change over time and across contexts.[2] Moreover, the benefits may accrue over time, as properly befits an investment.

A thornier problem is that the payoffs accrue from the constellation of investments in new types of equipment, training for those using the equipment, and reorganizing the very way in which production is carried out. Parceling out the contribution of each is conceptually challenging. The challenge is even greater when these contributions are made by different actors.

Measuring the payoff from investments in a specific type of research—chemicals—is even more challenging. Moreover, it becomes important to specify whether we wish to measure the payoff to an individual firm or to society at large. These distinctions are important because in many cases the costs and benefits of investing in research are not confined to the entity that undertakes the research. Instead, they may spill over to others. The existence of these spillovers, discussed in some detail below, give rise to a number of issues relevant to the measurement of payoffs at a more disaggregate level.

There are three major types of spillovers, as shown in Slide 1. First are knowledge spillovers. Research as an economic activity is peculiar in that some of the input and output are similar, i.e. knowledge. When a firm invests in R&D it is also using knowledge that has been produced by others: universities, government labs, and so on. There is no direct recompense for this use. The point is particularly compelling for what Francis Narin and Michael Albert call public science in their section. Members of a scientific community at universities and even in corporate labs are expected to disseminate their findings to the community at large by publishing their research. Others are then free to draw upon these with no recompense other than an acknowledgement through citation.[3]

Such open and free disclosure is believed to be the most efficient way of facilitating the effective application of knowledge for the greater good. It does, however, considerably complicate the matter of measuring the economic contribution of the R&D that a firm invests in because that R&D draws upon a much larger body of knowledge to which many others have contributed. Absent this recognition, the measured private returns are likely to be smaller than the social return in



Slide 1. Measuring the Payoff from Research.

the sense that some of the costs (e.g., investments in research) have not been made by the firm in question but by others.

By the same token, the knowledge created by the research project may be used not only by the firm that owns the lab but also by researchers elsewhere, be it in other firms or in government or university labs. Since the firm itself is unable to capture the full benefits of its own research, it follows that the social payoff is greater than the private one—the part that accrues to the firm investing in R&D. It seems plausible that these spillovers are the greatest for basic research. The existence of spillovers and the inability of firms to capture the full benefits of their investments in research has been the basic intellectual justification of the continued public support for research, particularly basic research.

In the 1980s, growing concerns about American industrial performance focused attention on spillovers across international borders. Simply put, some people argued that that the large U.S. investments in research were also benefiting other nations, most notably Japan. Examples such as color televisions and VCRs were put forward as evidence of the benefits of U.S. research investments spilling over to Japan. More recent research provides evidence that these spillovers are spatially limited, and Narin and Albert's analysis confirms this. They find that citations to the scientific literature are not merely disproportionately national; patents from inventors in one state of the U.S. are disproportionately likely to cite scientific publications from the same state. While this does not solve the problem that spillovers raise for measuring the payoff from research, it does suggest that one need not look too far to find the spillovers. These results should also soothe some of the more narrow, parochial concerns about the beneficiaries of U.S. public investments in science.

The second type of spillover arises because innovations are frequently part of a system, and advances in one part of the system create greater value when complemented by advances in other parts. The major advances in software technology would be of only limited value without the corresponding advances in hardware and processing power. Similarly, most of the major polymers, such as polyethylene, polypropylene, PVC, and polyester, would have been confined to niche applications without the tremendous improvements in refining and process technologies that allowed the costs of these products to drop to levels where they could substitute for cotton, steel, and wood. Conversely, the great advances in process technology would have been less valuable but for the development of new products that could generate the demand for these process technologies to be applied on a large scale. In other words, the system-wide returns on investment in research may be greater than the individual returns.

Finally, the private returns to firms from investments in research may understate the social payoff because some of the benefits are transferred to buyers. The extraordinary advances in chemical science and technology have been accompanied, in the post World War II period, by marked increases in the degree and intensity of competition (Arora and Gambardella, 1998). The competition has a global dimension as well. Taken together, the industrialized countries accounted for virtually all of the world chemical production in 1938 but only two thirds of it in 1993. The growth of chemical production in countries such as South Korea, China, India, Russia, and Saudi Arabia owes a great deal to the spread of chemical technology (Arora and Gambardella, 1998).

The increase in competition has meant that the benefits of chemical research have frequently been passed to,user industries (e.g. textiles, automobiles, construction, electronics, and consumer goods) and through them to the final consumer. This is, of course, what competition is supposed to do. The important point here is that the diffusion of chemical process and technology worldwide has meant that even firms on the cutting edge of technology have rarely been able to enjoy their exclusivity for too long without technically sophisticated competitors breathing down their neck.

Endnotes

[1] The long delay led Robert Solow to observe that he saw computers everywhere except in the productivity statistics.

[2] Baruch Lev addresses this to the extent feasible by including R&D investments in earlier years.

[3] Narin and Albert track this process using citations from patents to other patents, and to scientific publications. They show that the typical chemical patent by a U.S. inventor contains six references to scientific publications, indicating the extent to which advances in chemical technology draw on public science. Moreover, this measure has increased in recent years for U.S.-invented chemical patents but not for European- or Japanese-invented patents, suggesting that U.S. chemical technology is drawing more heavily on public science than is European or Japanese chemical technology. This is an intriguing finding which needs to be explored further.

Introduction to David Sicilia
by Ashish Arora

The complexity of measuring the payoff from chemical research has lead to a variety of approaches, three of which are reflected in the following Study Team Reports. Each of the principal investigators used a different methodology, capturing somewhat different dimensions of the contribution of chemical research.

David Sicilia provides historical background on the trends in U.S. chemical research since the late 19th century, when the industrial research labs were founded. He begins by discussing the contribution of technological innovation to aggregate economic growth, drawing upon the pioneering work of Robert Solow, Moses Abramovitz, and others. He points out that R&D investments are made by different actors in the economy, and discusses the trends in publicly financed and company financed R&D investments. He also places these trends in context by comparing them to trends in aggregate R&D spending and trends in production of chemicals and total manufacturing.

Evolving Patterns of American Chemical R&D
by David Sicilia

The chemical industry was the quintessential American enterprise of the 20th century. It exemplified the century's key business trends, most notably diversification, conglomeration, and the growing reliance on science-based technological developments. In the same way the railroad was perhaps the key industry of the 19th century, the chemical industry was the key industry of the 20th century.

This essay reviews 20th century R&D in the chemical industry, in the context of overall R&D for the nation. Funding and performance patterns are identified. The paper also discusses the methodological challenges to be surmounted when posing the central question: to what extent does chemical research and development contribute to rising productivity and economic growth?

Modern research and development, or institutionalized efforts to control the pace and direction of technological development, was born with the 20th century. Thomas Edison's labs at Menlo Park and West Orange are well known. Among the facilities at West Orange, there was a chemical R&D building where Edison tried to regularize the process of invention. He even dubbed this lab an "invention factory." Chemical companies were prominent among the pioneer firms in building U.S. R&D facilities. The chemical industry was highly represented from the beginning. (*See Slide 2.*)

While most of the motives and goals of these early firms were concerned with business competition, some also spoke to political and public relations concerns. These issues are also prominent today in funding and regulatory domains. Thus, R&D has always been a kind of politicized activity.

World War I was in many ways a chemists' war. Cut off from Germany, the leading producer of dyestuffs and pharmaceuticals, the United States was forced to rely more on its own resources to produce organic intermediates. The war pushed the nation and the chemical producers toward greater reliance on domestic R&D resources.

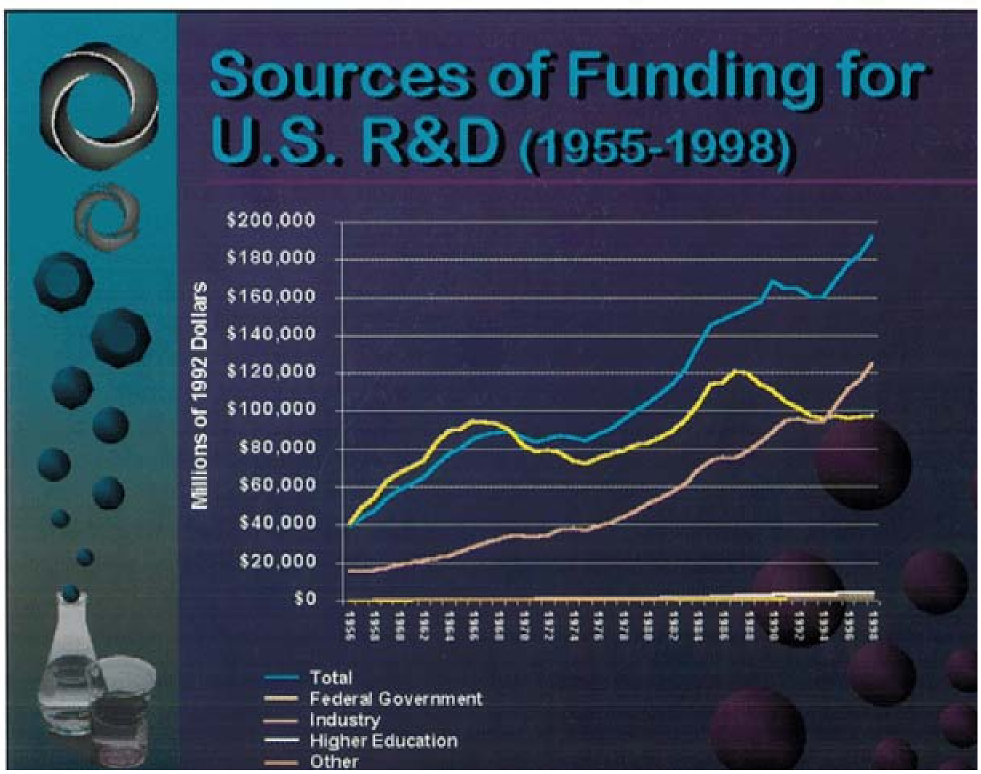
In the period between the two world wars, American R&D in general gained a firmer institutional footing with the permanent establishment of the National Research Council. Despite this, an effort by Secretary of Commerce Herbert Hoover to secure ongoing federal funding for pure research failed. Nevertheless, there was overall domestic growth in research. Twelve hundred new laboratories were established, both industrial and government. With this, the number of scientific researchers grew tenfold to 27,700.

The chemical industry was strongly represented in this expansion, and in spite of the Great Depression it turned out a vast array of new products including neoprene and polyester, which became hugely popular commercial products.

Chemists, physicists, and other scientists were lauded as saviors during World War II. With the strong urging of Franklin Roosevelt's science Czar Vannevar Bush, the federal government began to invest heavily in big science after World War II.

Much of this R&D spending was Cold War related. Billions of R&D dollars flowed to research universities and defense contractors with the dual expectation that tire resulting new technologies would not only help contain communism world-wide but would also produce positive spillover effects for the nonmilitary economy.

Slide 2: Origins of American R&D



Slide 3: Sources of Funding for U.S. R&D 1955-1998

Chemical companies followed the trends toward bigness, concentration, and fundamental research. Leading firms spent heavily on research in the hope of discovering the next great commercial success, such as nylon. Research was focused on looking for blockbuster products. Chemistry, chemical engineering, industrial chemistry, and related fields were high prestige, relatively well-paid fields at this time, and U.S. universities were hard-pressed to keep up with the robust demand for such professionals.

It is important to note that most national security-related R&D spending on the part of the federal government went into fields such as electrical and electronics equipment, aerospace, and nuclear energy. While large numbers of chemists were employed in those fields, the chemical sector as a whole did not benefit as much as several others from the federal government's heavy Cold War spending. In this sense, those other industries were given a Marshall Plan whereas the chemical industry was left to be more self-reliant.

The period following the first oil shock of 1973 ushered in volatility and increasing economic pressures for the U.S. economy and for its chemical enterprises. Foreign competitors, particularly in Germany and Japan, were investing heavily in R&D and expanding aggressively into U.S. and other foreign markets. Meanwhile, leading chemical firms had found that the costs associated with taking new products from the scientist's bench to commercial production were rising dramatically, as was the time required to do so. As a result, many companies began to buy rather than build new technologies. These acquisitions often took place in non-chemical fields so that when the chemical industry embraced the conglomerate trend, it usually met with disastrous results.

Later in this period, chemical enterprises adopted a more successful strategy of forging complementary linkages with each other and with leading research universities. The industry's performance in the global arena since the I970s has been impressive, with rapidly rising exports that have allowed it to maintain its world market share. Chemical industries have been one of the few so-called high tech industries that have actually held up well in the face of increasing global competition.

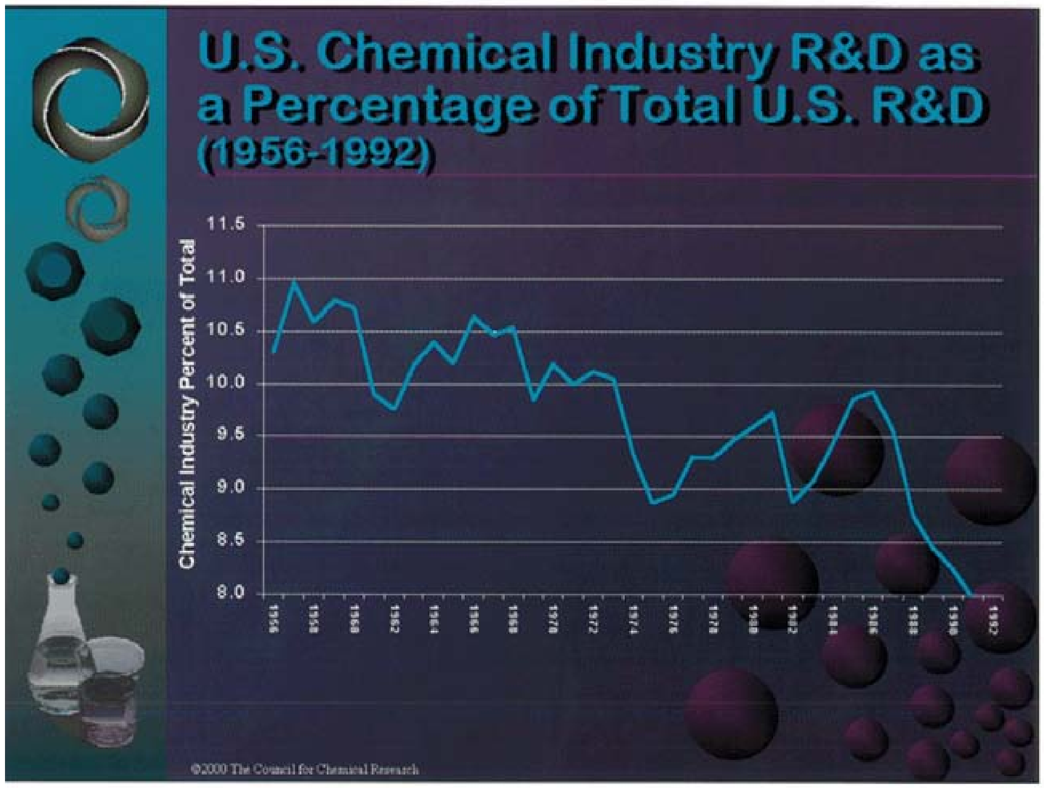
When looking at the national trend for R&D between 1955-1998, one can characterize federal funding as unpredictable or inconstant. (*See Slide 3*.)

This changeability in federal funding has had ripple effects in industry. By 1994, total U.S. industry spending on R&D surpassed that of the federal government. That gap continues to widen. It seems that the predictability of R&D funding is most significant to industry. Howard Stevenson of the Harvard Business School and others have shown that **industry performs best in stable revenue and regulatory environments**. Stevenson shows that it doesn't matter if taxes are high or low, or that Republicans or Democrats are in office. **Business has performed better when policy has changed slowly or remained stable over long periods of time, even if taxes are higher**. For industry, unpredictability is most injurious to long-term endeavors such as strategic planning and fundamental research.

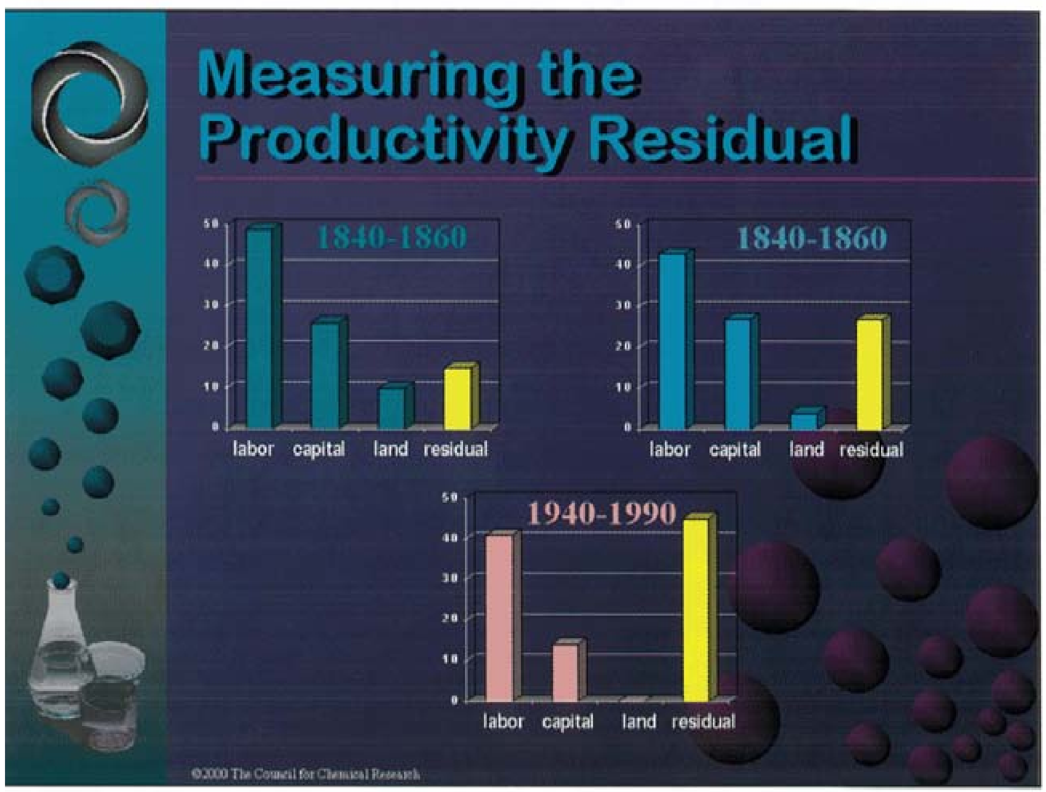
Another trend shows that the chemical industry's share of total U.S. R&D has fallen from 11 percent in 1956 to 8 percent in 1992, the last year the industry reported reasonably complete data to the NSF. (*See Slide 4*.) During this period the total volume of U.S. manufacturing grew threefold, but the total output of chemicals and allied products grew roughly fivefold. So while the industry was growing at a much more robust pace than the manufacturing sector as a whole, the percentage of its share of investment in R&D was decreasing. Historically, technological innovation has been a powerful engine of economic growth. This seems to pose a problem for the chemical industry.

Recognition of the important role R&D plays in productivity and economic growth has grown steadily. Beginning in the 1950s a small cadre of economists set about to measuring the factors responsible for economic growth. Robert Solow's pioneering work in 1957 found that technological innovation was contributing about 1.5 percent to economic growth. This may not sound significant, but it is almost as much as the economy was growing. Therefore it represented some 90 percent of the total gains in productivity. Five years later, Edward Dennison, using a more complex methodology that measured multiple inputs, estimated that technology was responsible for about 40 percent of U.S. economic growth.

The basic approach here was to take all the inputs—land, labor, and capital—and then measure and correlate them with the outputs in order to isolate the increases in productivity that cannot be explained by increasing inputs. Economists affectionately refer to this inexplicable gain as the "residual." The famous economic historian Moses Abramovitz once called the residual "a measure of our ignorance." In other words, it is inexpli-



Slide 4: U.S. Chemical Industry R&D as a Percentage of Total U.S R&D 1956-1992



Slide 5: Measuring the Productivity Residual

cable.

There is historical data which shows how important the residual is to the economy. (*See Slide 5*.) During the period of 1840 to 1860, the residual is insignificant while new labor, capital and land can explain growth and productivity. As we move to the period of 1870 to 1930, the residual grows. When the post-war period 1940 to 1990 is examined, the economy is much more productive. The residual has grown considerably. Economic historians are unified in their opinion that the 20th century's economic growth came largely through the addition of increases in knowledge capital: particularly education and research and development. These are major components of the residual.

Among the challenges to this kind of work, one of the most important is the failure to quantify changes in quality. For example, in the field of television, there is a great increase in quality over the last few decades while the price has not increased significantly in constant dollars. However, this scrutiny focuses on the actual product and does not include the quality of programming. Such studies measure only what it costs to produce an item and what it sells for without factoring in the dramatic qualitative change. The mysterious attributes of these distinctions cause some to rename the residual the "black box." The inputs are entering in one side, something happens in the way that they combine, and the outputs emerge at a higher rate. Our challenge is to demystify and quantify the components of the black box.

Introduction to David Aboody and Baruch Lev by Ashish Arora

Baruch Lev's objective is to measure the private rate of return on R&D. He is not really concerned with measuring the social payoff to investments in R&D: instead, his focus is squarely on what private returns chemical firms are able to capture from their own R&D investments. His methodology is widely accepted in economics and allied fields, where controlled experiments are not possible. The hypothetical experiment that the methodology tries to capture is one of measuring the additional income generated by a given increase in R&D spending. In practice this implies correlating variations in income to variations across firms in R&D spending. This is easier said than done because of course firms differ from one another (most notably in terms of physical capital and other assets). Lev uses an econometric model, with operating income as the output (measure of the payoff), and investments in physical capital and R&D as the inputs.

In addition to the analysis using all firms in the sample, Lev conducts separate analyses for firms with different levels of R&D intensity. This is important since firms may face different market conditions and may operate in segments with different levels of technical opportunity. To account for the lags between investments in research and the economic payoff, Lev's econometric approach allows for several years of past R&D expenditures to also have an impact on current period payoffs.

It is worth emphasizing that the payoff to R&D here is the private payoff to private R&D investments. R&D investments by a firm may benefit others, including rivals, customers, and suppliers. These benefits may be embodied in better and cheaper goods and services, as well as new and useful knowledge. On the other hand, R&D investments by a firm also benefit from such investments made by others in the past, and benefit from the stock of knowledge created by publicly funded research at universities and elsewhere.

R&D Productivity in the Chemical industry

by David Aboody and Baruch Lev

I. Origins of the Study

The chemical Industry is among the largest and most prominent economic sectors in the U.S. and in several other developed countries. Chemical production amounts to about 2 percent of annual U.S. GDP and 11 percent of the total product of all manufacturing companies. Chemical companies employ close to 1.5 million people in the U.S., and as a group are the largest exporter, generating over 10 percent of all U.S. exports.[1] These few statistical highlights, chosen from amongst many, demonstrate the central economic and social roles played by chemical companies.

The prowess of the chemical industry has been in a large measure driven by research and development conducted by corporations, universities and national laboratories. The industry currently produces more than 70,000 different chemical substances, generated by over a century of intensive R&D effort.[2] In fact, the chemical industry was the first to establish formal industrial R&D laboratories in the late 19th century. A staggering number of path-breaking innovations emerged during the 20th century from chemical laboratories: plastics, PVC, polyethylene, corfam (synthetic leather), Lycra, polyester, silicone oxide, liquid crystal, and quartz crystal, among others.[3] In addition to fostering chemical innovations, chemical R&D provided much of the scientific and industrial foundations in such diverse sectors as agriculture, transportation, housing, communications, pharmaceutics, and biochemistry. A relentless pace of innovation has been the outcome of chemical R&D.

So far so good: the chemical industry is undoubtedly very **large** (e.g., global chemical production exceeded in 1998 $1.5 trillion[4]), **pervasive** (involved in almost every aspect of life and commerce), and highly **innovative** (due to persistent and successful R&D activities). However, economic history teaches us that complacency often causes the demise of success. Innovative companies (e.g., IBM in the 1960s and 1970s) tend to rest on their laurels, after a successful innovation period. Temporary setbacks, such as currently experienced by genetically-engineered crop developers, often lead to disillusionment of investors and managers with radically new research and development. Furthermore, since R&D outlays are fully charged (expensed) against earnings, it's hard for managers to resist the temptation (particularly during hard times) to slow the growth of investment in innovation in order to meet short-term earnings targets.

Indeed, evidence suggests the presence of a certain complacency, and perhaps even disillusionment, with investment in innovation in the chemical industry. For example, over the 10-year period 1989-1998, the R&D spending of the major chemical companies stagnated at an annual level of $3.25 billion, while the R&D spending of the major pharmaceutical companies, for example, increased at an average annual rate of 22 percent per year (from $3.35 billion in 1989 to $10.08 billion in 1998[5]). The total number of utility patents issued annually to the major chemical companies in fact decreased from 2,942 in 1989 to 2,722 in 1998, while the patent activity of the major pharmaceutical companies has increased from 800 in 1989 to 1,115 in 1998.[6] Similarly, while the number of R&D scientists and engineers in the chemical industry increased by 14 percent during 1989-1998 (from 78,300 to 89,500), the corresponding increase in the drug industry was 32 percent (from 34,400 to 45,300).[7]

The apparent slowing of investment in innovation by chemical companies during the 1990s—a period of unprecedented innovation and growth in the U.S.—is clearly reflected by the volume of "Intangible Capital," or intellectual assets, of these companies. As elaborated in Section II below, in terms of intangible capital, the chemical industry ranks roughly in the middle of all major industries, lagging behind such innovative sectors as electronics, software, pharmaceutics, and even oil and gas.

This situation raises various intriguing and important questions for chemical manufacturers, their partners in innovation—universities and national laboratories—and given the pervasiveness of the chemical industry, for the U.S. and global economy as well.

■ What is the productivity (return on investment) of chemical R&D?

A slow growth investment in R&D, currently characterizing the chemical industry, is an appropriate policy when the return on R&D is close to the firm's cost of capital. If, on the other hand, the return on R&D is substantially higher than the cost of capital, a low growth policy is detrimental to corporate and shareholder value growth, reflecting misallocation of corporate and investor resources. Assessment of the return on chemical R&D is, therefore, crucial for optimal resource allocation at both the corporate and national levels.

■ Are all forms of R&D born equal?

The chemical industry is very heterogenous: products can be broadly classified into **commodity** and **specialty** chemicals; and further into basic chemicals, organic chemicals, plastics, and fertilizers. The nature of R&D conducted by chemical companies can be categorized into product development, process (R&D aimed at enhancing production efficiency), and customer support (R&D aimed at addressing specific customer's problems). It stands to reason that the productivity of chemical R&D varies by product and type of research. It is, therefore, important to penetrate the "R&D black box" and estimate the productivity of different types of R&D, in order to assist and direct the allocation of resources, as well as the research at universities and national laboratories.

■ What are the drivers of successful chemical R&D?

The previous two questions dealt with the primary **outcome** of the R&D process—return on investment, in R&D. If one wants to **change** the outcome (e.g., enhance R&D productivity), a thorough understanding of the drivers (causal factors) of R&D and the value linkages (e.g., the effect on R&D productivity of an increase in the number and quality of scientists) is required. Accordingly, it's of major importance to identify the central drivers of R&D and quantify the cost-benefit linkages. Optimal allocation of corporate and national resources hinges on a thorough understanding of R&D drivers and their impact on innovation and growth.

■ Lastly, what are the externalities (spillovers) of chemical R&D?

Case studies and anecdotal evidence indicate that chemical R&D historically had and continues to have considerable "positive externalities": contributions to the scientific and technological development of other industries, such as pharmaceutics, biotech, transportation, agriculture, semiconductors, food, and apparel. A comprehensive assessment of the contribution of chemical R&D (return on investment) must therefore extend beyond the measurement of R&D contribution to the productivity of **chemical companies** to encompass the contribution of chemical R&D to other industrial sectors and society at large (the social return on chemical R&D).

The Council for Chemical Research embarked in 1999 on an ambitious research program aimed at addressing empirically the aforementioned questions. Given the complexity of the issues and the size as well as heterogeneity of the chemical industry, such an investigation is obviously a multi-phase, multi-year endeavor. The study reported below constitutes the first phase of the investigation—an empirical assessment of the **overall** productivity of chemical R&D—addressing the first of the four questions posed above.

The following section (II) provides a bird's-eye view of the knowledge (intangible) capital generated by the chemical industry, relative to other major economic sectors. Section III elaborates on the sample of chemical companies used in this study and Section IV discusses the statistical methodologies underlying the study. Section V presents the major findings, while Section VI provides further results, based on partitioning of the sample companies. Section VII presents concluding remarks and charts the course of future research on chemical R&D.

II. Intangible Capital

Corporate wealth and growth is generated by the deployment of **physical** (property, plant & equipment, inventory, etc.), **financial** (working capital, equities, bonds), and **intangible** (patents, brands, human resources) capital. During the last 20-30 years, much of corporate growth was generated by intangible assets, particularly in the developed economies.[8] Intangible assets can be broadly classified into those related to **discovery** and **innovation** (e.g., new products, patents), **human resources** (e.g., specific compensation and work practices enhancing employee productivity), and **organizational capital**. The latter intangibles are unique organizational designs, such as Cisco's web-based product installation and maintenance system, Wal-Mart's integrated inventory and supply operations, and Dell's built-to-order computer distribution channels, which create considerable and sustained value. For example, Cisco's web-based product installation system was estimated by its CFO to save $1.5 billion in three years.[9]

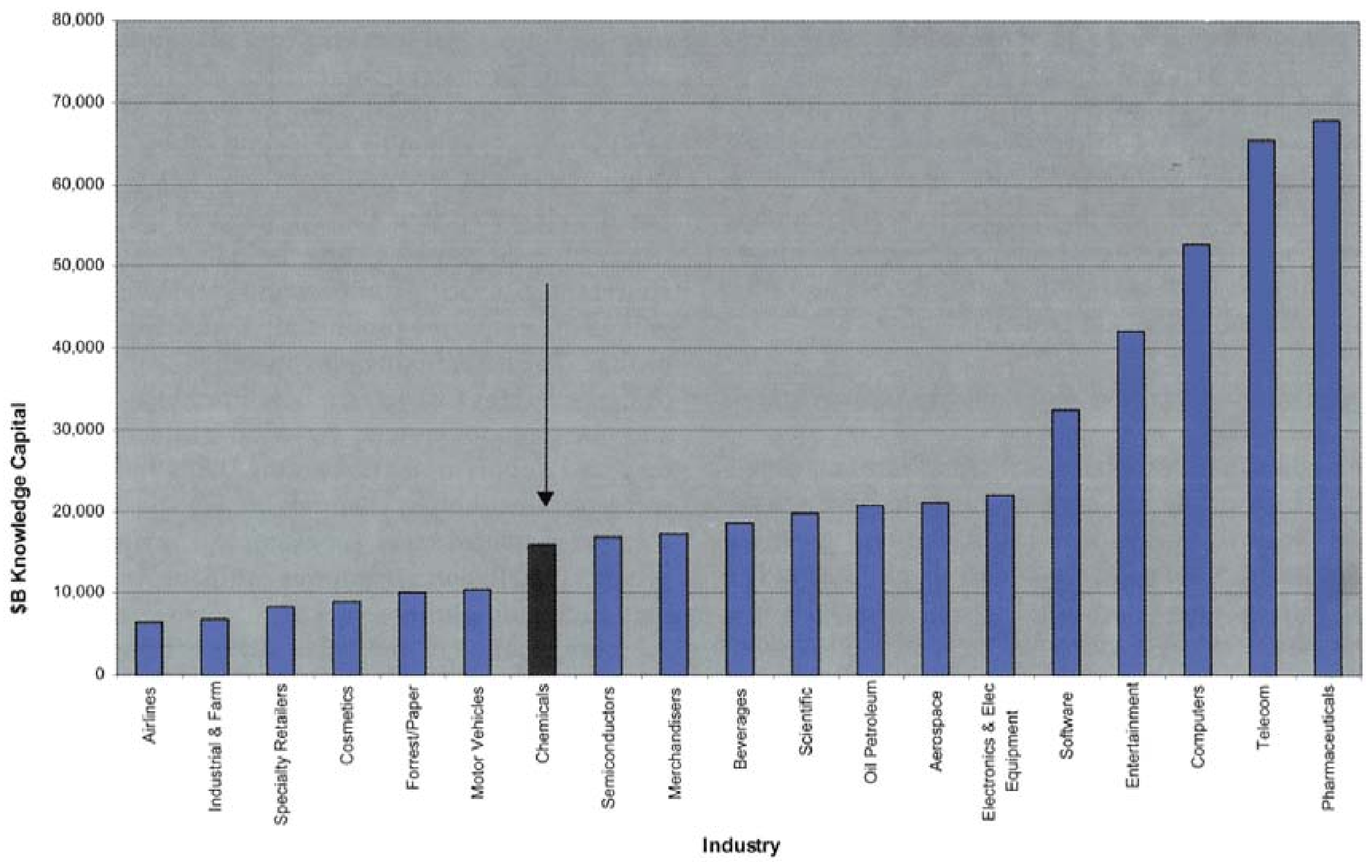
The valuation of intangible assets is complicated, in part due to the nature of these assets (high risk, not traded in organized markets, often associated with incomplete property rights), and in part due to archaic accounting rules which deny them the status of assets presented on corporate balance sheet. However, one of the authors of this study has recently developed a methodology to estimate the value of corporate intangible assets and the earnings derived from these assets.[10]

In essence, this methodology estimates a company's intangible capital by a multi-stage process: (a) the company's **annual performance** is estimated as a function of both historical and expected (growth potential) core earnings (expected earnings are derived from the consensus forecasts of the financial analysts following the company); (b) a "normal return" on the physical and financial assets of the company (stated on its balance sheet) is subtracted from the estimated annual performance (previous stage), to yield the part of the company's performance contributed by the third asset category—intangible capital (this residual performance is termed "intangibles-driven earnings"); and (c) the future stream of these earnings is capitalized (i.e., the present value of the stream is computed) to yield an estimate of the company's **intangible capital**.

The value of intangibles-driven earnings is thus derived from a "production function" which relates a company's performance to the three major asset groups generating this performance—physical, financial and intangible assets. The only unknown in this equation (the residual) is the value of intangible capital. The other values are either given (physical and financial assets) or estimated (company's performance, and the normal returns on physical and financial assets). The value of intangibles-driven earnings is thus derived as a residual, after "physical and financial earnings" are subtracted from the total performance of the company.

Extensive empirical examination (Gu and Lev, 2001) has established that intangibles-driven earnings are more strongly correlated with changes in corporate market values (stock returns) than widely used performance measures, such as corporate earnings and cash flows. Strength of correlation with value changes is a commonly used indicator of the informativeness of a performance measure or other signals (e.g., a corporate acquisition announcement). Furthermore, the estimated value of intangible capital—the major missing asset from corporate balance sheets—when combined with book value

Figure I.
Intangible Capital: Industry Medians (1998)



(the balance sheet value of net assets), provides an effective yardstick for the estimation of corporate value and predicting future stock performance (Gu and Lev, 2001).

Figure 1 presents median values of intangible capital (for the year 1998) for 19 industries, derived from the 1998 CFO magazine's ranking. Each industry is represented by the five largest public companies operating in the industry. There are three distinct groups of industries in Figure 1: Those with intangible capital per company below $10 billion (e.g., airlines, specialty retail, forest/paper, motor vehicles), those with intangible capital between $10 and $20 billion (semiconductors, scientific instruments, oil & gas, aerospace), and the third group—industries with intangibles values per firm exceeding $20 billion (software, entertainment, computers, telecom, and the highest—pharmaceutics).

The chemical industry is, as evident from Figure 1, situated in the middle group—median intangible capital per firm of roughly $16 billion, with large variability within the industry.[11] A sample of some leading chemical companies' intangible capital (in 1998) is: Dupont—$41B, Monsanto—$22B, Dow—$16B, PPG Industries—$9B, and Union Carbide—$4B,

A different perspective of intangibles' value and contribution is provided in Figure 2 (derived from Gu and Lev, 2001), which portrays the **growth** rate of intangibles-driven earnings, by industry, over the 1990s. This figure is based on a much larger sample than Figure 1—roughly 2,000 public companies (Figure 1 is based on 100 companies). We can once more classify the industries in Figure 2 into three classes: Low growth rate of intangibles earnings (0-10 percent annual growth), medium growth rate (11-15 percent annual growth), and high growth rate (16 and higher percent annual growth). As indicated in Figure 2, the chemical industry is at the high end of the low growth group, with 8.2 percent annual growth rate. Also in this group are oil and gas companies (9.9 percent), insurance (8.3 percent), and primary metals (3.7 percent). In the intermediate group we find drugs (13.7 percent), medical instruments (13.1 percent), and telephone communication (12.2 percent). The high intangibles earnings growth group includes special machinery (24.3 percent), computers (19.4 percent), and software (17.6 percent).

Summarizing, the message emerging from the intangible measures presented in Figures 1 and 2 is that the intangible capital of chemical companies ranks at about the median (mid-point) of nonfinancial industries (Figure 1). However, in terms of **growth** in the contribution of intangible assets to overall corporate performance over the 1990s, chemical companies reside among the low rate of growth group (Figure 2). The latter finding is consistent with (perhaps, the outcome of) the slow growth during the 1990s in the investment in innovation by the chemical industry, noted in the preceding section.

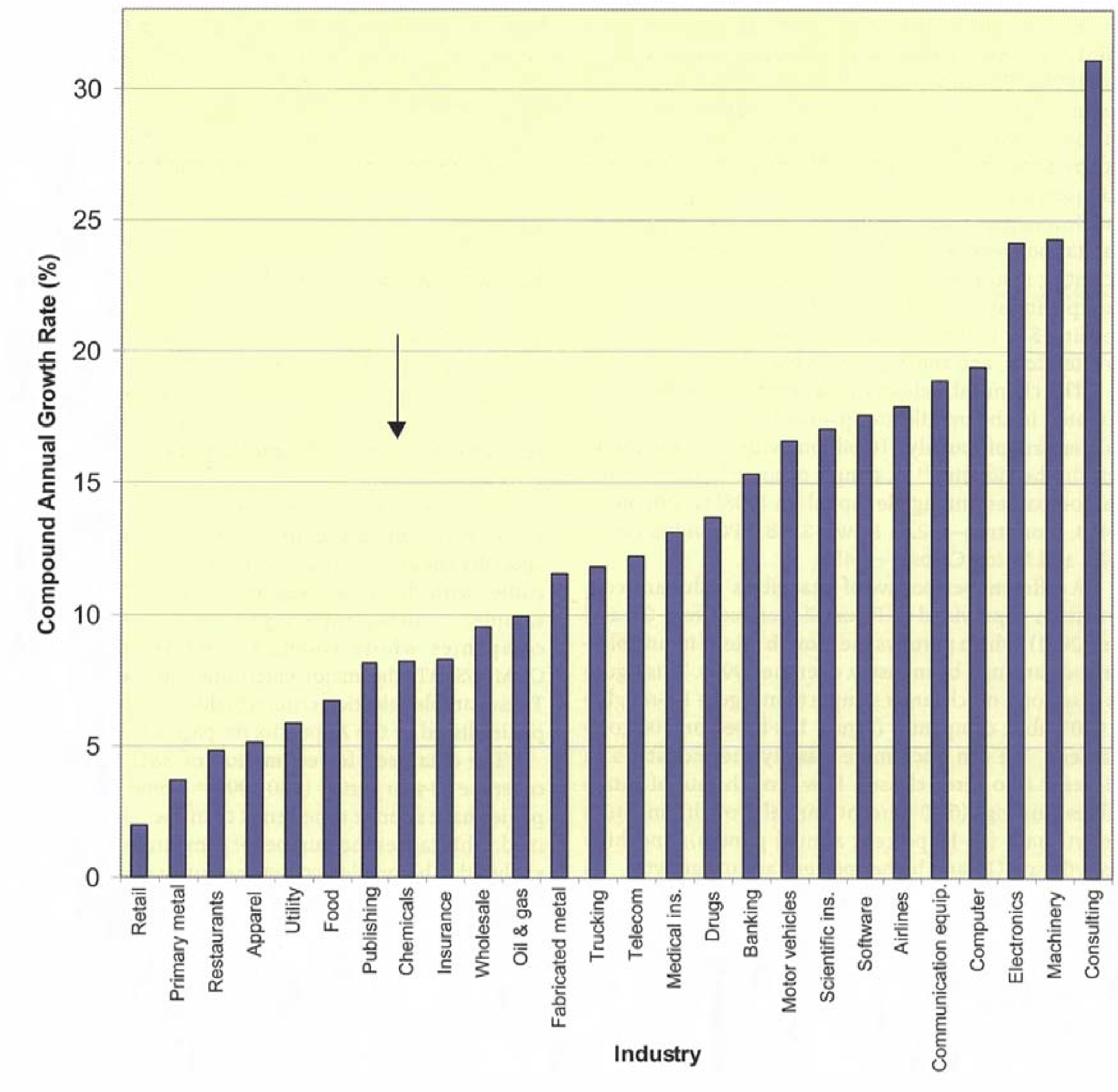
Intangibles earnings and capital are driven, in part, by investment in R&D.[12] We accordingly proceed in the following sections to analyze the return on chemical R&D.

III. Sample Characteristics

The sample of companies whose data were used in this study to estimate the productivity of chemical R&D was carefully chosen to represent the broadest cross-section of chemical companies. To secure data availability, we restricted the sample to **publicly traded** companies, since these enterprises publish annually audited financial statements. We further restricted our sample to companies whose **main activity** involves commodity and/or specialty chemicals. Thus, for example, oil and gas companies with chemical divisions are not included in our sample.[13] Finally, the sample had to be restricted to companies whose financial data are included in COMPUSTAT, the major electronic database we used. These sample selection criteria yielded 83 chemical companies listed in the Appendix on page 32.

The data used for estimation of R&D productivity cover the 20-year period 1980-1999.[14] Some sample companies have shorter time series than the 20 years examined. This causes the number of companies in each year analyzed to be smaller, sometimes substantially so, than 83. Table 1 provides summary statistics characterizing our sample. The next to left column in the top panel of Table 1 indicates that the average **R&D intensity** (the ratio of annual R&D expenditures to sales) of the sample companies increased from 2.47 percent in 1980 to 4.70 percent in 1999, a robust increase.[15] However, compared with other economic sectors, the overall R&D investment of chemical companies is less impressive. While the average R&D intensity of chemical companies in 1999 was 4.70 percent (Table 1), the avenge R&D intensity of other sectors were: pharmaceutics–12.14 percent, software–11.06 percent, computers–9.16 percent, and oil and gas–3.02 percent. The average R&D intensity of all U.S. public companies having R&D operations was 4.84

Figure 2
Average Growth Rate of Intangibles-Driven earnings 1990-1998



percent in 1900.[16]

The bottom panel of Table 1 breaks the sample to large and small firms—above or below the sample median of market capitalization. It is evident that the R&D intensity of large companies (4.86 percent in 1999) is higher than that of small companies (2.75 percent in 1999), as was the rate of growth of R&D intensity over the sample period (1980-1999). While the ratio of R&D to sales in the chemical industry is modest relative to some other R&D intensive sectors, the ratio of R&D to operating earnings (third column from left) is quite high: 56.7 percent in 1999 for the whole sample, and 46.7 percent for small companies. This high ratio of R&D to operating earnings (i.e., earnings before finance and tax expenses), which of course is even higher relative to net earnings, indicates the existence of a serious constraint on substantial increases in R&D budgets. Stated differently, earnings (profits) of chemical companies are quite sensitive to R&D expenditures, an issue which must weigh heavily on chemical executives.

The right column in the top panel of Table 1 (RDCAP/BV) provides an indication of the value of R&D relative to other corporate investments. RDCAP (from R&D capitalized), represents the value of corporate R&D investment if the annual R&D expenditures were capitalized (i.e., treated as an asset, rather than a regular expense), and then amortized annually according to the economic amortization rates generated by our estimation procedure (Table 2). The data in Table 1 indicate that if R&D were treated as an asset, it would have constituted, on average, in 1999, 33.9 percent of book value (the net value of physical and financial assets, as stated on corporate balance sheets).[17]

Summarizing, the average R&D intensity of chemical companies has increased over the last quarter century, yet in the late 1990s it stands slightly below the

Table I
Sample Summary Statistics

	Annual R&D expenditures as percent of:				
Year	Sales	Operating Earnings	Dividends	BV	RDCAP / BV
1980	2.47	47.1	115.4	6.00	14.9
1985	3.26	109.0	146.3	8.06	21.4
1990	3.56	67.7	141.7	9.45	24.7
1995	3.20	42.5	97.3	8.90	27.6
1999	4.70	56.7	312.3	13.5	33.9

	Large firms				Small firms			
Year	Sales	Operating Earnings	Dividends	BV	Sales	Operating Earnings	Dividends	BV
1980	2.47	49.8	117.5	6.01	2.42	30.4	97.9	5.86
1985	3.31	117.1	150.8	8.21	2.63	56.9	100.9	6.34
1990	3.63	68.9	143.7	9.57	2.73	51.9	114.4	7.78
1995	3.24	41.9	94.8	8.96	2.75	52.6	148.8	8.12
1999	4.86	57.2	324.3	14.2	2.75	46.7	173.1	6.50

U.S. average, and below that of several R&D intensive sectors. While low in intensity, R&D expenditures constitute about 57 percent of the operating earnings of chemical companies, and an even higher percentage of net earnings—a serious constraint concerning significant increases in R&D budgets, unless such R&D promises a reasonably quick return on investment.

IV. Statistical Methodology[18]

The Model

Our estimation of R&D productivity is derived from a "production function," reflecting the fundamental relation between the value of corporate assets and the earnings, or operating income generated by them. Accordingly, we define the operating income (OI_{it}) of firm i in year t, as a function of tangible, TA_{it}, and intangible assets, IA_{it}, where the latter includes the R&D capital:

$$OI_{it} = g(TA_{it}, IA_{it}). \qquad (1)$$

While the values of operating income and tangible assets (at historical costs) are reported in financial statements, the intangible capital, IA, is not reported and therefore has to be estimated.

Given our focus on R&D, we single it out of all intangible assets and define its value, RDC_{it}, as the sum of the *unamortized* past R&D expenditures. Those are the expenditures that are expected to generate current and future income:

$$RDC_{it} = \sum_k \alpha_{ik} RD_{i,t-k}, \qquad (2)$$

where α_{ik} is the contribution of a dollar R&D expenditure in year $t - k$ ($k = 0, \ldots, N$) to subsequent earnings (i.e., the proportion of the R&D expenditure in year $t - k$ that is still productive in year t). Substituting expression (2) into (1) yields:

$$OI_{it} = g(TA_{it}, \sum_k \alpha_{ik} RD_{i,t-k}, OIA_{it}), \qquad (3)$$

where OIA_{it} are other (than R&D) intangible assets (e.g., brand values).

The variables in relation (3) are defined thus. Operating income, OI_{it}, is measured as reported operating income (sales minus cost of sales) before depreciation and the expensing of R&D and advertising. Operating income is used as a measure of R&D benefits, since R&D investment and its consequences seem largely unrelated to nonoperating items, such as administrative expenses and financing charges. Depreciation, R&D, and advertising expenses were excluded from (added back to) operating income since they represent largely ad hoc write-offs of the independent variables in (3)—tangible and intangible assets.

Tangible assets, TA_{it}, in (3), consist of all assets reported on the balance sheet, including, among others, plant and equipment and inventories. The major intangible asset, R&D capital, is represented here by the "lag structure" of annual R&D expenditures, expression (2), where R&D expenditures stretch over the preceding nine years. Advertising expenditures on product promotion and brand development may create an additional intangible asset for some sample firms. This may raise an omitted variable problem in expression (3), if R&D capital were the only intangible asset included. Conceptually, advertising capital can be estimated from its lag structure (current and previous expenditures), similarly to the procedure applied to R&D (expression 2). However, inspection of our data source revealed that annual advertising expenditures were occasionally missing for many sample firms, straining the requirement for reasonable length of lag structure for reliable estimation. We therefore employed a procedure frequently used by economists (e.g., Hall, 1993), in which the advertising intensity (advertising expenses over sales) is substituted for advertising capital. Empirical evidence (e.g., Bublitz and Ettredge, 1989; Hall, 1993), indicated that, in contrast to R&D, the effect of advertising expenditures on subsequent earnings is short-lived, typically one to two years only. Accordingly, an advertising proxy based on annual expenditures may account reasonably well for the brand value in expression (3).

The following model (4) is used to estimate the returns on R&D, by means of least squares regression. The variables are scaled (divided) by sales to mitigate the econometric problem of heteroscedasticity, due to different sizes of sample companies. We also use the Almon lag procedure (for details see Johnston, 1984), to alleviate the multicolinerity problem due to the relative stability of firms' R&D expenditures over time. The estimated model is:

$$(OI/S)_{it} = \alpha_0 + \alpha_1 (TA/S)_{i,t-1} + \sum_k \alpha_{2,k} (RD/S)_{i,t-k} + \alpha_3 (AD/S)_{i,t-1} + e_{it}, \qquad (4)$$

where:

OI = annual operating income, before depreciation, advertising and R&D expenses, of firm *i* in year *t*,

S = annual sales in *t*,

TA = the balance sheet value of total assets at year *t*,

RD = annual R&D expenditures in *t*,

AD = annual advertising expense in *t*.

Intuitive Interpretation

Following is an intuitive, nontechnical interpretation of the estimation model (4) and its parameters. We assume that the productivity of a company's R&D expenditures is manifested by the contribution of these expenditures to current and future (up to eight years) operating income. This underlies model (4), where operating income in a given year is related to (a function of) the firm's R&D expenditures in that year as well as R&D expenditures in each of the preceding eight years. The nine R&D coefficients to be estimated by our econometric technique, $\alpha_{2,k}$ reflect the **contribution** to current operating income of each vintage of R&D expenditures. Thus, for example, an $\alpha_{2,0}$ of 0.372 (Table 2) indicates that a dollar R&D spent in the current year (year 0) increases current operating income by $0.372. Similarly, an estimated value of $\alpha_{2,4}$ of 0.206 (Table 2) indicates that a dollar R&D spent four years ago increases current operating income by $0.206.

Once we have estimated the contribution to income of each vintage of R&D (we examine nine annual vintages), we can estimate the **total contribution** of a dollar R&D to current and future income by adding up the annual contributions. From the yearly contributions we derive, as will be seen in the next section, the rate of return on R&D investment.

Back to model (4) above. R&D is, of course, not the sole contributor to chemical companies' operating income. Physical assets and advertising (promotion, brands) contribute as well. Accordingly, we include in the estimation model (4) the values of assets (*TA*/*S*) and advertising (*AD*/*S*), to enable us to focus on the **incremental contribution** of R&D to a firm's profitability. Stated differently, in estimating the contribution of R&D to profitability, we **control for** the contribution of other productive factors to profitability.

The parameters (contribution to profitability) in model (4)—the various α coefficients in the equation—are estimated by the widely used **regression technique** applied to our sample. Recall that we have 83 companies in the sample, and a maximum of 20 years of data for each company.[19] Thus, for example, one data point in the sample will be Du Pont's operating income (*OI*) in 1995. This value is accompanied by DuPont's total assets (*TA*) at the beginning of 1995, its advertising expenditures (*AD*) in 1995, as well as the series of nine annual R&D expenditures of DuPont, starting with 1995 and going back to 1987. Each company in the sample has 20 similar annual data sets (some companies have less than 20 data sets).

For those not versed in econometrics, we would like to emphasize that we don't introduce **any judgmental** factors into the estimation, beyond the underlying assumptions (e.g., that operating income is generated by tangible and intangible assets). In other words, we don't estimate **subjectively** the contribution of R&D to income. Rather, we let the data (our sample) "speak for itself." The estimated coefficients (contributions to income), to be reported in the next section, are the results of statistically estimating the fundamental model (4) from our sample data.

Finally, the important issue of **causality**. So far, we have interpreted model (4) in a strictly causal manner—from R&D to income. R&D expenditures (and other assets) were assumed to contribute to current and future income. The fact that assets contribute to profits is undisputed, but a simultaneous **reverse causation** cannot be ruled out A decrease in current or expected profitability (due, say, to sharp increases in energy prices, or the onset of an economic recession) will undoubtedly have a dampening effect on firms' willingness to invest in R&D. To allow for such **simultaneity** (from R&D to income and from expected income to R&D), it is possible to employ a statistical technique known as simultaneous equations. However, the experience of one of the authors with this technique applied to a similar assessment of R&D contribution to earnings (Lev and Sougiannis, 1996) indicated that it did not yield significantly different results than those estimated by model (4) using ordinary least squares regression. Accordingly, at this phase I of the project we did not use simultaneous equations to estimate return on R&D.

V. The Estimated Return on R&D

Table 2 presents the main findings of this study. It reports the results of estimating the coefficients (α) of model (4) which relates operating income to tangible assets, advertising expenses, and the series of current and past R&D expenditures. Model (4) was estimated separately for every year, 1980-1999, and the coefficients reported in Table 2 are averages of the yearly estimated coefficients. Following is a detailed interpretation of the estimates reported in Table 2. We will focus first on the middle column of the table—Chemical companies. The right column—estimates for software companies—is presented for comparison purposes.

The Return on Physical and Advertising Capital

The estimated coefficient, 0.070, presented at the top of Table 2, indicates that a dollar of total assets of chemical companies contributes, on average, $0.070 annually to operating income.[20] This 7 percent estimated annual return on assets is close to the weighted average (equity and debt) cost of capital of chemical companies. A recent estimate of the cost of **equity** capital of chemical companies (Fama and French, 1998) indicated a rate of 10.28 percent. Since the cost of debt is lower than the cost of equity, the weighted average cost of capital of chemical companies is reasonably close to 7–8 percent. Thus, balance sheet assets in the chemical industry earn, according to our estimates, approximately the cost of capital.

This is an important finding, suggesting that, on average, physical assets of chemical companies do not contribute substantially to new value creation. **New value** is created, or **corporate growth** generated, only if the assets employed yield a return which is consistently higher than the cost of capital.[21] The reason that physical assets yield the cost of capital, and are not major contributors to growth and shareholder value, is that these assets are essentially **commodities**. Dow's plant and machinery are by and large equivalent in productivity to DuPont's. Every major producer tends to employ state-of-the-art equipment, and to use such equipment at maximum efficiency, hence no unusual competitive advantage (growth opportunities) are conferred by these assets. The commoditization of physical assets is generally corroborated by our estimates. This finding has, of course, important implications for managers' expec-

Table 2
Estimates of R&D Productivity
(from the Production Function – Model 4)

Input	Contribution to operating income: **Chemicals**	Contribution to operating income: **Software**
Physical assets (α_1)	0.070	
Advertising (α_3)	0.062	
R&D:		
Current year ($\alpha_{2,0}$)	0.372	0.643
Preceding (year - 1) ($\alpha_{2,1}$)	0.439	0.434
Year-2 ($\alpha_{2,2}$)	0.407	0.284
Year-3 ($\alpha_{2,3}$)	0.316	0.180
Year-4 ($\alpha_{2,4}$)	0.206	0.110
Year-5 ($\alpha_{2,5}$)	0.116	0.063
Year-6 ($\alpha_{2,6}$)	0.085	0.025
Total R&D contribution	1.941	1.739
Return on R&D	**26.6%**	**29.3**

tations from further significant investment in physical assets.

The estimated return on advertising, 0.062 (second coefficient in Table 2), appears slightly below the cost of capital. We caution against drawing far-reaching inferences from this estimate, since the reporting of advertising expenditures by chemical companies is incomplete (e.g., some companies lump this item with administrative expenses), and the content of this item is probably inconsistent across companies. In any case, advertising (brand building) is not a particularly important activity for some major chemical sectors (e.g., commodity chemicals).

The Return on R&D—the Focus of Analysis

The seven R&D coefficients presented in the middle column of Table 2 (starting with 0.372 and ending with 0.085) represent the estimated contributions of a dollar invested in R&D to current and subsequent operating income.[22] Thus, our estimates indicate that a dollar R&D increases current operating income (OI) by 37.2 cents, on average, and next year's OI by 43.9 cents.[23] The impact of a dollar R&D on OI of the subsequent two years is 40.7 and 31.6 cents, respectively. The impact of R&D on subsequent income peters out after seven years.

The estimated duration of the benefits from R&D projects is seven years, on average, while most of the operating income benefits are generated by current and the preceding three years of R&D (see the large contribution estimates in Table 2). This relatively short duration period probably reflects the importance of the short-term "process R&D" in the chemical industry. It may also reflect a shift of emphasis in the chemical industry from the discovery and development of **radically new** products with long gestation periods (akin to basic pharmaceutical research) to the modification and improvement of current products, as well as customer technical services, which are generally associated with shorter benefit periods. This finding, suggesting a change in the nature of R&D activities, if valid, is of considerable importance to chemical corporations and society at large. We will return to this issue in the concluding comments.

The medium gestation period of R&D indicated in Table 2 may also reflect a limitation of our estimation model (4). This model in fact focuses on the impact of R&D on the **profit margin** of chemical companies (the dependent—left hand—variable in model (4) is the ratio of operating income to sales). Accordingly, R&D which leads to benefits not reflected by the profit margin (e.g., new products having the same profitability as current ones), will not be captured by our estimates. We will revisit this issue too in the concluding section.

Most importantly, our estimates (Table 2) indicate that, on average, a dollar R&D is increasing current and future operating income by $ 1.941 (the **sum** of the seven estimated yearly coefficients). The internal rate of return of this series of seven contributions to operating income—the return on a dollar R&D—is 24.0 percent.[24] This, indeed, is a substantial return on investment. It is equivalent to an 17 percent return **after tax** (26.6 x [1-0.35]), a rate which is substantially higher than chemical companies' weighted average cost of capital (roughly 8 percent). True, R&D is riskier than investment in physical assets, but the return differential (R&D versus cost of capital) is very large, most probably compensating for the additional risk and then some. Thus, chemical R&D by our estimates is a significant contributor to value creation and growth of chemical companies. This is the main finding of our analysis.

Comparison with Software R&D

To provide a benchmark for our chemical R&D estimates, we estimated model (4) for software companies. Findings are presented in the right column of Table 2. Focusing on R&D (the physical assets of most software companies are relatively insignificant), we observe marked differences between chemical and software R&D.[25] The development period of software R&D is short relative to chemical R&D—most of the benefits (78 percent of the total benefits) accrue over a 1-2 years period (the current year coefficient, 0.643, and previous year coefficient, 0.434, are by far the largest estimated coefficients). The total software R&D benefits, $1.739, is somewhat lower than the total chemical R&D benefits, $1.941, but the annual return on software R&D (29.3 percent) is somewhat higher than the estimated return on chemical R&D (26.6 percent). The reason: the benefits of software R&D materialize quicker than chemical R&D, a fact which increases the return to invested capital. The differences in the benefit profiles of chemical and software R&D reflect differences in the nature of innovation activities in these industries. Product development in the software industry (1-2 years, on average) is generally shorter than in the chemical industry.

VI. The Sample Companies Classified

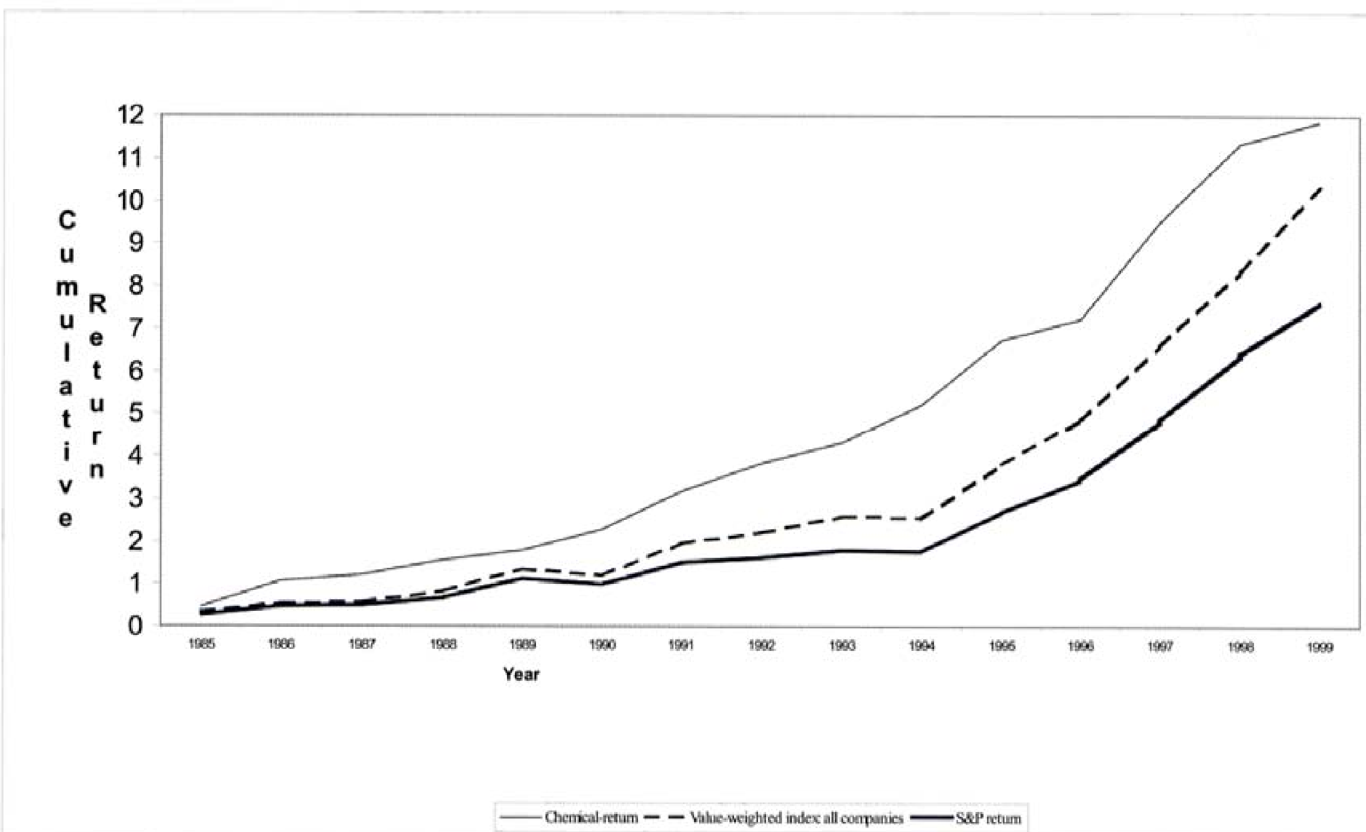
We have seen in Table 1 that the R&D intensity (R&D expenditures to sales) is higher for large companies than for small ones: 4.86 percent vs. 2.75 percent in 1999. Does the return on R&D (investment outcome) also vary with R&D intensity? This will be the case if there are significant **economies of scale** in R&D, namely when the efficiency of R&D in developing new products and economizing on the production of chemicals increases with the magnitude of the firm's R&D operations. A case for economics of scale in R&D can easily be made. For example, if an R&D project fails, a large, multi-project company can nevertheless apply the knowledge gained and lessons learned from the failed project to other projects under development. In contrast, a small, single project company will not be able to benefit from the knowledge gained from the failed project. Examples and *a priori* arguments, however, do not indicate the extent and pervasiveness of economies of scale. We therefore examine our data for economies of scale.

To examine the extent of economies of scale in chemical R&D we split the sample companies to high and low (below and above median) R&D intensive companies. We then estimate model (4) for each of the two groups of companies separately.[26]

Our estimates indicate a large difference between the returns on R&D of the high and low R&D intensive companies, roughly 40 to 20 percent, respectively. Furthermore, the pattern of benefits is also different: The benefits of R&D in the high intensity group extend over a substantially longer period than in the low intensity group. Our evidence thus indicates the existence of substantial economies of scale in chemical R&D.

We should caution, however, that this analysis which splits the sample into two groups, is based on a rela-

Figure 3
Market Performance:
Chemical Companies vs. S&P 500 and All Public Companies



tively small number of companies in each intensity group and is, therefore, sensitive to influential observations. This section's results should, therefore, be considered as suggestive. In addition, to the extent that significant chemical R&D is done by non-chemical companies, such as biotech firms, divisions of oil companies, or joint ventures, the above estimates may not fully represent R&D benefits. However, we have no information about such R&D and its consequences.

VII. The Capital Market Performance of Chemical Companies

Our estimates indicate that the return on physical assets in the chemical industry is roughly equal to the cost of capital, while the return on R&D substantially exceeds the cost of capital. In that case, substantial economic value (growth) should be created by chemical companies, and this should be reflected by favorable capital market performance over the long haul. Indeed, Figure 3 indicates that over the 1985-1999 period, the cumulative return on a portfolio of the sample chemical companies (top line in Figure 3) exceeded the return of the S&P 500 companies (bottom line) and the average value-weighted return of all public companies (middle line).[27] Thus, a dollar invested in our sample of chemical firms at the beginning of 1985 grew to $11.86 at the end of 1999. A dollar invested in 1985 in the S&P 500 companies grew to $7.59 by the end of 1999 (the exact figures are presented in columns 5 and 4 of Table 3).

An examination of Table 3, which provides the raw data for Figure 3 (columns 4 and 5 of Table 3 provide the data for the top and bottom lines in Figure 3), indicates that the superior market performance of chemical companies relative to the S&P 500 firms occurred over the 1985-1994 period only (see the individual year returns in columns 1 and 2). However, in each of the years 1995-1999, the S&P return was higher than that of chemical companies. Thus, during the above-average economic growth period in the U.S., starting around the mid 1990s (and apparently coming to a halt in 2001), chemical companies lagged the S&P 500, which was mainly propelled by technology and science-based (e.g., pharmaceutical and biotech) stocks.[28]

Table 3
Market Performance

Year	S&P return	Chemical return	Chemical ROE	Cumulative S&P return	Cumulative Chemical return	Cumulative chemical return large firms
1985	0.2633	0.4471	0.1186	0.2633	0.4471	0.5856
1986	0.1462	0.4190	0.1365	0.4480	1.0534	1.1867
1987	0.0203	0.0723	0.1476	0.4774	1.2019	1.2413
1988	0.1240	0.1544	0.1893	0.6606	1.5419	1.5825
1989	0.2725	0.0939	0.1713	1.1132	1.7806	1.9496
1990	-0.0656	0.1747	0.1423	0.9745	2.2663	2.4675
1991	0.2631	0.2727	0.1147	1.4940	3.1570	3.2779
1992	0.0446	0.1582	0.0924	1.6053	3.8147	3.7435
1993	0.0706	0.1020	0.0775	1.7891	4.3058	4.1447
1994	-0.0154	0.1690	0.1625	1.7461	5.2025	4.8678
1995	0.3411	0.2461	0.1735	2.6828	6.7289	6.7379
1996	0.2026	0.0629	0.1622	3.4289	7.2150	7.0936
1997	0.3101	0.2792	0.1566	4.8024	9.5087	9.2436
1998	0.2667	0.1743	0.1272	6.3499	11.3403	10.904
1999	0.1953	0.0461	0.1405	7.5900	11.8631	11.545

Return data were derived from the CRSP database.

The favorable capital market performance of chemical companies (up to 1994) thus indicates that the high return on R&D indeed contributed to corporate value and growth. This contribution, however, was constrained by the fact that the total investment in R&D by chemical companies is modest (Table 1).

VII. Conclusions and the Road Ahead

Our statistical estimates, based on a relatively large and diversified sample of chemical companies, indicate that R&D in the chemical industry is highly productive, yielding on average a return on investment of 26-27 percent (before tax). This return is substantially above the cost of capital of chemical companies, suggesting that chemical R&D contributes significantly to the value creation and growth of these companies. The R&D contribution to corporate value is, however, restricted by the current modest level and intensity of R&D investment in the chemical industry. As discussed in Section III, the average R&D intensity of chemical companies (4.70 percent in 1999) is slightly below the R&D intensity of all U.S. companies with R&D activities (4.84 percent in 1999). To use an analogy, a highly productive, yet small engine, cannot generate a high performance from a heavy car, or aircraft.

Should chemical companies substantially increase R&D expenditures, given our findings? Should universities and national laboratories significantly increase their research budgets? In answering these questions we should first note that statistical inferences are generally limited to the **range of sample observations** from which the estimates were derived. Most of the sample R&D intensities (80 percent) are in the range of 0.5 percent.[29] Hence, we cannot state with confidence the expected return on R&D if, for example, R&D budgets will be doubled. Second, given that current R&D levels already constitute a substantial portion of firms' earnings (recall Table 1 data), it does not seem realistic to expect public companies, sensitive to decreases in reported earnings, to substantially enhance R&D budgets over the short term.[30]

Our findings, however, indicate the desirability of modest (e.g., 15-20 percent) increases in R&D budgets, perhaps over several years. It seems reasonable to expect that the return on such modest R&D increases will be in the range of the estimated returns—well above cost of capital.

Our findings, indicating a medium benefit period of chemical R&D—seven years, where most of the benefits are attributable to current and last three years' R&D—are consistent with heavy emphasis of chemical companies on process R&D and improvements of current products. It seems that the investment in radically new innovations is either low or not highly successful (or, the benefits not being recognized by our statistical tools). A reassessment of efforts aimed at the development of new products, in cooperation with universities and national laboratories, is called for.

Economics of scale in chemical R&D are pronounced. This probably explains the success and longevity of the large chemical companies, in the U.S. and abroad, and the tendency to consolidate in the chemical industry. This, however, poses a potential problem concerning innovation in the chemical industry, given that in many other sectors (e.g., biotech, software) much of innovation is carried out by small enterprises.

This study constitutes the first phase of the research sponsored by the Council for Chemical Research in 1999, addressing the first question posed in Section 1 (the overall productivity of chemical R&D). The second question—are all R&D types born equal?—is of considerable importance. A thorough understanding of the contribution of chemical R&D requires penetration of the black box of total R&D. In particular, an attempt should be made to assess the contribution of R&D in major product categories, such as commodity (industrial) chemicals, specialty (performance) chemicals, plastics, agricultural, and pharmaceutics. In addition, the contribution of different **types** of R&D—product, process, and technical services—should be thoroughly investigated. To the extent of data availability, the contribution of external R&D—conducted at universities and national laboratories—should also be assessed. Such a penetration of the R&D black box—crucial for optimal resource allocation at both the corporate and society level—will constitute the core of the second phase of the research.

The third phase of the research will focus on the **drivers** of successful R&D in the chemical industry. The intensity of investment in R&D, as well as investment in related areas (IT, for example), collaboration with universities and national laboratories, the quality of human resources (e.g. "star scientists") engaged in R&D, and alliances with non-chemical enterprises, are examples of possible drivers of successful R&D.

The main findings of the first phase of the research reported above—the substantial growth-driving return on investment in chemical R&D—set the stage for the future phases of research.

Endnotes

[1] Data derived from the 1998 U.S. Chemical Industry performance and Outlook, Chemical Manufacturers' Association, November 1999.

[2] Rick Gross, "Growing Through Innovation," Chemical Engineering News, October 25, 1999, p. 5.

[3] See Chris Freeman and Luc Soete, 1997, The Economics of Industrial Innovation (Third edition), The MIT Press, Cambridge, MA, Chapter 5, for a historic survey of chemical R&D.

[4] Gross, 1999, op. cit.

[5] Data on R&D spending were derived from Chemical & Engineering News, October 25, 1999, p. 62 (originally derived from National Science Foundation, 1999, "Research and Development in Industry"). The chemical companies whose R&D is computed in the text consist of 17 major companies, including DuPont, Dow, Union Carbide and Air Products. The pharmaceutical companies sample consists of Pfizer, Merck, Eli Lilly, American Home Products, Bristol Myers, and Schering-Plough.

[6] Chemical & Engineering News, op. cit., p. 63.

[7] Chemical & Engineering News, op. cit., p. 64.

[8] There are various estimates of the relative contributions of physical and knowledge capital to productivity and growth. John Kendrick, for example, estimates that in the early 1990s intangible assets contributed about 60% of corporate product vs. 40% contribution of physical capital. (see Kendrick, 1994).

[9] For an extended discussion of intangibles, their attributes, contribution to growth and valuation, see Baruch Lev, 2001 (available in the website, baruch-lev.com).

[10] This valuation methodology, developed by Baruch Lev, is featured annually by CFO magazine (a subsidiary of the Economist), which ranks the major U.S. and European companies by the knowledge measure. The recent (February 2000) ranking can be viewed in Baruch Lev's website: baruch-lev.com (Section of "Media Mentioning," item: The Second Annual Knowledge Scorecard). The next ranking of companies by knowledge capital will be published by CFO magazine in April 2001.

[11] This figure represents the median knowledge capital value of the five largest chemical companies.

[12] Other drivers of intangible capital include investment in IT, brands, and human resources.

[13] Divisions of public companies do not disclose publicly their financial statements.

[14] Our starting year is 1980 to ensure sufficient observations for our statistical procedures.

[15] The R&D intensity in Table 1 increased from 3.56% in 1990 to 4.70% in 1999. This seems to be inconsistent with the data provided in Section I indicating a stagnant investment in R&D during 1989-1998 at a level of $3.25 billion a year. One reason for the difference is that the data in Section I relate to 17 companies, while the data on R&D intensity in Table 1 are for the entire sample of 83 companies. Second, our data indicates a significant increase in R&D expenditures beginning in 1998, while the data in section I relates to the 1988-1998 period. Total R&D expenditures of the sample companies increased from $6.75 billion in 1990 in $7.97 billion in 1999.

[16] Data for the computation of R&D intensity of all companies, and selected sectors were derived from the COMPUSTAT database.

[17] Note that this value of R&D investment is cost based, namely derived from R&D expenditures. The current, or market value of R&D can deviate substantially from cost values, usually upward.

[18] This somewhat technical section can he skipped by those mainly interested in the study's findings, which are summarized in Section V. In the second part of this section, an intuitive interpretation of the model is provided.

[19] Since we require for estimation purposes that each company will have at least nine years of data, some sample companies with fewer years (young, recently gone public) are not included in the estimation. For estimation of model (4), we have typically 10 to 50 firms a year.

[20] We interpret the estimated coefficients in Table 2 as dollar contribution to operating income. This is appropriate since all the variables (dependent and independent) in the estimated model (4) are scaled (divided) by the same variable—sales. Accordingly. given the level of sales, a dollar increase in the value of an independent variable (R&D, or physical assets), will be associated with an increase in operating income equal to the estimated coefficients, α.

[21] Stated differently, if earnings are higher than the cost of capital employed, then "economic value" is created. This is the fundamental concept underlying the various measures of economic value added (EVA), or in the accounting parlance—"residual earnings."

[22] We have estimated the contribution to operating income of same year and 8 preceding years of R&D. The coefficients of R&D in years –7 and –8 were negative and hence not reported in the table.

[23] Our estimation (model 4) focuses on the association between current OI and current as well as lagged (past) R&D expenditures. Thus, the estimated coefficient of R&D in year –1 (preceding year), 0.439, can be interpreted as the impact of last year's R&D on current OI. Equivalently, it can be interpreted as the impact of current R&D on next year's operating income. In the text we use the latter interpretation.

[24] The internal rate of return is the rate which discounts the series of seven annual contributions to $1.0. Stated differently, the present value of the seven R&D estimates in Table 2, discounted at 26.6% is one dollar.

[25] Most software companies term their R&D as "product development."

[26] We deleted from this analysis the year 1980 which had insufficient number of observations.

[27] The periodic (e.g., annual) rate of return on a stock or a port - folio of stocks is measured as the value of the stock at the end of the period, minus its value at the beginning of the period (capital gain/loss), plus cash dividends, all divided by the value of the stock at the beginning of the period. The S&P 500 index includes 500 leading U.S. companies, and represents roughly 75% of the value of all listed companies in the U.S. The value-weighted stock return is an index reflecting the average return on all traded stocks, where the individual stock returns are weighted, by the size (market capitalization) of each company.

[28] The data in Table 3 also indicate that the stock performance of large chemical companies did not outperform that of small companies—compare column 5 reflecting the entire sample with column 6 pertaining to large companies. Table 3 also indicates that the accounting return on equity (earnings divided by balance sheet equity value), presented in column 3 is more stable than the stock return (column 2).

[29] In 1999, for example, the 80 percentile of sample R&D intensities (ranked from lowest to highest) was 4.86%, and the 90 percentile was 8.69%.

[30] We encounter here, however, the classic "chicken and egg" problem. Current earnings of chemical companies may be low, in part at least, because of insufficient investment in R&D.

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Appendix

List of Sample Companies. Simple Period 1980-1999. Number of Firms: 83

(Sample companies are publicly traded whose main operations are in chemicals)

Name	SIC Code
AGRIUM INC	2870
AIR PRODUCTS & CHEMICALS INC	2810
AIRGAS INC	5084
AKZO NOBEL NV -ADR	2800
ALBEMARLE CORP	2890
AMERICAN VANGUARD CORP	2870
AMOCO CORP	2911I
ARCADIAN PARTNERS LP -PREF	2870
ARCH CHEMICALS INC	2800
ARISTECH CHEMICAL CORP	2821
AT PLASTICS INC	2821
BALCHEM CORP -CL B	2810
BORDEN INC	2860
BUSH BOAKE ALLEN INC	2860
CABOT CORP	2890
CALGON CARBON CORP	2810
CAMBREX CORP	2836
CELANESE CORP	2820
CHEMFIRST INC	2860
COURTAULDS PLC .ADR	2800
CROMPTON & KNOWLES CORP	2820
CYTEC INDUSTRIES INC	2890
DETREX CORP	2800
DEXTER CORP	2821
DOW CHEMICAL	2821
DU PONT (E I) DE NEMOURS	2820
EASTMAN CHEMICAL CO	2821
ENGELHARD CORP	3330
ETHYL CORP	2860
FERRO CORP	2851
FINA INC -CL A	2911
FMC CORP	2800
FULLER (H. B.) CO	2891
GENERAL CHEMICAL CORP	2810
GENTEK INC	2810
GEON COMPANY	2821
GEORGIA GULF CORP	2810
GRACE (W R) & CO	2890
GREAT LAKES CHEMICAL CORP	2890
GWIL INDUSTRIES	2820
HARRIS CHEMICAL NTH AMER INC	2800
HERCULES INC	2821

Name	SIC Code
HOECHST CELANESE CORP	2820
IMPERIAL CHEM INDS PLC -ADR	2800
INTL FLAVORS & FRAGRANCES	2860
INTL SPECIALTY PRODS INC	2860
KERR-MCGEE CORP	2810
LAWTER INTERNATIONAL INC	2821
LOCTITE CORP	2891
LSB INDUSTRIES INC	2810
LUBRIZOL CORP	2860
LYONDELL CHEMICAL CO	2860
MACDERMID INC	2890
MCWHORTER TECHNOLOGIES INC	2821
MILLENNIUM CHEMICALS INC	2810
MINERALS TECHNOLOGIES INC	2810
MISSISSIPPI CHEMICAL CORP	2870
MORTON INTERNATIONAL INC	2890
NALCO CHEMICAL CO	2890
NL INDUSTRIES	2810
NORSK HYDRO AS -ADR	2870
NOVA CHEMICALS CORP	2860
OLIN CORP	3350
OM GROUP INC	2810
PHOSPHATE RES PARTNERS -LP	2870
PPG INDUSTRIES INC	2851
PRAXAIR INC	2810
QUAKER CHEMICAL CORP	2990
REXENE CORP	2821
RHODIA -SPON ADR	2800
RHONE-POULENC RORER	2834
ROHM & HAAS CO	2821
RPM INC-OHIO	2851
SCOTTS COMPANY	2870
SIGMA-ALDRICH	2836
SOLUTIA INC	2821
STEPAN CO	2840
STERLING CHEMICALS HLDGS INC	2860
SYBRON CHEMICALS INC	2840
TERRA INDUSTRIES INC	5190
TERRA NITROGEN CO -LP	2870
UNION CAMP CORP	2631
UNION CARBIDE CORP	2860

Introduction to Francis Narin And Michael Albert
by Ashish Arora

Reducing the extent of our ignorance, or penetrating the black box, has been a long, arduous, and highly incomplete journey for economists, historians, and other social scientists. There are many different sources of inputs into research and many different beneficiaries. As we have observed, the process through which knowledge is translated into useful goods and services and improved living standards is exceedingly difficult to measure.

In many cases, the costs and benefits of investing in research are not confined to the entity that undertakes the research. Instead, they may spill over to others. The existence of these spillovers, investigated by Francis Narin, gives rise to a number of issues relevant to measuring of payoffs in more specific categories.

When a firm invests in R&D it also uses knowledge that has been produced by others. There is no direct recompense for this use. The point is particularly compelling for what Narin calls public science in this section. Members of the scientific community in universities and in corporate labs traditionally publish their research findings. Others are then free to draw upon these with no recompense other than an acknowledgement through citation.

Such open and free disclosure is believed to be the most efficient way of facilitating the effective application of knowledge for the greater good. It does, however, considerably complicate the matter of measuring the economic contribution of the R&D that a firm invests in because that R&D draws upon a much larger body of knowledge to which many others have contributed. Absent this recognition, the measured private returns are likely to be smaller than the social return in the sense that some of the costs (i.e., investments in research) have not been made by the firm in question but by others.

By the same token, the knowledge created by the research project may be used not only by the firm that owns the lab but also by researchers elsewhere, be it in other firms or in government or university labs. Since a firm is unable to capture the full benefits of its own research, it follows that the social payoff is greater than the private one—the part that enhances the firm investing in R&D. The existence of spillovers and the inability of firms to capture the full benefits of their investments in research has been the justification for the continued public support for research.

Francis Narin examines the contribution of chemical research with bibliometric techniques using patent citation data. This study has two aspects. First, it tries to measure how knowledge flows between firms, and from universities (public sector) to firms. Second, it measures the quality of knowledge produced in U.S. firms and universities by using these measured flows. The more useful the knowledge produced, the more likely others will draw on it in some way, resulting in citations. Thus, this study is one way to tackle the contribution that is not mediated by market forces.

Navin is careful to distinguish chemical patents from those in life sciences, a distinction of some importance because of the possible divergence in the returns to R&D in the two sectors.

His results are fairly consistent with those reported by Lev. Narin finds that the quality of U.S. chemical technology is high (compared to chemical technology from countries such as Germany and Japan) and increasing over time. Further, U.S. chemical scientific output, most of which is by universities and government, is contributing in significant ways to technological improvements. His measures do indicate that chemical technology is mature, in that the cycle time—the median age of the patent cited by the typical U.S. chemical patent —is greater than for electronics or information technology. Moreover, chemicals appears to be becoming more mature, in contrast to life sciences, information technology and electronics, where the cycle time is decreasing. This finding provides concerns about the growing maturity of chemical technology.

Narin's findings also point out that knowledge spillovers are geographically bounded. Firms are disproportionately likely to benefit from R&D that is conducted in their own backyard, so to speak. Thus, although in principle new and useful knowledge that is created by chemical R&D in the U.S. can spill over and benefit other countries and regions, Narin's findings suggest that spillover benefits to other countries are likely to be small. (Although, of all countries, U.S. chemical R&D has the greatest international spillovers.) Indeed, his results suggest that the individual states would capture a substantial fraction of the spillovers from R&D conducted within their boundaries. Taken in conjunction with the previous studies, these results make a strong case for policies encouraging chemical R&D in the U.S. In particular, they argue for the importance of a domestic science base in fostering technological innovation in the chemical sector.

Chemical Technology as Enabling Technology: Filling in the White Spaces

by Francis Narin and Michael Albert

Introduction

In this section we are going to use the U.S. patent system to assess the state of U.S. chemical technology. We will compare U.S.-invented Chemicals patents to other U.S. patents and to foreign-invented Chemicals patents, and will look at the linkages and connections between U.S.-invented Chemicals patents and other technologies, scientific research, and financial performance.

All of these analyses will be based upon the U.S. Patent System and the patents granted therein to U.S. and foreign inventors. We will use the number of these patents to get some idea of the technological size of the chemical enterprise, and the citation properties of the patents to generate indicators of the quality of U.S. Chemicals patents and the impact that they are having.

There are three patent citation indicators that we will use to provide qualitative insight into the properties of chemical technology: the Current Impact Index for the patents, their Science Linkage, and their Technology Cycle Time.

The Current Impact Index (CII) is a patent citation indicator which looks back from the current year at the previous five years of a set of granted U.S. patents, and measures how highly these patents have been cited from patents granted in the current year. It is based on the well-established idea that the more highly cited a set of patents is, the more technological impact it is likely to have. Current Impact Index is a normalized indicator such that the average for all U.S. patents is 1.0, and a set of patents with a CII of 1.1 is cited, from the current year, ten percent more than would be expected. CII is thus a forward-looking indicator in that it provides a normalized measure of the impact an earlier set of patents is having on technology appearing in the current year.

The second and third indicators used here are Science Linkage (SL) and Technology Cycle Time (TCT), both of which, in a sense, are backward-looking. Science Linkage counts the number of times a patent cites to scientific papers or similar research publications, and thus is a measure of how close a given set of patents is to fundamental scientific research.

Technology Cycle Time is defined as the median age of the earlier U.S. patents referenced on the front page of a U.S. patent. It is a measure of the speed at which a company or industry is innovating. TCT is fastest in electronics and information technologies, at three to five years, and very slow in some old technologies, such as ship and boat building, with chemical technology in the middle of the range.

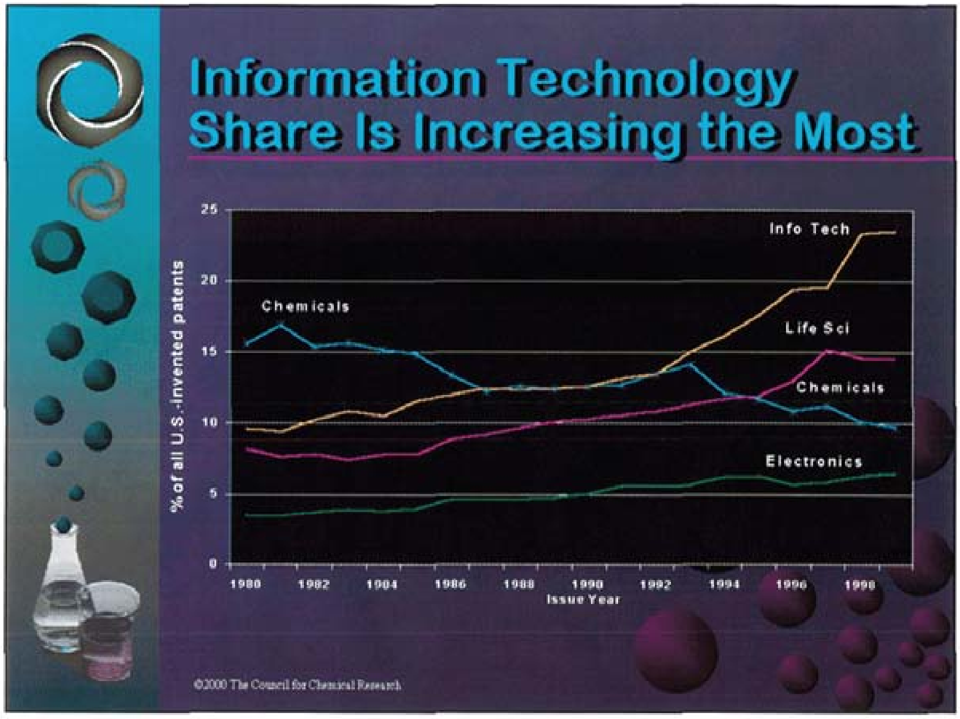
Science Linkage is strongest in very advanced areas of biotechnology such as genetics engineering and virtually zero in the older mechanical technologies. Chemical technologies, at roughly six science references per patent, is toward the high end of the range. A very straightforward application of these indicators to the automotive industry is contained in our paper "The Strategic Applications of Technology Indicators Based on Patent Citation Analysis."[1] A much more in-depth discussion of patent citation analysis itself can be seen in our Tech-Line® Background paper[2], a version of which is available on the web at http://www.chiresearch.com.

U.S. Chemical Technology Compared to Other U.S. Technologies

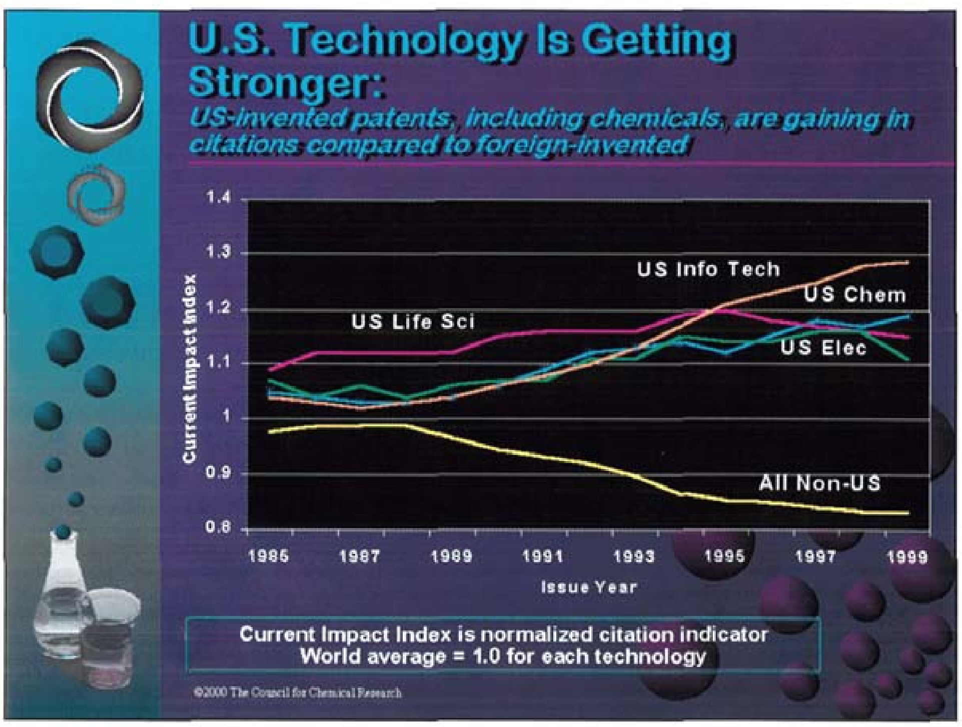
In this section we provide a snapshot of **U.S.-invented** Chemicals patents versus **U.S.-invented** patents in other technologies. Note that while all the data in this paper are based on patents in the U.S. patent system, only about half of the U.S. patents are U.S.-invented. In this section we are specifically comparing U.S.-invented patents in four major categories: **Life Sciences**, composed mainly of pharmaceuticals, biotechnology, medical equipment, and agriculture; **Chemicals Technology**, composed of chemicals, plastics, polymers, and rubber patents; **Electronics**, composed of semiconductors, electronics, and medical electronics: and **Information Technology**, composed of computers and peripherals, telecommunications, office equipment, and camera patents.

There were about 5,800 U.S.-invented Chemicals U.S. patents in 1980, comprising 16 percent of all U.S.-invented U.S. patents. While the number of these patents had grown to 8,200 in 1999, patenting in other areas has grown even faster: all U.S.-invented grew from 37,200 in 1980 to 83,600 in 1999, with the result that the Chemicals patents share has decreased, from 16 percent in 1980 to 10 percent in 1999.

Corresponding to that decrease in share of the



Slide 6: Information Technology Share is Increasing the Most



Slide 7: U.S. Technology is Getting Stronger

Chemicals patents, there has been a rather rapid increase in the share of U.S. patents in information Technology, from less than 10 percent in 1980 to close to 24 percent in 1999, and a similarly large increase in Life Sciences, from about 8 percent to almost 14 percent. That is seen in Slide 6, which shows that Information and Life Sciences have both passed Chemicals in patenting activity by U.S. inventors.

When we look at Current Impact Index, the Chemicals indicator is becoming much stronger, as shown in Slide 7. In fact, almost all U.S.-invented technologies appear to be becoming more highly cited as time goes on, whereas, in general, non U.S.-invented patents are getting less highly cited in the U.S. patent system. The figure indicates that the increase in impact became particularly noticeable at the beginning of the 1940s, and certainly corresponds to the resurgence in many U.S. technologies in the last decade. While U.S. Information Technology patents appear particularly highly cited compared to foreign-invented patents, U.S. Chemicals, Electronics, and Life Sciences are all doing quite well.

The trend in Technology Cycle Time is not quite as favorable. As Slide 8 shows, TCT for U.S.-invented Chemicals patents seems to slow from about 8 years in 1980 to about 11 years in 1999, during which time the TCT for Life Sciences has shortened from 10 to 9.5 years. As mentioned previously, Electronics and Information Technology are much faster, with cycle times around 7 years, with Information Technology changing even faster. Thus we see that current Chemicals technology is built on relatively old patent prior art, somewhat more so than Life Sciences, and certainly much more so than Electronics or Information Technology, where the rate of improvement on prior patented technology seems to be much faster.

Somewhat more positive is the Science Linkage indicator, shown in Slide 9, for these major sectors of U.S. patenting. Life Sciences, of course, is the most science-linked since it is driven and affected strongly by the very advanced areas of biotechnology, where the average patent often has 20 or more references to scientific literature. Chemicals, however, is the second most science-driven of the technologies, with an increasing link to basic science over time. Electronics and Information Technology are only one-third as heavily linked to science as current Chemicals technology. In those two areas a much higher fraction of the prior art driving the technology is coming from prior patented technology, compared to Chemicals and Life Sciences, which are largely driven by fundamental research published in research papers.

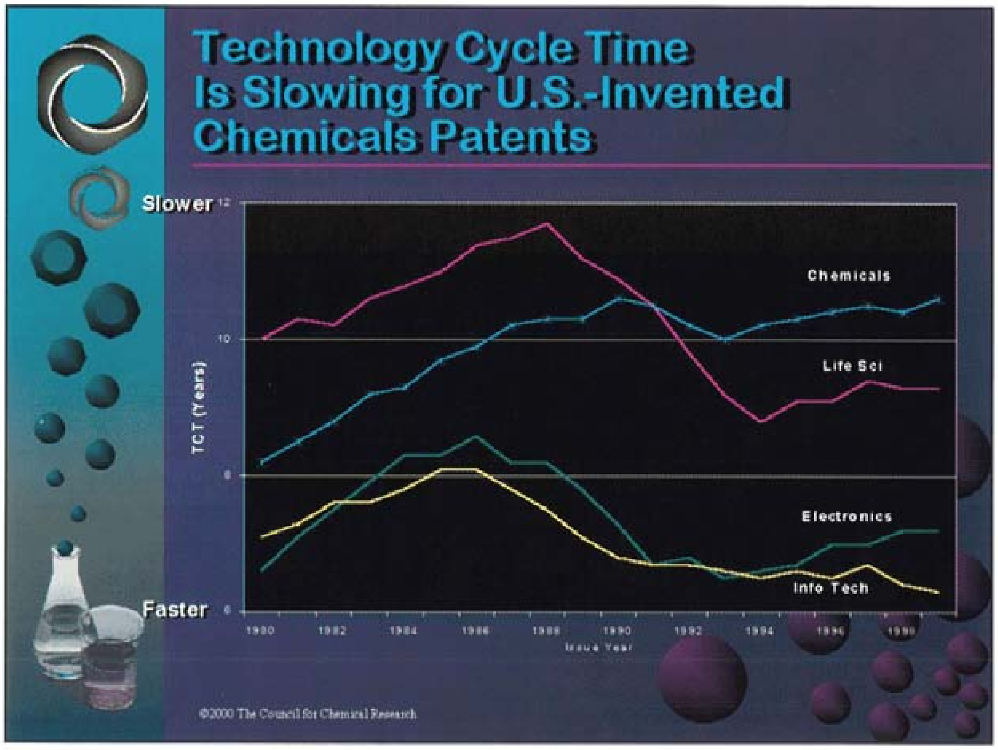
Thus we see that Chemicals patents are growing relatively slowly, and are reasonably highly cited, second only to Information Technology. They are, however, slowing somewhat in cycle time, but markedly increasing in science linkage. Chemicals technology seems to be a strong second in various parameters; it is not leading in any one characteristic, but it is a strong second in most.

U.S.-invented Chemicals Patents versus Other Chemicals Patents

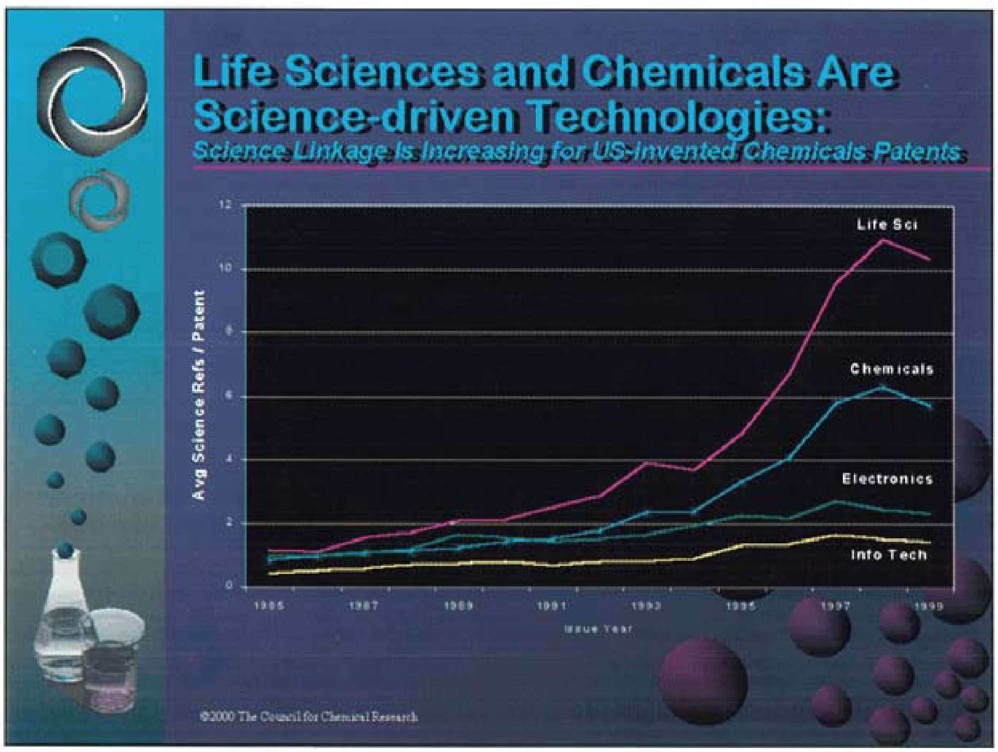
In a wonderfully named 1967 paper entitled "Nations Can Publish or Perish," Derek de Solla Price showed that the amount of scientific publication from a country was roughly proportional to its GDP. It was not dependent on population or land area or any physical characteristic, but on the wealth of the country as measured by GDP. More recently we followed up on this work and showed in "Globalization of Research, Scholarly Information and Patents–Ten Year Trends" that the same relationship holds true for U.S. patents.[4] To a large degree each country's inventors obtain patents in the U.S. Patent System roughly proportional to their GDP. This also certainly holds in Chemicals patents, where the U.S. has about 52 percent, Japan 18 percent, Germany 12 percent, and the rest of the world 18 percent, including notably Switzerland and some of the other European countries.

The properties of these patents, however, are much more interesting than their share, although over the last 20 years there has been a slight decrease in the U.S. share, from roughly 56 percent in 1980 to around 52 percent in 1998, with a slight rise in patenting by smaller countries and Japan.

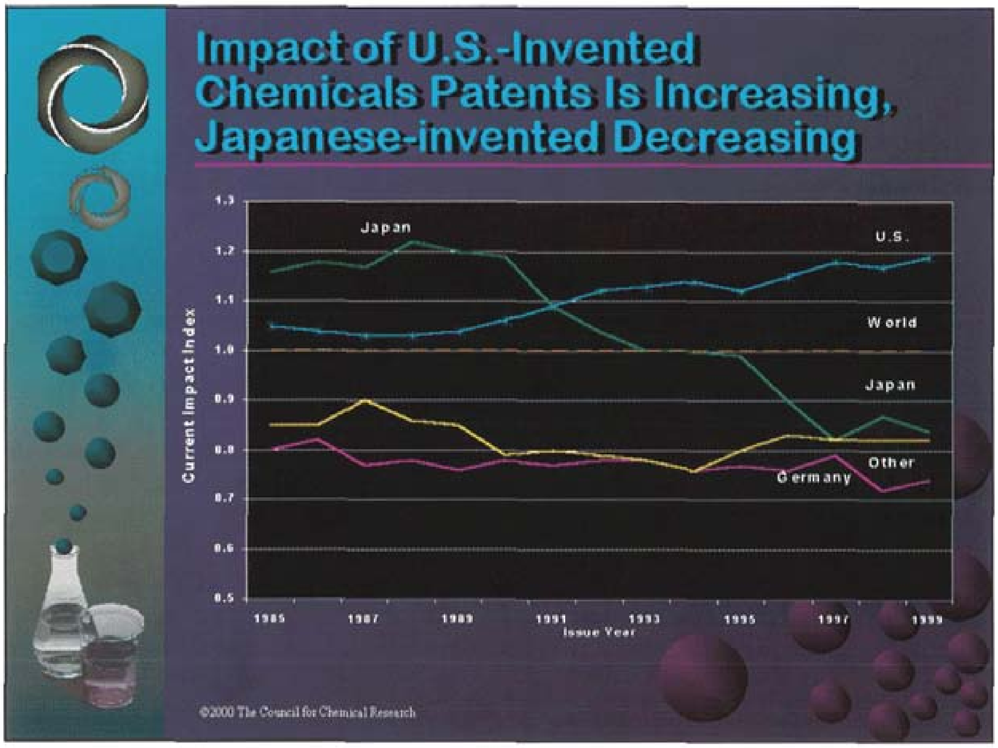
The impact of U.S. Chemicals patents however is rising steadily, as shown in Slide 10. The Current Impact Index for U.S. Chemicals patents was slightly higher than the world in 1986, at approximately 1.05, but rose to 1.2 by 1999. Corresponding to the U.S. rise is a rather precipitous drop in the impact of Japanese Chemicals patents. They are much less highly cited now than they were 15 years ago, falling almost to the level of Germany and other countries. We do want to note that this rather precipitous drop in the impact of Japanese technology is not confined to Chemicals patents; we see it in other areas too, and this very well may be associated with the



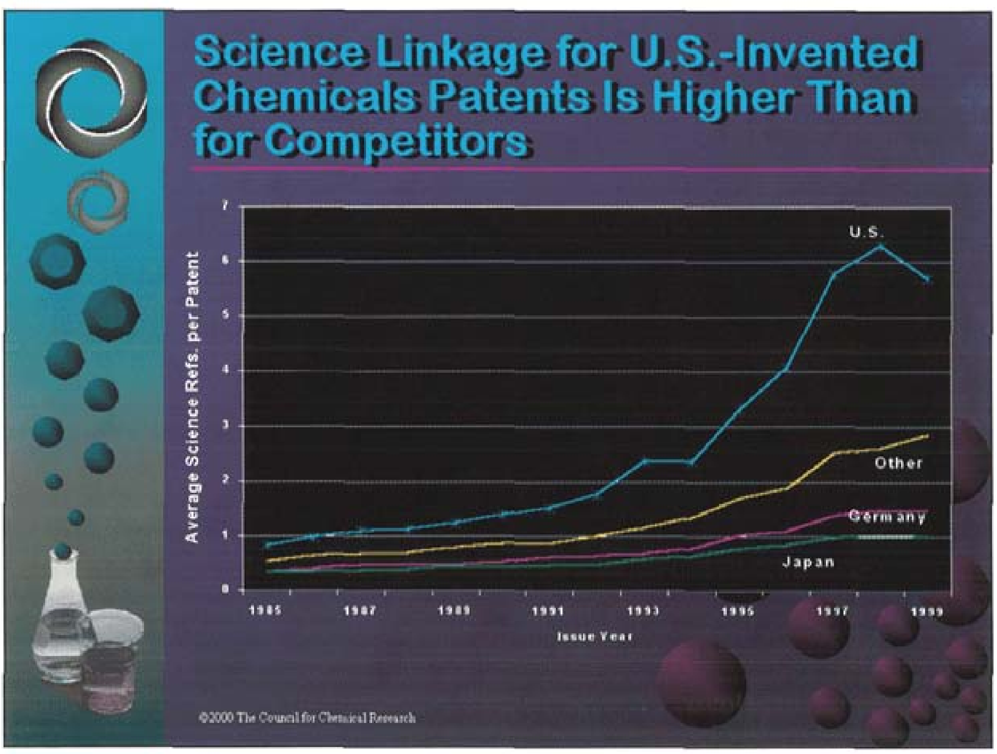
Slide 8: Technology Cycle Time is Slowing for U.S.-invented Chemicals Patents



Slide 9: Life Sciences and Chemicals are Science-Driven Technologies



Slide 10: Impact of U.S.-Invented Chemicals Patents is Increasing, Japanese-Invented Decreasing



Slide 11: Science Linkage for U.S -Invented Chemicals Patents is Higher than for Competitors

economic stress that the Japanese system has experienced over the last ten years.

The Technology Cycle Time for U.S., German, and other countries' Chemicals patents have all been slowing from a bit more than 8 years in 1980 to around 10 years in 1999. Technology Cycle Time is one area where Japanese-invented Chemicals patents are distinctly different. They were faster (at about 7 years in 1980) and are still faster (at 8½ years or so in 1999). This relatively short cycle time for Japanese-invented patents holds in most non chemical technologies also, and it seems to reflect a tendency for Japanese companies to patent what are perhaps relatively incremental advances, as compared to the somewhat longer and perhaps more substantial patents of most other countries' inventors.

The one characteristic that is strikingly different between Chemicals patents invented inside and outside the U.S. is Science Linkage. Slide 11 shows that Science Linkage has always been higher in U.S.-invented patents; but it has markedly increased in the last five years, and now is more than twice that of the smaller competitor countries, and some five times that of the average German- or Japanese-invented U.S. patent.

While some of the heavy science referencing in U.S.-invented U.S. patents may be due to the sensitivity of U.S.-based applicants and their patent attorneys to the highly litigious legal framework in the United States, we think that a significant faction of it is due to a genuinely strong link between U.S. Chemicals patents and science.

Chemicals as Enabling Technology

In this section we are going to discuss briefly some of the connections between Chemicals patents and (1) patents in other technologies, (2) the scientific literature, and (3) stock market performance.

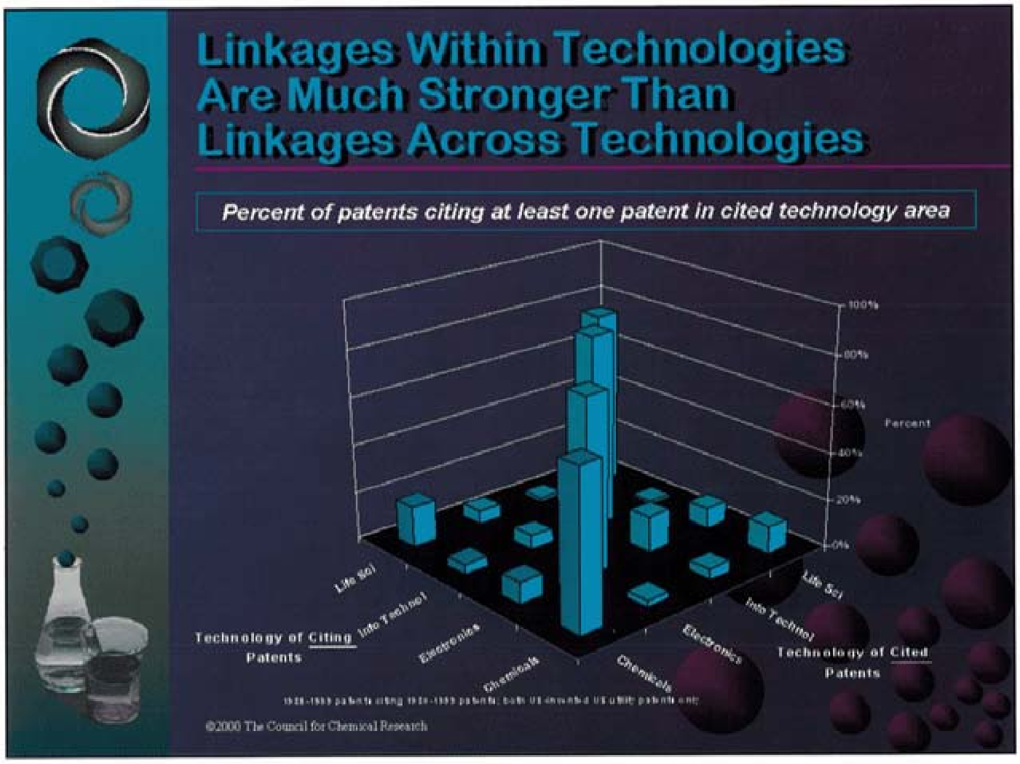
When we look at how Chemicals patents cite to Chemicals patents, we find that there is an increase in referencing from U.S.-invented Chemicals patents to earlier U.S.-invented Chemicals patents, rising from about 2.1 references per patent in 1990 to close to 3.2 in 1999. While this rise may not seem remarkable, the average references per patent from Japanese-invented Chemicals patents to Japanese-invented Chemicals patents, and from German-invented Chemicals patents to German-invented Chemicals patents are much lower. German-to-German has grown from about 0.7 to almost 1 in this time period, whereas Japanese-to-Japanese has been essentially flat at 1.3, again leading to the conclusion that while German invented U.S. Chemicals patents cite more to other German-invented Chemicals patents and U.S. markedly more to U.S., over the last decade Japan has shown no such increase in impact, even to its own patents.

When cross-citing between the technologies is considered, it turns out that while each technology's patents cite to some degree to other technologies, there is a much stronger pattern of citation within technology than across. This is illustrated in Slide 12, which shows that most patents in every technology cite to at least one earlier patent in their own technology, but only a small fraction cite to patents outside of their own technological area. Chemicals clearly contributes most to its own technology, and second most highly to Life Sciences, where close to 20 percent of the patents cite to at least one Chemical patent. The contribution of Chemicals to other technologies is considerably lower.

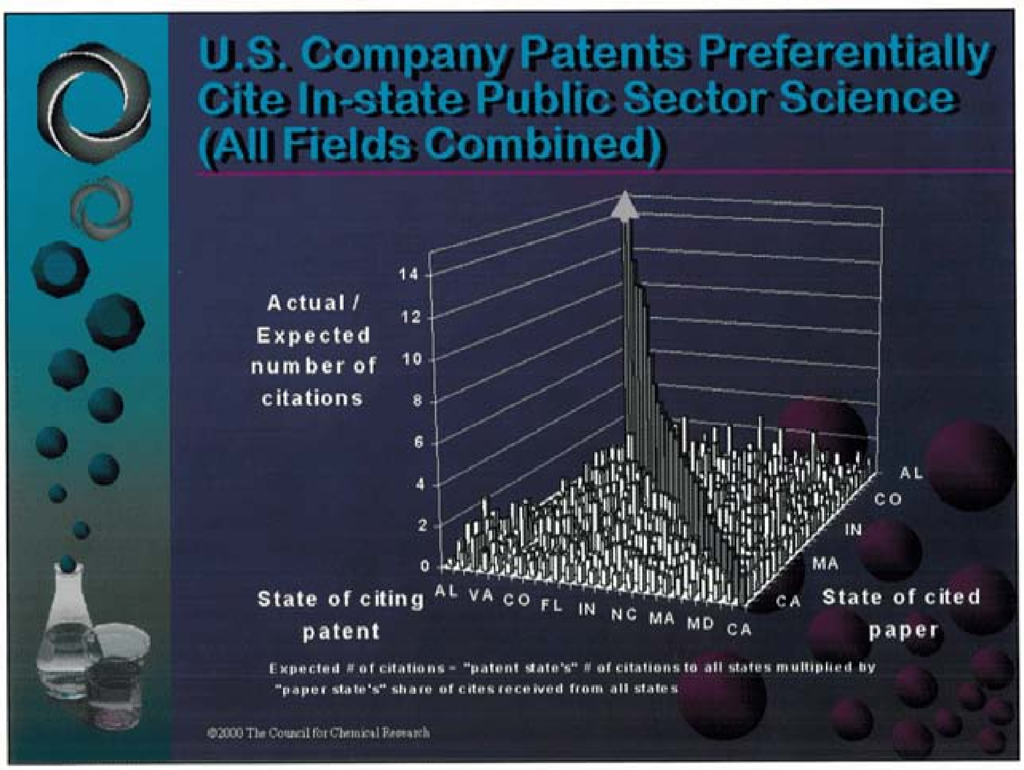
Another aspect of the world around Chemicals patents is the source of the science they cite so heavily. For 1993 and 1994 U.S. Chemicals industry patents, some 43 percent of their scientific references are to U.S. public science papers from universities, federal labs, and other public institutions, and 18 percent are to U.S. private institutions.[5] The remaining 39 percent are to non-U.S. institutions, which are largely public in roughly the same proportion as U.S. institutions. From this viewpoint, the science base of Chemicals patents is about 70 percent public, and U.S. industry supplies only a fraction of its own science base.

A particularly interesting aspect of the enabling science and technology is the fact that it is distinctly local. Slide 13, which is for all U.S.-invented patents, not just Chemicals, shows that there is a very strong tendency for private industry patents within a given state to cite to public sector science in their own state. If every company cited to research papers in proportion to the occurrence of the research papers on a state-by-state basis, the height of every bar would be 1; thus the height of the diagonal, considerably larger than one for every state (and very high for some of the very small states with only a few papers), indicates that there is a strong geographic component to the industry-to-science linkage. In our earlier paper we showed that this is true at a national level. Even at the state level it is certainly interesting to observe the importance of local science to local technology.

Our final comment about chemistry as an enabling



Slide 12: Linkages within Technologies are Much Stronger than Linkages across Technologies



Slide 13: U.S. Company Patents Preferentially Cite in-state Public Sector Science

science relates to the impact of quality technology on a company's stock market-to-book values.

In a paper recently published with Professor Lev at NYU, we showed that chemical companies that had highly cited and highly science-linked patents had an average market-to-book ratio of 2.0, compared to 2.1 for chemical companies with lower impact and lower science linkage. That is, the market-to-book value of companies with high impact patents was roughly 25 percent higher than that of companies with lower quality patents, an early indication that the quality of Chemicals research is quite important in the future stock valuation of the company.

Conclusions

We conclude from this overview of U.S.-Invented Chemicals patents that U.S. Chemicals technology is strong and getting better, but it is not the leading technology in any single indicator. Its quality is clearly increasing when compared to foreign-invented Chemicals patents, and its science linkage is increasing rapidly, especially when compared to foreign Chemicals patents. It is more highly linked to science than any other major U.S. technology, except for the Life Sciences, and it is highly linked to public science and to local science. While Chemicals technology is not exploding in the U.S. Patent System in the same way as Information Technology and, to some degree, Life Sciences, it is growing and its impact is increasing.

Endnotes

[1] Francis Narin, *Patent World*, 25-30, April 1993.

[2] Francis Narin, In *From Knowledge Management to Strategic Competence*. Series on Technology Management, Vol. 3, Joe Tidd, Editor, Imperial College Press, 155-195, 2000.

[3] Derek J. de Solla Price, *Science and Technology*, *70*, October 1967, 84-90.

[4] "Globalization of Research, Scholarly Information and Patents–Ten Year Trends," Francis Narin. *The Serials Librarian*, *21*, 2-3, 1991.

[5] "The Increasing Linkage between U.S. Technology and Public Science," Francis Narin, Kimberly S. Hamilton and Dominic Olivastro. *Research Policy*, *26*, 317-330, 1997.

[6] "Science & Technology as Predictors of Stock Performance," Zhen Deng, Baruch Lev, and Francis Narin. *Financial Analysts Journal*, *55*, 3, 20-32, May/June 1999.

Final Comments

It is clear that the three studies presented here have set the stage for further inquiries to measure the payoff of research investments in the chemical industry. Future studies could provide further insights in two ways. First, they could combine bibliometric and financial data, in a variety of ways. This approach could permit quantitative estimates of the extent of knowledge spillovers, and therefore, of the social returns to R&D investments. These studies could also measure the returns from publicly funded research. Another fruitful approach for future studies would be to study R&D at a more diverse level by separating R&D into research and development, and explicitly allowing for the synergies between research and other types of investments. Another type of diversification could involve studying the payoffs from individual research projects within a firm and trying to measure the spillovers to other firms, both competitors as well as firms further down in the value chain. Such studies would benefit not only the membership of the CCR but would also be valuable to a larger community of scholars, policy makers, and managers interested in understanding the payoff from research.

ERRATA
for “Measuring Up: Research & Development Counts for the Chemical Industry”

1) These references were inadvertently omitted following the Introduction by Ashish Arora in the Study Team Reports, which begins on page 9:

Abramovitz, M., 1956, “Resource and output trends in the United States since 1870”, American Economic Review, 46(2): 5-23.

Arora, A. and Gambardella, A., 1998, “Evolution of industry structure in the chemical industry” in Chemicals and Long Term Economic Growth, Asish Arora, Ralph Landau, and Nathan Rosenberg (eds.), John Wiley and Sons, 1998.

Bush, V., 1945, Science: The Endless Frontier, Washington DC, Office of Scientific Research and Development.

David, P. A., 1990, “The computer and the dynamo: A historical perspective on the modem productivity paradox”, American Economic Review 80: 355-361.

Romer, P. M., 1986, “Increasing returns and long run economic growth,” Journal of Political Economy, 94:1002-1037.

Solow, R. M., 1957, “Technical change and the aggregate production function”, Review of Economics and Statistics, 39:312-320.

2) The graph on the top right of Slide 5, page 15, is incorrectly labeled. The correct label should be 1870-1930.

3) The chapter “Evolving Patterns of American Chemical R & D” was written based on the presentation by David Sicilia at the Council for Chemical Research annual meeting, September 10, 2000, in New Orleans, LA. Professor Sicilia’s research was conducted while he was the Gordon Cain Fellow in Technology, Policy, and Entrepreneurship at the Chemical Heritage Foundation.

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