MEASURE FOR MEASURE: CHEMICAL R&D POWERS THE U.S. INNOVATION ENGINE

A Study Sponsored by
The Council for Chemical Research

MEASURE FOR MEASURE:
CHEMICAL R&D POWERS
THE U.S. INNOVATION ENGINE

A Study Sponsored by the Council for Chemical Research

The Council for Chemical Research
1730 Rhode Island Avenue, NW, Suite 302
Washington, DC 20036
202-429-3971
202-429-3976 (fax)
ccrmail@ccrhq.org (email)
http://www.ccrhq.org

Table of Contents

INTRODUCTION

In 2001, the Council for Chemical Research (CCR) released its study, "Measuring Up: Research & Development Counts for the Chemical Industry." This study addressed the void in quantitative assessments of the value of research by applying proven econometric and bibliometric methodologies in new ways to a particular sector – the U.S. chemical industry. The study's findings, based on data from more than 80 chemical companies over a twenty-year period, concluded:

- Every dollar invested in chemical R&D produces, on average, $2 in corporate operating income over six years – an average annual return of 17% after taxes. This return compares favorably to the weighted average cost of capital of roughly 8% for the chemical industry over the same timeframe.
- Research funded by the federal government and other public sources makes significant contributions to new technologies in the chemical industry, based on citations in patent filings.
- The linkage of public funded science to chemical patents is higher than in most industries, at roughly six citations per patent, and is increasing.

These results and the continued interest in the value of chemical research led to a follow-up study, titled "Measure for Measure: Chemical R&D Powers the U.S. Innovation Engine" (Phase II), which addressed three specific questions:

a. Does the quality of a chemical company's patent portfolio correlate with its financial success?
b. Is chemical research and technology an enabling technology for other industries, e.g., pharmaceuticals and electronics?
c. What is the time required from initial funding of scientific research to the first commercialization of new technology?

The results of Phase II, now completed, once again confirm the value of chemical research. The findings, based on a detailed bibliometric analysis of patents and scientific literature, concluded:

- Shareholder value is significantly higher (35-60%, on average) for chemical companies with high quality patent portfolios, based on citation impact, innovation speed and links to scientific literature.
- Chemistry is the most enabling science/technology; it underpins technology development in every industry. Chemical technology is unrivaled in its reach and enabling capability for other manufacturing industries.
- The time frame from initial public-funded basic research in chemistry to commercial scale utilization is roughly twenty years.

On the cusp of the nanotechnology revolution and other game-changing technologies, chemical science and technology can be expected to expand its influence as an enabling force throughout the economy. Already, findings from phase I of this study show that funds invested in R&D sooner rather than later enhance profitability. However, the chemical industry as well as other industries, still faces the seemingly intractable time frame from fundamental research to patented invention. Reducing this time-span presents the chemical industry with the opportunity to enhance its competitive and prosperous posture in the global marketplace and to continue to be a primary enabler of all U.S. innovation.

EXECUTIVE SUMMARY

Measure for Measure: Task 1

Prepared by:
Patrick Thomas and Michael Albert

This examination addresses the question of whether there is any correlation between the patent holdings, or technology portfolios, of chemical companies and their financial performance. In essence this tells us whether investing in high quality research and development brings financial benefit to chemical companies.

ipIQ's (formerly CHI Research) Tech-Line data-base was used for this analysis. The database contains patents for all organizations that have received 45 U.S. patents in the previous five years. This report's specific focus is on all Tech-Line U.S. chemical companies for each year between 1991 and 2001. There are 65 such companies.

To achieve comprehensive findings, the study uses several indicators of financial performance. These include the internal measures of revenue and profit and the stock market indicators of market valuations and stock price changes.

Chemical company patents and patent portfolios are the vehicles used to judge a company's technology.

Patent citation analysis is culled from "prior art" citations shown on the front page of patents. Each patent application requires historical listings of previous patents on which the new patent builds but clearly advances in a unique and novel way.

When a company's patents receive many repeated patent citations on new patent applications, the cited technology can be judged of high quality and value. There is a strong, but not absolute, relationship between citations and technological importance.

In the Task 1 analysis, three patent portfolio indicators were used. Each indicator allowed the assessment of a company's patent portfolio independent of the varying sizes of the companies examined.

The indicators:

- Current Impact Index or CII: a measure based on the frequency that a patent is cited by subsequent patents.

For more specific accuracy the CII is divided into two categories:

  - Internal CII: based solely on a company's citations from its own patents to its own previous patents – an internal process.
  - External CII: based on citations that do not come from a company's own patents, but rather from patents outside that company – an external process. External CII reveals the extent to which a company exerts influence on the technologies developed by other companies.

- Science Linkage or SL: the average number of citations a company's patents make to scientific papers provides a measure of its links to scientific research.

- Innovation Speed or IS: the median age of patents cited by a company's patents indicate the speed of the company's innovation process.

This analysis sheds light on the difference between the financial performances of companies with strong versus weak technology indicators. Several financial indicators were examined: market to book value, stock price change, operating revenue, and net income.

In each area, the relationship between a chemical company's different technology indicators and a specific measure of financial performance is examined. The accompanying charts separate companies into two groups based on their being above or below the median for each technology indicator.

- Market to Book Value (MTB) is the valuation placed on a company by the stock market. High MTB indicates that the stock market deems the firm to have value that exceeds the value of assets on its balance sheet.

- Stock Price Changes are examined to grasp the dynamic relationship of how a company's technology indicators influence changes in the company's stock price over time, as opposed to at a snapshot moment.

- Operating Revenues and Net Income (profit) are internal company measurements that allow an examination of the relationship between a company's technology – specifically investment in high quality R&D – and future financial benefits.

Findings:

- Chemical companies with highly cited patents have stronger financial performance than companies with lower impact patents.

- Chemical companies with high impact patents also tend to have higher stock market valuations, 35–60% higher on average, and greater increases in stock prices, operating revenues, and profits.

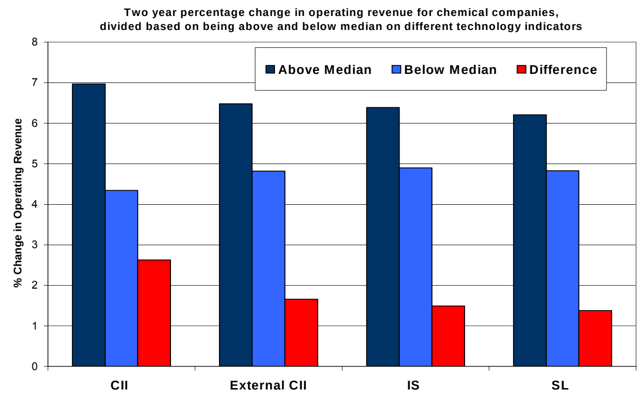
- It should be noted that the companies building, in large part, on their own technology tend to have greater future increases in operating revenues.

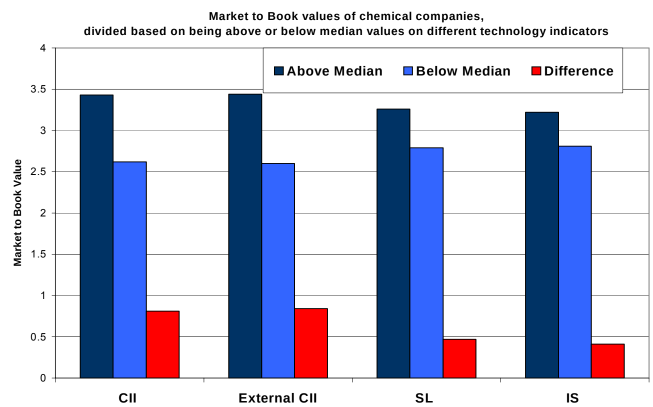
- Chemical companies with strong patent portfolios, building on their own technology, and those with patents that have strong impacts on other companies have, on average, strong financial performance.

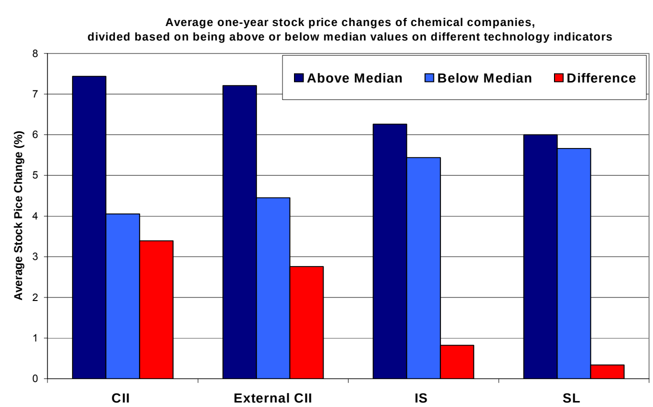
- Chemical companies with science linkage as well as innovation speed have favorable financial performance, however, the link between these indicators and positive financial performance is definitely weaker than the connection between high impact patents and strong financial performance.

- Companies that invest in high quality technology that continues to influence the technological directions of the chemical industry have the most favorable financial performance.

The three figures below illustrate the impact of the four key indices on revenue growth, market to book valuation, and stock price increases, respectively.







Measure for Measure: Task 2

Prepared by:
Michael B. Albert, Diana Hicks and Peter Kroll

Task 2 in the Phase II study verifies that chemical technology is a pervasive force in US innovation. While phase I of this study analyzed patents technology-by-technology, it did not provide the kind of evidence that would show the true indisputability of chemical technology as an enabling technology for other industries. In Phase II, the focus was to look at patenting technology by industry, thereby expanding our understanding of chemical technology's overarching role in the economy.

In the Task 2 analysis, the term chemical technology includes chemicals, plastics, polymers, and rubber.

Task 2 was based on industry-by-industry analysis of 477,000 U.S. patents granted between 1999-2001, and their front-page citations to patents and science papers. For the study's purpose, industry is defined as a group of companies belonging to only one industry. Out of the 477,000 patents examined, 287,000 are attributable to industry. For purposes of comparison in the study, fifteen industries comprising 1,151 companies were used. They represent 29 technologies.

Methodology:

- Data analysis is by frequency, or how often an industry patents in a particular technology. Technologies are divided into three categories: Core, Important, and Irrelevant.

- Core technology accounts for at least 10 percent of an industry's patents. Important technology accounts for between 1 and 10 percent of an industry's patents. Irrelevant technology accounts for less than 1 percent of an industry's patents.

- In order to quantify the enabling capability of chemical science and technology, the prior art references of the patents were examined. These are previous patents upon which the new patent builds. In this analysis, the cited patents are identified as the "technology base".

- To measure base technology, it was divided into three levels. Core Base Technology: technology that accounts for at least 10 percent of citations from an industry's patents. Important Base Technology: technology that accounts for between one and ten percent of citations from an industry's patents. Irrelevant Base Technology: technology that accounts for less than one percent of citations from an industry's patents.

- Analysis of cross-industry spillovers represents another mechanism to gauge the importance of chemical technology. This approach looks at how many industries utilize and build upon chemical technology.

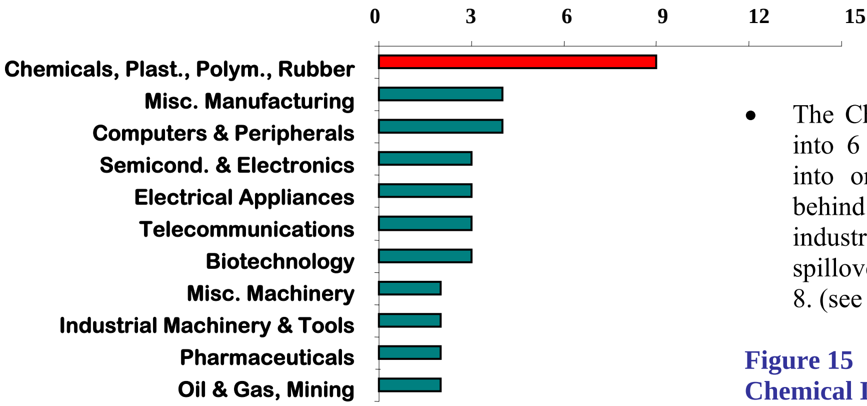
- Technology spillover is also divided into three categories: high, medium, and low. Low spillover into an industry indicates that the cited industry accounts for less than one percent of the citing industry's citations, medium spillover for 1-10 percent, and high spillover for over 10 percent.

- The final approach in Task 2 is to measure chemistry's importance as a science-base in comparison to other sciences. Published papers in scientific fields are cited from patents in each industry. Counting these direct citations quantifies yet another indicator of how chemistry is used as an enabling technology. Research papers are categorized in 8 fields, depending on the journal in which each has been published. Cited papers are called the science base.

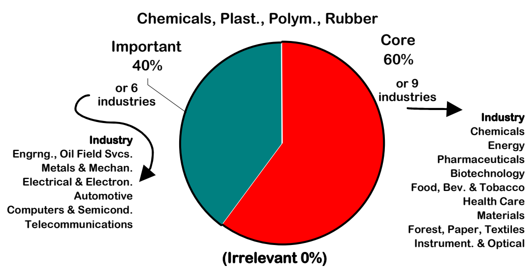
Findings:

- Chemical technology is in the top three technology areas of patenting in 9 of the 15 major industries examined as shown in Figure 5. No other technology is as omnipresent in as many industries.

Figure 5
Chemical Technology is Among The Top Three Patenting Areas in 9 Industries

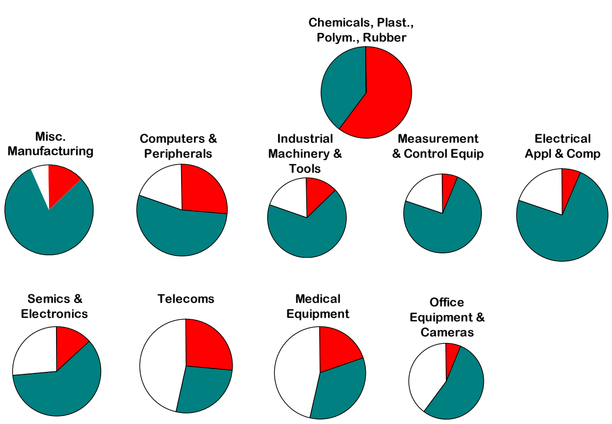


- Chemical technology is "Core" in 60 percent (9) of the 15 industries, is "Important" in 40 percent (6), and is "Irrelevant" in none as shown below.



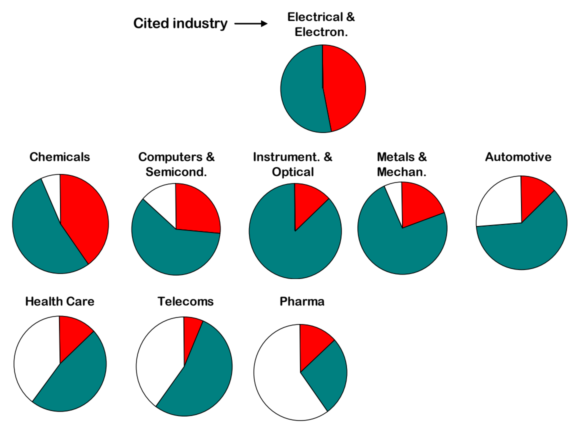
- Figure 12 illustrates the comparisons with other technologies. No other technology is as prevalent and influential as chemical technology in all industries. By contrast, Computers and Peripherals is Important in 8 industries and Core in only 4.

Figure 12
Technology Base Across Industries: Again Chemical Technology Ranks First



- The Chemical industry, with high spillover into 6 industries, medium into 8, and low into one, comes in a close second right behind the Electrical and Electronics industry, whose numbers indicate high spillover into 7 industries and medium into 8. (see Figure 15)

Figure 15
Chemical Industry Spillover Ranks Second Only to Electrical & Electronics



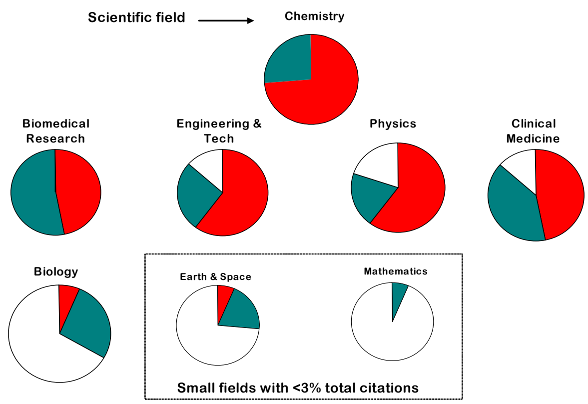
- Chemistry again shows its significance by being among the top three cited scientific fields in 13 of the 15 industries, ranking first even over physics, which is among the top three in only 10 industries. (Figure 20)

- Figure 20 also indicates the number of industries in which each scientific field is Core, Important, or Irrelevant. Both chemistry and biomedical research are Core or Important across all industries, but chemistry is Core in 11 industries, versus biomedical research in 7.

- With this information, it is easy to see that chemistry is the most enabling science/technology. Without the force of chemistry in all its forms, the rate of discovery and innovation for all industries would be significantly diminished.

Figure 20

Science Base Across Industries: Chemistry Ranks First



Measure for Measure: Task 3

Prepared by:
Peter Kroll

Through bibliometric methodology, Task 3 has measured the average length of time from the fruition of a successful commercial innovation back to the onset of the supported research.

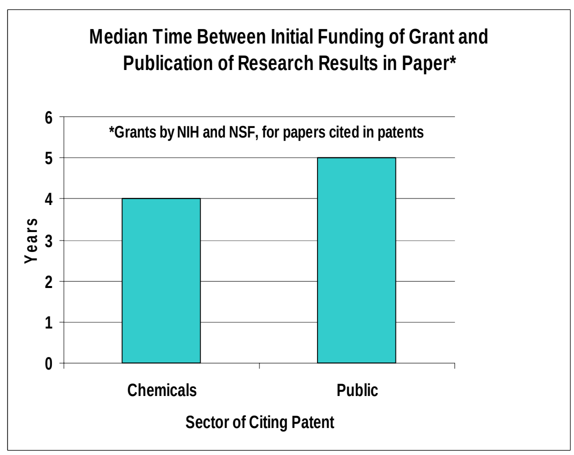
To measure each development period of the process to innovation, the Task was separated into four stages. The total time required for each of the four stages (T-1, T-2, T-3, T-4), when combined, represents the average time for supported chemical research to emerge as innovation.

Task 3 used patents in two technology areas: Chemicals and Plastics, Polymers, and Rubber. The comprehensive term used for these two technologies in Task 3 is chemical technology.

Definitions and Results:

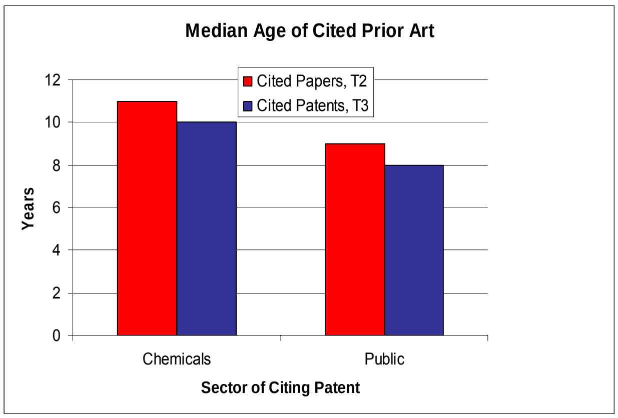
- The T – 1 period, which represents the time from initial funding to the publication of results in a science paper, breaks down into two distinct categories: (Figure 9)
    - A – a median age of four years for papers cited in chemical industry patents
    - B – a median age of five years for papers cited by public sector patents

Figure 9 Time from Grant to Paper



- T-2 period, is the time from science paper publication to citing patent grant date (science-to-technology cycle time). The results from this period are comprised of two components, Chemical technology patents cited by Chemical companies, which are a median age of ten years, and cited science papers, which have a median age of eleven years, as shown in Figure 7.

Figure 7 Age of Cited Prior Art



- T-3 period encompasses the time from issuance of predecessor patent to the grant date of new patent (technology cycle time). The results indicate that public sector Chemical technology patents build on previous patents and science papers that are almost two years more recent than for Chemical industry patents, on an average of 8 and 9 years, respectively. This is also shown in Figure 8.

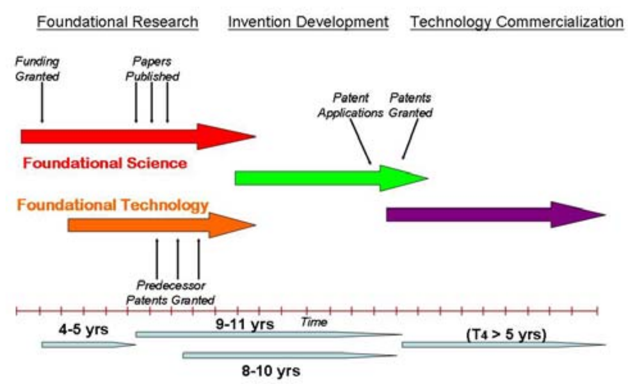
- T-4 time is portrayed in Figure 10 and indicates that the average time from patent issuance to scale-up for marketplace commercialization is estimated to be at least five years for significant innovations.

Findings:

- The average time-cycle from the fundamental research grant to the patented invention is usually 13 – 16 years. (T-1 through T-3 periods)

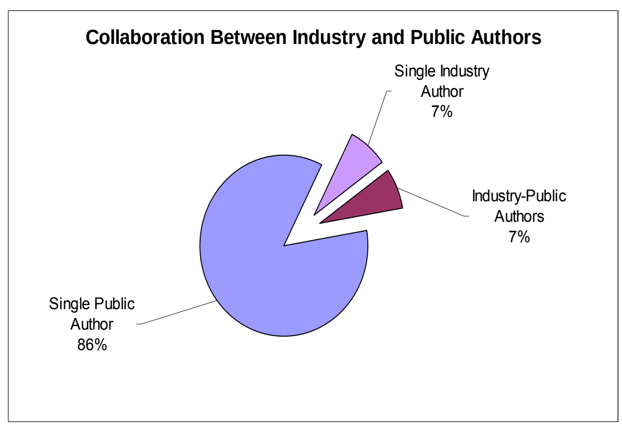
- Factoring in the T-4 period, the complete cycle from initial funding of a research grant to the technology's emergence as marketable product is 18 - 21 years as illustrated in Figure 10.

Figure 10 Timeline from Conception to Market



- As shown in Figure 12, 86% of the cited science papers are published by single authors in the public sector, 7% by single authors in industry, and the remaining 7% are published by a combination of industry and public sector authors in collaboration. Thus, it is clear that the chemical industry and the public sector rely on public research.

Figure 12 Sectors Collaborate in Cited Papers



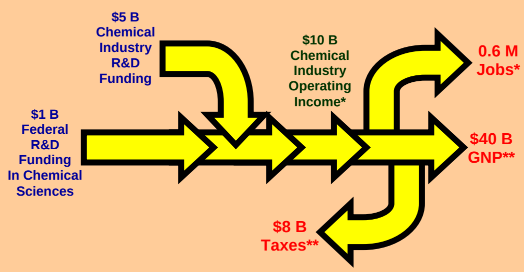
Macroeconomic Implications

The federal government spends just over $1 billion a year of R&D in round numbers on the chemical sciences. The chemical industry "leverages" that government investment in basic research with approximately $5 billion of its own R&D spending. The CCR Phase I study showed that for each dollar of chemical industry R&D investment, the industry on average earned $2 in increased operating income.

In 2005, researchers from the Los Alamos National Laboratory working for the Chemical Industry Technology Vision2020 group and the Department of Energy completed a report examining the macroeconomic impacts of chemical industry income changes on GNP and jobs using the REMI Policy Insight model. The model predicted a GNP multiplier of 4.

Applying that multiplier to the incremental industry operating income predicted in the Phase I study would yield $40 billion in incremental GNP, 600,000 new jobs and roughly $8 billion in additional tax revenues each year, not a bad return on the government's $1 billion investment.

Schematically, the implications look like this:



Basis:
*estimated from CCR study
**extrapolated from LANL study by Thayer, et al., April 2005 using REMI economic model

Phase II Task 1:
"The Links between the Quality of Chemical Companies' Technology and their Financial Performance"

Prepared by:
Patrick Thomas and Michael Albert, ipIQ, formerly CHI Research, Inc.

INTRODUCTION

CHI is pleased to present the results of its analysis examining the links between the quality of chemical companies' science and technology and their financial performance. The report examines various measures of financial performance, including internal measures such as revenue and profit, and stock market measures such as market valuations and stock price changes. By relating these measures to different characteristics of chemical companies' science and technology, we are able to highlight relationships between technology quality and financial performance.

This phase of the CCR project is designed to complement previous phases of the project, and to contribute to its overall objective of developing a greater understanding of the role of chemical technology. Previous phases of the CCR project have examined the relationship between research and development expenditures and operating revenues for chemical companies; and how chemistry is an enabling technology – a technology upon which many other technologies build extensively. The current phase adds to these studies by examining the financial benefits of investing in high quality science and technology.

This report contains three main sections. In the first of these, we outline the methodology used in our analysis. This section includes a description of the data employed, and the indicators used to measure both technological quality and financial performance. Also described is the approach used to examine the relationship between chemical companies' technology quality and their financial performance. The results of the analysis are reported in the second main section of the report. This section is divided according to the financial indicator being examined. It is structured to show the relationship between technology quality and revenues, profits, stock market valuations, and stock market returns. The final section of the report summarizes the results, and provides a discussion of their implications for chemical companies.

METHODOLOGY

This study is designed to examine the relationship between chemical companies' technology and their financial performance. In the study, we use patents as a proxy for the technology of these companies. Patents are becoming increasingly important to commercial organizations, both to secure internal technological developments, and to generate revenue from licensing initiatives. This is especially true in technology intensive industries such as chemicals.

Given the steady growth of the patent system and the importance of managing intellectual property, it has become increasingly important to be able to analyze patent portfolios without sifting through thousands of individual patent documents. For this reason, a technique referred to as patent citation analysis has been developed to analyze statistically the quality and strength of patent portfolios.

Patent citation analysis is based on the prior art citations that appear on the front page of patents. When a patent is applied for, its inventor must show that the invention is novel, useful, and non-obvious to someone with average expertise in the same industry. To do so, the inventor will cite to earlier patents, and explain why the new patent improves on the earlier inventions. The patent examiner may also add earlier inventions that limit the scope of the new invention.

Given that almost all patents cite to earlier patents, it is possible to count up the citations a patent receives from later patents. The underlying principle in patent citation analysis is that a highly cited patent (i.e. a patent that is referred to by many subsequently issued patents), is likely to contain technological advances of particular importance that have led to numerous subsequent technological improvements. It follows that a company whose patent portfolio contains a large number of highly cited patents is generating high quality technology. Hence, one would expect that companies whose patents are highly cited would tend to be more successful innovators, and so perform better in both commercial and capital markets than companies whose patents are cited less frequently.

This does not mean that every important patent is highly cited, or that every highly cited patent is important. However, numerous validation studies have shown the existence of a strong positive relationship between citations and technological importance. In a series of research papers, CHI has shown that patent citations are related to various measures of technological importance, such as pioneering status, patent renewal decisions, and peer review by scientists.

Data

There are a number of barriers that must be overcome before using patent citation analysis to evaluate companies' technology. Perhaps the most complex problem is that of matching patent assignee names to individual companies. Companies may patent under many different names, including subsidiary names. It is also a major challenge to account for company mergers, acquisitions, and divestitures. In addition, large numbers of patents are often reassigned from one company to another, many due to mergers and acquisitions. Hundreds of thousands of reassigned patents therefore have to be assigned as accurately as possible to the company that currently owns them.

The analysis presented in this paper is based on data taken extracted from CHI Research's Tech-Line® database. This database contains patents for all organizations that have been issued at least 45 U.S. patents in the previous five years. There are currently around 1,800 of these organizations worldwide. CHI has constructed accurate organizational structures for each of these organizations, to account for the over 30,000 different assignee names under which they patent.

Our analysis in this report covers all US chemical companies in the Tech-Line database each year between 1991 and 2001. There are a total of 65 such companies (including a small number of energy companies with extensive chemicals patent portfolios). Not all of these companies are in the analysis in all years. Due to the minimum patent threshold, some companies are only in the analysis in more recent years. Alternatively, a number of companies are only in the analysis in the earlier years, because they were subsequently taken over by another company. The total number of companies included in the analysis in each year is shown in Table 1.

Table 1 – Number of companies included in the analysis in each year

Year	Number of Companies in Analysis
1991	42
1992	43
1993	44
1994	44
1995	47
1996	44
1997	49
1998	47
1999	42
2000	40
2001	41

Indicators

The Tech-Line database does not only contain patent lists for each company. It also contains various quantitative indicators that measure different characteristics of companies' patent portfolios. In this analysis, we used a number of these indicators to examine the relationship between chemical companies' technology and their financial performance. In addition, we constructed a new set of indicators that measure chemical companies' links to the science and technology produced by public organizations. These indicators were developed to enable us to examine the relationship between chemical companies' links to public organizations and their financial performance.

A number of companies in our analysis have relatively small numbers of patents, and barely meet the minimum threshold for inclusion in the Tech-Line database. As a result, their technology indicators are based on relatively small numbers of patents. These indicators can therefore vary widely across years, and be skewed heavily by one or two unusual patents. Since our purpose is to examine the relationship between companies' investment in high quality research and development and their future financial performance, it is useful to reduce the effect of short-term fluctuations in technology indicators. To achieve this, we used three year moving averages for each of the indicators. For example, to calculate a Science Linkage indicator for a company at the end of 1995, we took the mean of its Science Linkage values in 1993, 1994 and 1995.

Patent Indicators

As noted above, there are a number of patent indicators in the Tech-Line database. We used three of these indicators in this analysis, and these indicators are described below. One indicator we did not use is the number of patents. The chemical companies in our analysis are of vastly different sizes, and the size of patent portfolios is closely related to company size. By including the number of patents in the analysis, we would simply be examining the impact of company size upon financial performance, rather than the quality of companies' technology. The three patent indicators we used are all size-independent, in that they have no inherent bias towards larger or smaller patent portfolios. Their purpose is to measure the quality of companies' patent portfolios without reference to their size. The three patent indicators used in the analysis are:

Current Impact Index (CII): The CII shows the impact of a company's patents on the latest technological developments. It is a measure of how frequently the previous five years of a company's patents are cited by patents issued in most recent year, relative to all US patents. The CII is a synchronous indicator, and moves with the current year, looking back five years. As a result, when a company's patents from recent years start to drop in impact, this is reflected by a decline in the current year's CII.

The CII can be split into two components – ***Internal CII*** and ***External CII***. Internal CII is based solely on citations from a company's patents to its own earlier patents. It is therefore a measure of the extent to which a company builds on its own technology. External CII is based on citations that do not come from the same company's patents. By eliminating these self-citations, the External CII provides a measure of the extent to which a company is influencing the technologies developed by other companies.

Science Linkage (SL): Science Linkage is a measure of the extent to which a company's technology builds upon cutting-edge scientific research. It is calculated based on the average number of references on a company's patents to scientific papers, as distinct from references to previous patents. Companies whose patents cite a large number of scientific papers are assumed to be working closely with the latest scientific developments.

Innovation Speed (IS): In general, companies that are innovating rapidly tend to be more successful in product development than companies relying on older technologies. This leads to another citation indicator, the Innovation Speed (IS). Innovation Speed is a measure of the median age of the US patents cited on the front page of a company's patents. A tendency to cite older patents is an indication that a company utilizes older technology. The average Innovation Speed is as short as three or four years in rapidly evolving industries, such as electronics, and as long as fifteen years in industries that change more slowly, such as shipbuilding.

Indicators of Links to Public Science and Technology

As part of this report, we analyzed whether the financial performance of companies is related to their links to publicly funded science and technology. In this analysis, we used scientific papers as a proxy for science, and patents as a proxy for technology.

In order to carry out this analysis, we first had to define what we mean by publicly funded papers and patents. In this analysis, these designations are based on the organization producing a particular paper or patent. For the purposes of the analysis 'public' organizations are defined as organizations that are not commercial enterprises. These include universities and colleges, medical schools, non-profit organizations, and state and federal government agencies, including Federally Funded Research and Development Centers (FFRDCs).

Public papers are defined as papers that have at least one author whose institutional affiliation, as listed on the paper, is among the set of public organizations outlined above. CHI maintains a database containing a sub-set of published papers. This database contains all papers with at least one author with an affiliation to a US organization, either public or private. Further, the database is restricted to papers cited by at least one US patent in the ten years following their date of publication.

We used this database to examine chemical companies' links to public scientific papers. Our analysis therefore examines the citation links between chemical companies and papers with at least one US author from a US organization. For each company, we calculated what percentage of the papers they cite are from public organizations, and what percentage is produced by private institutions. Companies that cite a high percentage of papers from public organizations are assumed to be building on public science and technology to a greater extent than companies citing mainly papers from commercial organizations.

It should be noted that chemical companies do not cite scientific papers as frequently as companies in some other industries, such as pharmaceuticals and biotechnology. As a result, not all companies in the analysis cite enough papers to make it possible to produce a robust calculation of the percentage of these papers are authored by public organizations. We restricted our analysis to companies that cite a minimum of 10 papers in a particular year. This reduces the number of companies included in the analysis of the relationship between companies' links to public science and their financial performance. The results of this part of the analysis should therefore be approached with care.

Public patents are defined as patents that have at least one assignee among the same list of public organizations. The assignee is the individual or organization that owns, either fully or partially, the rights to a particular patent. CHI maintains a database containing all of the assignee names that represent public organizations. This database includes variant names for different organizations, including the names of their constituent parts. Using this database, we were able to determine which patents cited by chemical companies are assigned, either wholly or partially, to public organizations.

We identified all patents cited by patents assigned to each of the chemical companies included in our analysis. For each company, we then determined what percentage of these cited patents are assigned to public organizations. We carried out the same analysis with regard to patents citing to patents owned by the chemical companies. Again, we calculated the percentage of these citing patents that are assigned to public organizations. Companies with stronger citation links to public organizations are assumed to be working more closely with the technology produced by these organizations.

Relating Technology Indicators to Financial Performance

The primary purpose of this report is to examine the relationship between companies' investment in high quality research and development and their performance on various financial indicators. Due to the relatively small number of companies in the analysis, we were restricted in the analyses we could implement. The approach we used was designed to add robustness to the analysis, while still providing insights into differences between the financial performance of companies with stronger and weaker technology indicators.

This approach involved three stages, as outlined below. The stages are the same for each technology indicator and, to simplify the description of them, we use the example of the Current Impact Index (CII):

1. In each year, we divided companies into two groups – those with a CII value above the median value, and those with a CII value below the median. For example, in 1991, companies are divided into two groups according to whether their CII at this point is above or below the median.

2. The results from all years are combined into a single data set. This produces two sets of companies – those with CII values above and below the median at a given point in time. There were 241 companies in each of these groups (an average of around 22 companies in each group from each of the eleven years included in the analysis).

   It is possible for companies to appear in both groups at different points in time. For example, a company may have a CII above the median in 1994, but below the median in 1998. It will therefore form part of the above median group in 1994, but will be part of the below median group in 1998.

3. Having constructed the two groups (above and below median CII) we examined whether are differences between these two groups in terms of their mean (i.e. average) financial and stock market performance. We examined a variety of financial indicators, including operating revenue, net income, market to book value, and stock price change.

   We measured these financial indicators contemporaneously with the technology indicators, and also one, two and three years in the future. This helps to determine whether there are any time lags evident in the relationship between technology indicators and financial performance.

The same process was used for each of the technology indicators, with companies divided according to whether they are above or below the median for a particular indicator at a given point in time. Table 2 lists the indicators used in the analysis, and describes what is meant by the above and below median groups for each indicator.

Table 2 – Technology indicators included in the analysis

Technology Indicator	Above Median Group	Below Median Group
CII	Higher impact patents	Lower impact patents
Internal CII	Companies build extensively on their own technology	Companies do not build extensively on their own technology
External CII	Companies have stronger impact on other companies' technology	Companies have weaker impact on other companies' technology
Science Linkage	Stronger links to science	Weaker links to science
Innovation Speed	Faster innovation	Slower innovation
Cites to Public Patents	Higher percentage of cited patents are assigned to public organizations	Lower percentage of cited patents are assigned to public organizations
Cites from Public Patents	Higher percentage of citing patents are assigned to public organizations	Lower percentage of citing patents are assigned to public organizations
Cites to Public Papers	Higher percentage of cited papers are authored by public organizations	Lower percentage of cited papers are authored by public organizations

RESULTS

The results of our analysis are presented in four sections. Each section examines the relationship between the different technology indicators and a particular measure of financial performance. The charts used in each section are similar. These charts divide the companies into two groups based on being above or below the median for each technology indicator. For each group, the average (mean) for a particular financial indicator, such as stock market valuation, is shown. This reveals whether companies above the median for a particular patent indicator perform better or worse in financial terms than those companies below the median.

Market to Book Values

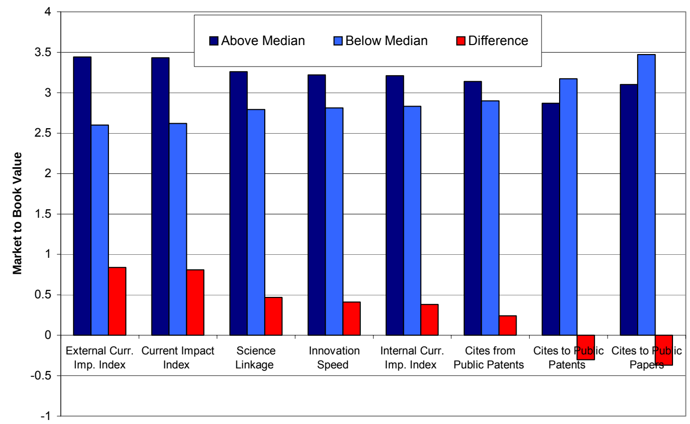
The first financial indicator we examined was companies' market to book (MTB) value. The MTB measures the relationship between the Market Value of a company (Share Price x Number of Shares Outstanding) and its Book Value (the value of the net assets on its balance sheet). For example, if a company has a Book Value of $10 million, and has 5 million outstanding shares priced at $4 each, it has an MTB of two ($20 million/$10 million). The MTB is a measure of the valuation placed on a company by the stock market. A high MTB shows a company that the stock market believes has a value over and above the value of the assets on its balance sheet.

Figure 1a shows the market to book values of chemical companies, divided according to whether they above or below the median on different technology indicators. This figure reveals that companies with Current Impact index values above the median at a given point in time have a mean market to book value of just below 3.5. This is much higher than the average market to book of 2.6 for companies below the median in terms of CII. This suggests that companies with high impact patents also tend to have higher stock market valuations.

We split the CII into internal (self-citing by companies) and external (citing by other companies) components. Figure 1a shows that companies with high External CII values have much higher average market to book values than companies below the median for this indicator. This suggests that companies whose patents have a strong impact on other companies tend to have higher valuations in the stock market.

Figure 1a reveals similar results for Science Linkage and Innovation Speed indicators. Companies with above-median values for each of these indicators have higher average market to book values than companies with below-median values. This suggests that chemical companies

Figure 1a
Market to Book values of chemical companies divided according to whether they are above or below median values on different technology indicators

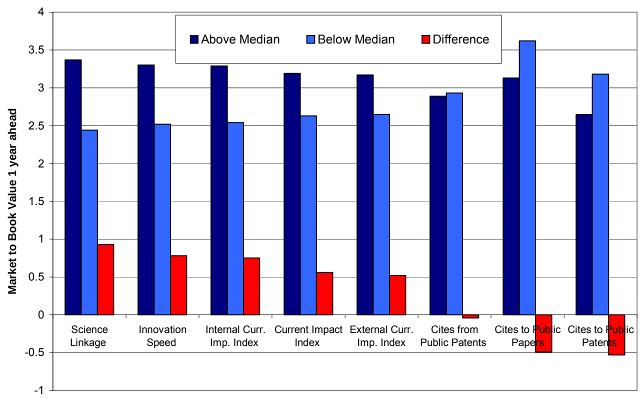


that innovate quickly, and have close links to scientific research, tend to have higher stock market valuations than companies with slower innovation and lesser links to science. However, the difference between the two groups is not as great as that discovered for the CII indicator.

The results with regard to links to public science are less clear. Figure 1a shows that there is little difference in the average market to book values of chemical companies with extensive links to public science and technology, and those companies with fewer such links. Indeed, companies that cite public patents and papers more than average tend to have slightly lower market to book values. This result suggests that there is no direct link between companies building on public science and technology and their financial performance.

Figures 1b, 1c and 1d also show the relationship between chemical companies' technology

Figure 1b
Market to Book values (one year ahead) of chemical companies divided according to whether they are above or below median values on different technology indicators



indicators and their market to book values. However, instead of the y-axes showing the market to book values at the same point in time as the technology indicators, they show market to book values one year ahead (Figure 1b), two years ahead (Figure 1c) and three years ahead (Figure 1d). This is designed to reveal whether the results change when a time lag is introduced between the technology indicators and market to book values.

Figure 1c
Market to Book values (2 years ahead) of chemical companies divided according to whether they are above or below median values on different technology indicators

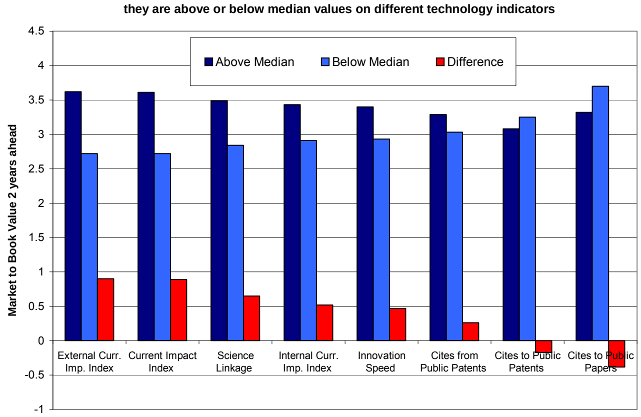
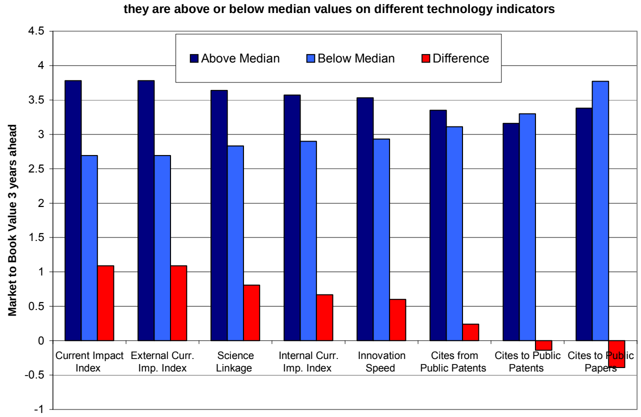


Figure 1d
Market to Book values (3 years ahead) of chemical companies divided according to whether they are above or below median values on different technology indicators



These graphs all show similar results to Figure 1a. In each case, companies above the median in CII, Science Linkage and Innovation Speed have higher average market to book values than companies that are below the median on these indicators. The results with respect to links to public science are again less clear. Companies with extensive links to publicly funded patents and papers do not appear to have higher stock market valuations than companies with weaker links to public science.

Having examined the relationship between individual technology indicators and stock market valuations, we then combined the technology indicators to evaluate whether this would result in stronger relationships. Figure 2 shows the results of combining the two technology indicators with the strongest links with stock market valuations – Current Impact Index and Science Linkage. In this figure, companies are divided into four groups according to whether they are above or below the median for both CII and SL. The figure reveals that companies above the median for both indicators have an average market to book value of 3.7. This is almost 50% higher than the average market to book value of 2.5 for companies below the median on both indicators. Companies above the median on one indicator but below the median on the other have average market to book values that fall between these two endpoints.

Figure 2 also shows that this pattern is similar if future stock market valuations are analyzed. Again, companies with above-median CII and SL values have the highest market to book valuations. These valuations are much higher than those of companies whose CII and SL values are below the median. This result suggests that companies with more than one strong patent indicator are particularly likely to have a higher market to book valuation.

Figure 2
Market to Book (MTB) values for chemical companies divided according to whether they are above or below median for Current Impact Index and Science Linkage

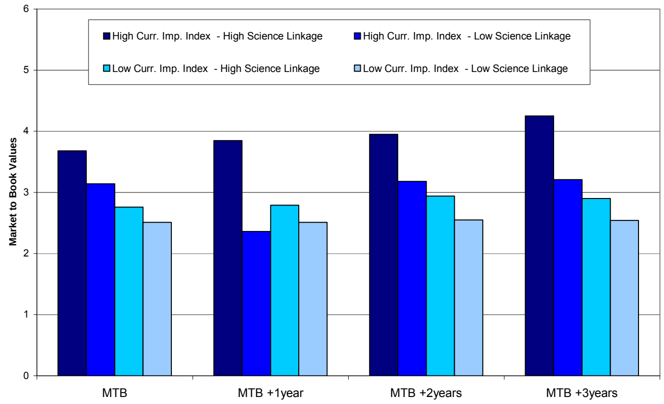
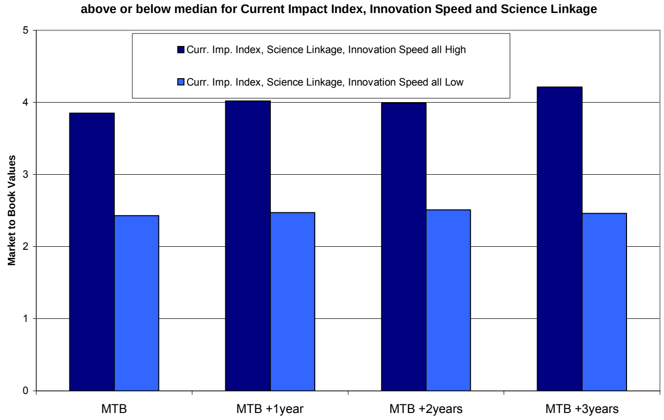


Figure 3 supports this finding. This figure shows two groups of companies – those above the median for Current Impact Index, Science Linkage and Innovation Speed, and those below the median for all three of these technology indicators. This figure shows that the former group of companies had an average market to book value of 3.85, while the average for the latter group was 2.4. This difference remains relatively constant even after time lags are introduced to map technology indicators against future market to book valuations.

Figure 3
Market to Book (MTB) values for chemical companies divided according to whether they are above or below median for Current Impact Index, Innovation Speed and Science Linkage

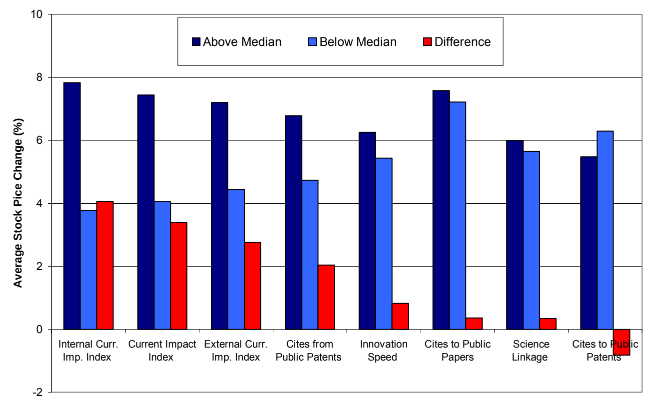


Stock Price Changes

The previous section examines the relationship between technology indicators and the stock market valuations of chemical companies. These valuations are static, in that they reflect stock market sentiment at single points in time. It is also interesting to examine how technology indicators are related to how this stock market sentiment changes over time. To study this, we analyzed the relationship between technology indicators and changes in stock prices over time.

Figure 4a shows the relationship between technology indicators and stock price changes one year later. For example, we related technology indicators for the end of 1995 to stock price changes from the end of 1995 to the end of 1996. Again companies are divided into two groups, depending on whether they are above or below the median for different technology indicators at a given point in time.

Figure 4a
Average one-year stock price changes of chemical companies divided according to whether they are above or below median values on different technology indicators



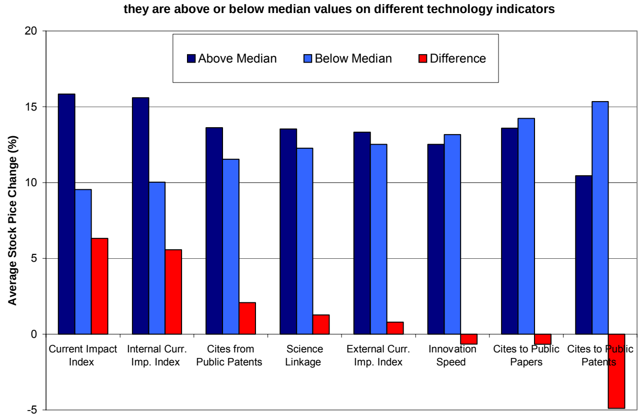
This figure shows that companies with a CII above the median at a given point in time have an average stock price increase of almost 7.5% in the following year. Meanwhile, companies with a CII below the median experience average stock price increases of just over 4%. Hence, on average, companies above the median in CII enjoy stock price increases almost twice as high as companies whose CII is below the median. The difference between the above and below median groups is even stronger with regards to

Internal CII (the portion of the CII that results from a company citing its own patents). The above median group has an average stock price increase of almost 8%, compared to less than 4% for the below median group.

Companies above the median in Innovation Speed and Science Linkage also had higher average stock price increases than companies below the median for these indicators. However, the differences were relatively small, suggesting that these two indicators were not strongly related to stock market performance. Links to publicly funded science and technology also proved not to be strongly related to stock market performance.

The results are similar if the period over which stock price changes are measured is increased from one year to two years. Figure 4b shows that companies with CII values above the median have an average two year return of 16%. This compares favorably with the return of less than 10% for companies whose CII is below the median. Again, Internal CII is particularly strongly related to stock price changes. There appears to be little relationship between Innovation Speed or Science Linkage and two-year stock price movements. In addition, there is no consistent relationship between links to public science and technology and two-year stock price

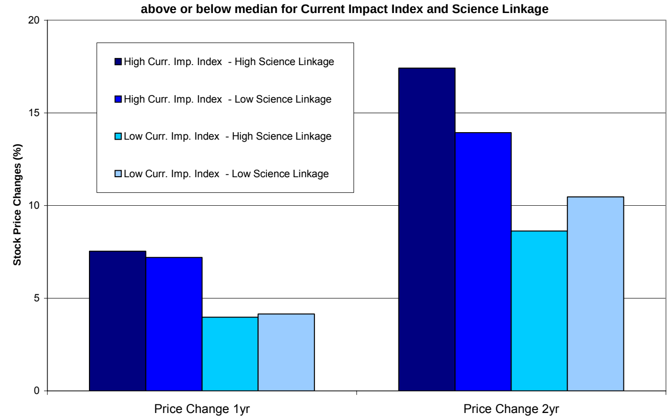
Figure 4b
Average two-year stock price changes of chemical companies divided according to whether they are above or below median values on different technology indicators



movements.

Figure 5 shows one and two year stock price changes of companies divided according to whether they are above or below the median for both CII and SL. This figure shows that companies above the median for CII have a

Figure 5
Average stock price changes for chemical companies divided according to whether they are above or below median for Current Impact Index and Science Linkage



higher average stock price return than companies below the median for CII. This finding is not affected by whether companies have a high or low SL value. This supports the finding reported above that CII is particularly strongly related to stock price changes, while SL has a much weaker relationship with stock price changes.

Operating Revenues

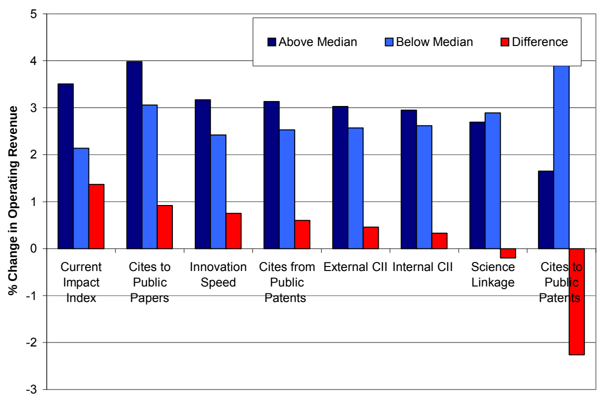
The previous two sections of this report examine the relationship between technology indicators and stock market valuations and performance. We also analyzed the relationship between technology indicators and internal measures of financial performance. The financial measures we examined were operating revenue and net income.

In studying the relationship between technology indicators and operating revenue, an analysis of static operating revenue figures is of little value. Large companies have higher revenues than smaller companies, irrespective of the quality of their R&D. It is more interesting to examine the relationship between technology indicators and changes in operating revenue over time, since these changes can be observed across companies of different sizes. We therefore related technology indicators at given points in time to changes in operating revenue one and two years later. It should be noted that this does not mean we are claiming a direct causal relationship between a particular set of patents and future revenues. Rather, we are examining how investing in high quality R&D over a period of time can have future financial benefits.

Figure 6a shows the relationship between technology indicators and one year changes in operating revenue. For example, technology indicators for the end of 1995 are mapped against changes in operating revenue between the end of 1995 and the end of 1996. This figure shows that companies with a CII value above the median at a given point in time have an average increase in operating revenue of 3.5% one year later. This compares favorably with the 2.1% increase experienced by companies with a CII value below the median.

The differences between the above and below median groups based on Internal and External

Figure 6a
One year percentage change in operating revenue for chemical companies divided based on whether they are above or below median on different technology indicators



CII are both smaller than the differences based on overall CII. This seemingly anomalous result occurs because of companies that are above the median for Internal CII and below the median for External CII, or vice versa. The most notable example of this involves the two groups of companies that have these characteristics, and are below the median for overall CII:

Group 1 - below median CII, above median internal CII, below median external CII
Group 2 - below median CII, below median internal CII, above median external CII

On average, these two groups of companies experience a reduction in operating revenues of 4-6%.

Both Group 1 and Group 2 fall into the below median overall CII group. The fall in operating revenue for Group 1 and Group 2 thus reduces the average increase in operating revenues for companies below the median for overall CII. There is no reduction in the average for companies above the median for overall CII.

The same is not true when companies are divided based on internal and external CII. The fall in operating revenues associated with Group 1 reduces the average percentage change for the above median internal CII group, since Group 1 companies have a high internal CII. Meanwhile Group 2 contributes to the above median external CII group, thus reducing the average percentage change for this group.

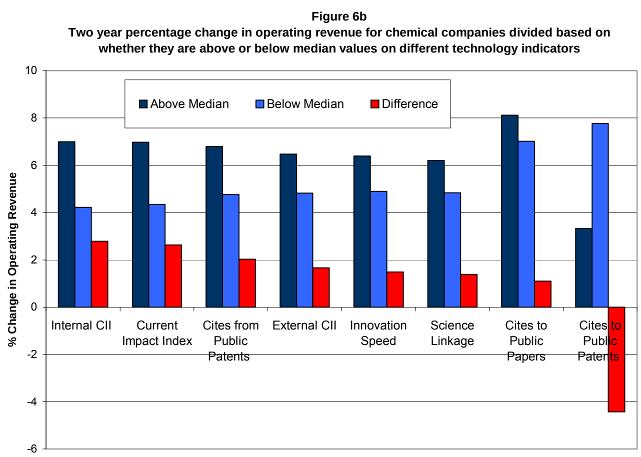
Not only are the average percentage changes for the above median internal/external CII groups adversely affected by Group 1 and Group 2. The below median groups experience higher average changes, since the reductions in revenue associated with Group 1 do not contribute to the below median internal CII group, and Group 2 companies do not contribute to the below median external CII group.

This helps to explain the result shown in Figure 6a, where the difference between the above and below median groups according to overall CII is greater than the differences based on both internal and external CII.

With reference to Innovation Speed, companies that innovate faster than the median have an average one-year increase in operating revenue of 3.2%. Meanwhile, companies that innovate slower than the median have an average increase of 2.4%. Although this difference is smaller than that for CII, it still suggests that faster innovation is related to increases in operating revenues. The same cannot be said for Science Linkage. The average change in operating revenue is similar for companies above the median for Science Linkage, and those below median for this indicator.

In terms of links to public science and technology, the results are mixed. Companies that cite large numbers of scientific papers authored by public organizations tend to enjoy higher increases in revenue. The same is true of companies whose patents are cited frequently by patents assigned to public organizations. However, companies whose patents cite frequently to patents assigned to public organizations tend to have much lower increases in operating revenue.

If the time period over which changes in operating revenue are measured is increased from one year to two years, the results remain similar, as shown in Figure 6b. Companies with CII values above the median have an average two-year increase in operating revenue of 7% compared to 4.3% for companies whose CII is below the median. The internal component of the CII has a particularly important role in this difference. This suggests that companies building extensively on their own technology tend to have greater future increases in operating revenue.



The results for Innovation Speed and Science Linkage are similar to each other. In both cases, companies above the median have an average two-year increase in operating revenue of just over 6%. Meanwhile, companies below the median have an average increase of just below 5%. Hence, companies that innovate quickly and have extensive links to science tend to have slightly higher future revenues. However, the differences in revenue changes between the above and below median groups for Innovation Speed and Science Linkage are lower than the difference based on companies being divided according to their CII values. This reinforces the finding that, among the different technology indicators, CII has the strongest relationship with financial performance.

The results with regard to links to public science and technology are again mixed. It is notable that companies that build extensively on patents assigned to public organizations tend to have lower increases in operating revenue. This finding is the same as that discovered for one-year changes in operating revenues. It suggests that there is no direct link between companies building on public technology and increases in their revenues.

Net Income

We examined the relationship between technology indicators and changes in chemical companies' net income (often referred to as profit). As in previous sections of the analysis, we divided companies into two groups according to whether they were above or below the median for different technology indicators at a given point in time. However, we used a different approach to evaluate differences between these two groups in terms of changes in net income.

In percentage terms, net income can change greatly over a short period of time. For example, a company could earn $10 million one year, and $50 million the next. This represents a 400% increase in net income. Changes in net income of this magnitude are not uncommon. The average (mean) change in net income for a group of companies could therefore be skewed by one or two extreme cases.

We therefore decided not to analyze the mean change in net income for the above and below median groups of companies (an approach that would have mirrored that used to study market to book, stock prices and operating revenues). Instead, we calculated the percentage of above and below median companies that experienced an increase in net income one and two years later.

The results of this analysis are presented in Table 3. The left half of this table is based on one year changes in net income, while the right half is based on two year changes in net income. This table shows that 56% of companies with a CII value above the median at a given point in time had an increase in net income one year later. The other 44% of companies in this group experienced a one year decrease in net income. Hence, well over half the companies with CII values above the median had increases in net income. The opposite is true of companies with CII values below the median. As Table 3 shows, only 42% of companies with a CII below the median had an increase in net income one year later. The other 58% of companies in this group experienced a fall in net income.

Companies with Innovation Speed values faster than the median are also slightly more likely to experience increased net income than companies whose Innovation Speed is slower than the median. Over 51% of the former group experienced a one-year increase in net income, compared to 47% of the latter group. The difference between these percentages is much smaller than that between the above and below median CII groups. This suggests that the relationship between Innovation Speed and changes in net income is weaker than that between patent impact and net income changes.

Table 3 – The relationship between chemical company technology indicators and changes in net income

	% of Companies with Increased Net Income One Year Ahead		% of Companies with Increased Net Income Two Years Ahead	
	Above Median	Below Median	Above Median	Below Median
Current Impact Index (CII)	56.0%	42.6%	58.9%	40.0%
External CII	50.8%	47.4%	53.3%	45.6%
Internal CII	53.7%	45.3%	49.1%	49.7%
Innovation Speed	51.6%	46.9%	50.6%	49.2%
Science Linkage	46.9%	50.8%	44.5%	54.5%
Cites to Public Patents	47.4%	51.4%	45.2%	54.7%
Cites from Public Patents	48.2%	50.5%	51.4%	53.8%
Cites to Public Papers	48.9%	52.1%	55.4%	44.4%

With reference to Science Linkage, companies below the median have a higher likelihood of experiencing increases in net income. Hence, increased links to science do not appear to result in improvements in companies' profitability. The same finding is true for links to public science and technology. The percentage of companies experiencing increases in net income did not differ greatly between the above and below median groups based on cites to and from public patents, and cites to public papers.

The results for two year changes in net income are shown in the right half of Table 3. The results are largely similar to those for one year net income changes. Current Impact Index again has the strongest relationship with net income changes. Almost 60 % of companies above the median for CII at a given point in time experience an increase in net income two years later. This is compared to only 40% of companies with CII values below the median. The weaker relationship between Innovation Speed and one year net income change disappears almost completely with regard to two year changes in net income. Meanwhile, the negative relationship between Science Linkage and net income change remains after two years. There is also little evidence to suggest that links to public science and technology are linked to increased profitability. While companies that cite public papers are more likely to have increased net income, those that cite public patents are less likely to do so.

CONCLUSIONS

This report presents the results of our analysis of the relationship between different aspects of chemical companies' technology portfolios and their financial success. We examined a range of technology indicators, including patent impact, links to scientific research, innovation speed, and links to science and technology produced by public organizations. We also examined a range of measures of financial performance, including stock market valuations, changes in stock prices, changes in operating revenue and changes in company profits.

The results of our analysis show that, on average, companies with high impact (i.e. highly cited) patents have stronger financial performance than companies with lower impact patents.

Companies in the former group tend to have higher stock market valuations and larger increases in stock prices, operating revenues and net income. This result is similar for companies that build extensively on their own technology, and companies whose patents have a strong impact on other companies.

Given the consistent positive relationship between high impact patents and financial performance, it may be interesting to know which are the most highly cited patents assigned to the companies included in the analysis. Appendix 1 contains a list of the 197 chemicals patents assigned to the companies in the analysis that have been cited by at least 50 subsequent patents. These 197 patents may be regarded as important patents that have had a strong impact on later technological developments. Thirty different companies have at least one patent in this list. The companies with the largest number of patents in the list are DuPont, Exxon, Dow, and Procter & Gamble.

The relationships between the Science Linkage and Innovation Speed indicators and financial performance are also generally positive, although they are much weaker than the relationship between patent impact and financial performance. Chemical companies that innovate quickly and build extensively on scientific research thus tend to produce slightly better financial results. However, it is the impact of these companies' patents on later technological developments that is particularly closely linked to financial performance. This suggests that companies investing in high quality technology that influences the technological direction of the chemical industry tend to be more successful in terms of financial performance.

The results with regard to chemical companies' links public science and technology and their financial performance are less clear. We did not find a consistent relationship between extensive citation links to public science and improved financial performance. However, this finding may be a reflection of the shortcomings of using direct citation links to analyze the links between companies' technology and public science. By their nature, direct citation links do not capture cases where companies build on public science indirectly. For example, basic science supported by public organizations may form the basis for a variety of important advances in the chemical industry. Chemical companies may build on this basic science in some way. However, because the science has become so widely accepted, there is no requirement for the companies to cite the original papers introducing it. Direct citation links may not therefore capture the complexity of the relationship between public science and corporate technology, and a more nuanced analysis may be necessary to study this relationship

Phase II Task 2
"Chemistry: the Enabling Science / Technology"

Prepared by: Michael B. Albert, Diana Hicks and Peter Kroll, **ipIQ, formerly CHI Research, Inc.**

INTRODUCTION

CHI Research is pleased to report here the completion of the Phase II task that directly addresses the following question: Is chemistry of significance in enabling technological advances across many industries? It turns out that the answer to the question is an emphatic "yes." The quantitative data on breadth and depth of applicability across all industries show that chemistry is *the* enabling science and technology. More so than any other science / technology we find that:

- All industries create chemical technology. The evidence is seen in the patenting activity within each industry; there is significant chemical technology patenting going on in all industries.

- The underpinning of all industries' technology relies on chemical technology. The evidence is found in industry-to-technology patent citations, that is, the degree to which the patents generated in each industry build on chemical technology as prior art.

- Cross-industry technology spillovers are highest from the electrical industry and the chemical industry comes in a close second. The evidence is in industry-to-industry patent citation counts; patents granted to companies in all industries build on patents granted to electrical industry and chemical industry companies.

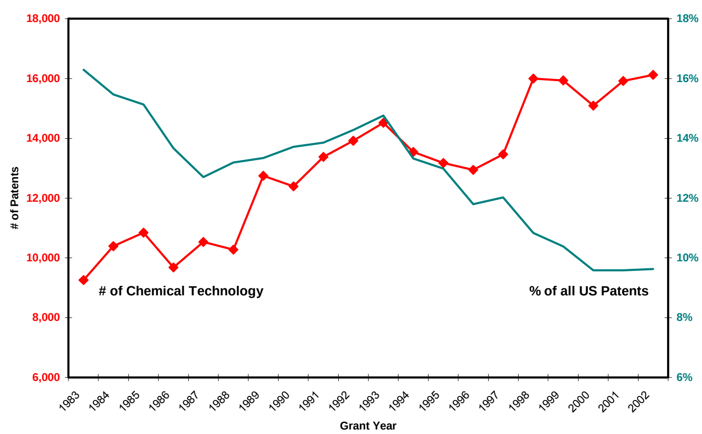
- Finally, chemistry is an important part of the science base of all industries. The evidence is found in patent-to-paper citations; patents granted to companies in all industries cite chemistry papers as prior art.

This study follows on from Phase I, completed in November 2000, where we compared U.S.-origin chemical technology U.S. patents to those in other major technology areas, as well as to non-U.S.-origin chemical technology patents. Based on a set of patent activity and patent citation indicators, in Phase I we found that:

- Overall, chemical technology patenting is growing, but has grown relatively slowly, compared to other technologies, such as life sciences and information technology (**Figure 1**).

Figure 1

Chemical Patent Share is Declining



- The impact of U.S.-invented chemical technology patenting has risen steadily, in contrast to the declining impact of Japanese-invented chemical technology patents and the steady but relatively low impact of German-invented chemical patents.

- U.S. chemical technology patents cite much more heavily to scientific research papers than any other U.S. technology except for life sciences, and most of the scientific papers cited by chemical technology patents are funded out of the public sector.

- For chemical technology, aside from contributing most to its own technology, the area it contributes to the most is life sciences, where close to 20 percent of the patents cite to at least one chemical technology patent. On the other hand, the contribution of chemical technology to other technologies is considerably lower.

While Phase I showed some indication of chemistry as an enabling science / technology, we realized that it was only telling part of the story. Because in Phase I we only looked at patenting technology by technology, and not by industry, we were not able to capture the richness of chemistry's contribution to different industries. But this is exactly what we are able to do in Phase II.

The balance of this report is organized as follows: In the next section we summarize the main points of our methodology. Then, in the sections that follow, we report in turn findings for four different industry-based approaches to the question of the enabling role of chemistry:

1. Is chemical technology created by many industries?
2. Is chemical technology a significant part of the technology base upon which new technology is created in many industries?
3. Is the chemical industry the source of significant technological spillover to many other industries?
4. Is chemistry a significant part of the science base upon which new technology is created in many industries?

METHODOLOGY

This study is based on industry-by-industry analysis of 487,000 1999-2001 granted U.S. patents and their front page citations to patents and papers. The four approaches examine, industry-by-industry, how these patents are distributed across technologies, and how their prior art citations are distributed by cited patent technology, by cited patent industry and by cited scientific paper field.

Industries: Two important and distinct concepts in this study are "industries" and "technologies." First, we are analyzing the patent portfolios of 15 industries, which are listed in **Figure 2.** We define an industry as a grouping of companies, each of which is a member of one, and only one, industry, and the patent portfolio of an industry is the combination of all the portfolios of the member companies in that industry. Since a very small percentage (~1 percent) of all assigned patents are co-assigned to more than one parent organization, we only use the first-given assignee name on co-assigned patents, in order to insure that no patent appears in more than one industry portfolio.

Figure 2

The 15 Industries (1151 companies)

- **Automotive* (90)**
- **Biotechnology* (41)**
- **Chemicals* (143)**
- **Computers & Semiconductors* (164)**
- **Electrical & Electronics* (116)**
- **Energy (34)**
- **Engineering, Oil Field Services (5)**
- **Food, Beverage & Tobacco* (28)**
- **Forest, Paper, Textiles* (37)**
- **Health Care (78)**
- **Instruments & Optical (49)**
- **Materials (24)**
- **Metals & Mechanical (238)**
- **Pharmaceuticals* (58)**
- **Telecommunications* (46)**

*** - denotes names that are very similar to the names of a technology**

In the figure, the number of companies in each industry is shown in parentheses beside the industry name; for example, 143 companies make up the chemical industry. In total, 1,151 U.S. and foreign industrial "parent" companies make up the 15 industries. These companies and their industry assignments are taken from CHI Research's Tech-Line® data product and database. In Tech-Line, CHI Research currently provides patent profiles for over 1,700 parent organizations that have received the most U.S. patents over the past five years. The 1,151 industrial companies included in this study are those that remain after eliminating approximately 600 organizations that are government agencies, universities or research institutes, plus a small number of companies in two hard-to-define industry groups we chose to exclude from this study: conglomerates and miscellaneous.

In Tech-Line we also designate a primary "industry group" for each parent company, based on a variety of sources such as industrial directories, company web pages, and reported primary Standard Industrial Classification (SIC) data. This industry group designation is used here to place each company in an industry. [1]

Technologies: The second concept concerns technologies. A technology is a way of characterizing patents by the art of their inventions, which is something quite different from characterizing the patents by the nature of the companies that own them. IBM, a computer industry company, owns patents in many technology areas, not only the obvious ones such as computers and semiconductors, but also less obvious technologies such as food, biotechnology, industrial machinery, and, of course, chemicals.

In this study we classify each patent into one, and only one, of 29 technologies, listed in **Figure 3**. (One of the technologies is Chemicals, Plastics, Polymers and Rubber, or "Chemicals" for short.) The classification is based on the main invention art International Patent Classification (IPC) given to each patent by the patent examiners. Typically, patents are given several IPCs, but for simplicity's sake, we only work with the "main classification." Since, as we indicated above, we insure that each patent is assigned to a single industry, we can now say that in this study each of the patents owned by any one of the 1,151 companies is (a) assigned to a single industry and (b) assigned to a single technology.

Figure 3
The 29 Technologies

- **Aerospace & Parts**
- **Agriculture**
- **Biotechnology***
- **Chemicals, Plastics, Polymers & Rubber***
- **Computers & Peripherals***
- **Electrical Appliances & Components**
- **Fabricated Metals**
- **Food & Tobacco***
- **Glass, Clay & Cement**
- **Heating, Ventilation & Refrigeration**
- **Industrial Machinery & Tools**
- **Industrial Process Equipment**
- **Measurement & Control Equipment**
- **Medical Electronics**
- **Medical Equipment**
- **Miscellaneous Machinery**
- **Motor Vehicles & Parts***
- **Office Equipment & Cameras**
- **Oil & Gas, Mining**
- **Other**
- **Other Transport**
- **Pharmaceuticals***
- **Power Generation & Distribution**
- **Primary Metals**
- **Semiconductors & Electronics***
- **Telecommunications***
- **Textiles & Apparel***
- **Wood & Paper***

*** – denotes names that are very similar to the names of an industry**

One word of caution, often the names of industries and technologies are the same or very similar. For example, when we refer to the telecommunications industry we are referring to the set of companies that make up that industry and when we refer to telecommunications technology we are referring to technology that has been assigned to specific telecommunications patent classifications (telephony,

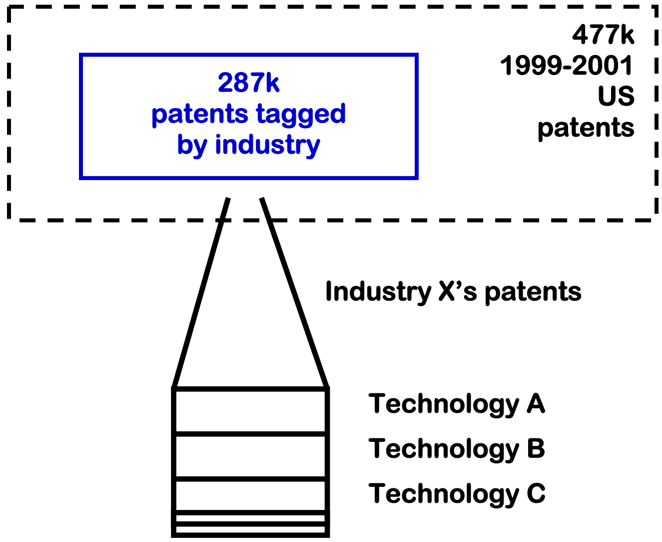
[1] A complete list of the companies is provided on the CHI Research, Inc. website at http://www.chiresearch.com/about/data/tech/co_byindustry.php3. Note that the list is arranged by Tech-Line "industry group." Twelve of the industries in this study are equivalent to industry groups. The other three are consolidations of several industry groups as follows: Metals and Mechanical is made up of four industry groups, Aerospace, Consumer Products, Materials, and Metals; Computers & Semiconductors is the combination of two industry groups, Computers and Semiconductors; and Forest, Paper Products, and Textiles combines two industry groups, Forest & Paper Products and Textiles.

television, etc.) by the patent examiners. Other technologies that are used in the telecommunications industry, such as semiconductors and electronics (IC chips) or plastics (cable shielding) or electrical (power supplies), are not classified as telecommunications technology *per se*.

<u>287,000 1999-2001 industry patents</u>: Each of the four analyses starts with U.S. patents granted in the three-year period from 1999 to 2001. We selected a three-year period, rather than a single year, to insure that each industry's patent set is robust. We selected a recent period because we are interested in knowing whether chemistry is enabling today, rather than whether it was enabling at some time in the past. Between 1999 to 2001, a total of 477,000 U.S. utility patents were granted, but not all of these 477,000 patents are assigned to organizations (about 15 percent of all granted patents are held by individual inventors) and not all of the patents that are assigned to organizations are assigned to the companies that make up our 15 industries. As is shown in the diagram in **Figure 4**, of the 477,000 1999-2001 U.S. patents issued, we are able to assign 287,000 to an industry.[2]

Figure 4

Industry Technology Creation Using Patent Counts



<u>Data environment:</u> The analyses described in the following sections are all based on relational database tables carefully designed and constructed in CHI Research's SQL server environment. The database is large and complex; in general, the tables in this database contain hundreds of thousands, in some cases millions, of records. Several examples of the tables are: (1) a table of each of 287,000 citing patents, pairing each patent to its technology, (2) a table of nearly 2 million citation linkage pairs between the 287,000 citing patents and the over 900,000 patents cited on their front pages and (3) a table listing the technology of each of these cited patents. Valid results depend both on correct design of the database tables and careful and correct formulation of database queries, many of which "join" together several tables in the database. For example, a joining of the second and third table examples in one query enables us to map citation linkages by cited technology.

INDUSTRY TECHNOLOGY CREATION

In the first of four approaches to our main question, we examine technology creation across industries, using patenting activity to measure technology creation. This is the most objective and viable way to measure industry R&D activity by type of technology. With the possible exception of perhaps a

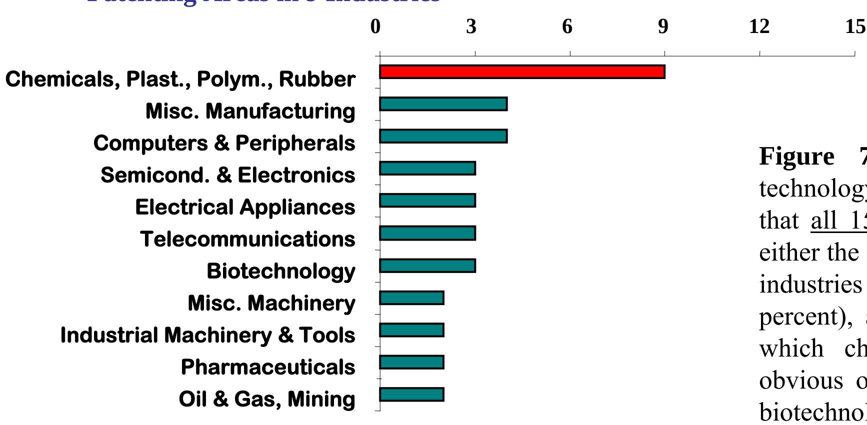
[2] The 1,151 companies that make up the industries account for approximately 80 percent of all granted patents that are assigned to organizations; that is, are not individually owned.

handful of companies, this is certainly something that is not possible to obtain from company reporting of R&D expenditures, which are not broken down by technology.

We quantify technology creation for each industry by determining how many patents, in the source set of patents for that industry, belong to a given technology. Again referring to **Figure 4**, as a hypothetical example, if we look at the source set made up of all the patents belonging to companies in Industry X, we can count how many in the set belong in technology A, how many in technology B, how many in technology C, and so on. Once we have done the same for each of the industries, we are then able to compare technology creation rankings and intensities across all the industries.

Let us now look at several useful ways to rank and compare technology creation across the industries. **Figure 5** plots the number of industries in which different technologies rank first, second or third by number of granted patents.[3] We see that chemical technology is among the top three technology areas of patenting in 9 of the 15 industries, and that this is a far broader fraction of the 15 industries than we find for any other technology. Miscellaneous Manufacturing and Computers & Peripherals both rank in the top three technologies in only 4 of the 15 industries, and the remaining technologies rank in the top three even less than that.

Figure 5
Chemical Technology is Among The Top Three Patenting Areas in 9 Industries



[3] Appendix Figures A1 and A2, respectively, provide detailed tables of patent counts and percentage distributions by industry and technology.

One may ask whether just looking at this ranking is sufficient to really understand what we are seeing here. That is why we introduce another way to examine the data, one that asks how often an industry patents in a technology. We define three levels of patenting:

- Core technology: technology accounts for at least 10 percent of an industry's patents.
- Important technology: technology accounts for between 1 and 10 percent of an industry's patents.
- Irrelevant technology: technology accounts for less than 1 percent of an industry's patents.

As is shown in the hypothetical example in **Figure 6**, we can use a simple pie chart to diagram the percent of industries for which a given technology is core, important or irrelevant. In this example, Technology A is core in one third of the industries (5 of the 15 industries), important in one third of the industries (another 5 industries) and irrelevant in one third of the industries (the remaining 5 of the 15 industries). For us the real question is whether chemical technology is core for many industries or not?

Figure 7 shows the distribution of chemical technology creation for the 15 industries. We see that all 15 industries create chemical technology at either the core or important level; it is core in 9 of the industries (60 percent), important in 6 industries (40 percent), and irrelevant in none. The industries in which chemical technology is core include the obvious ones - chemicals, energy, pharmaceuticals, biotechnology, food beverage and tobacco - and some that are not so obvious: materials, forest paper & textiles, and instrument & optical.

Figure 6
For What % of Industries is Technology A Core, Important and Irrelevant? – Sample Graphs

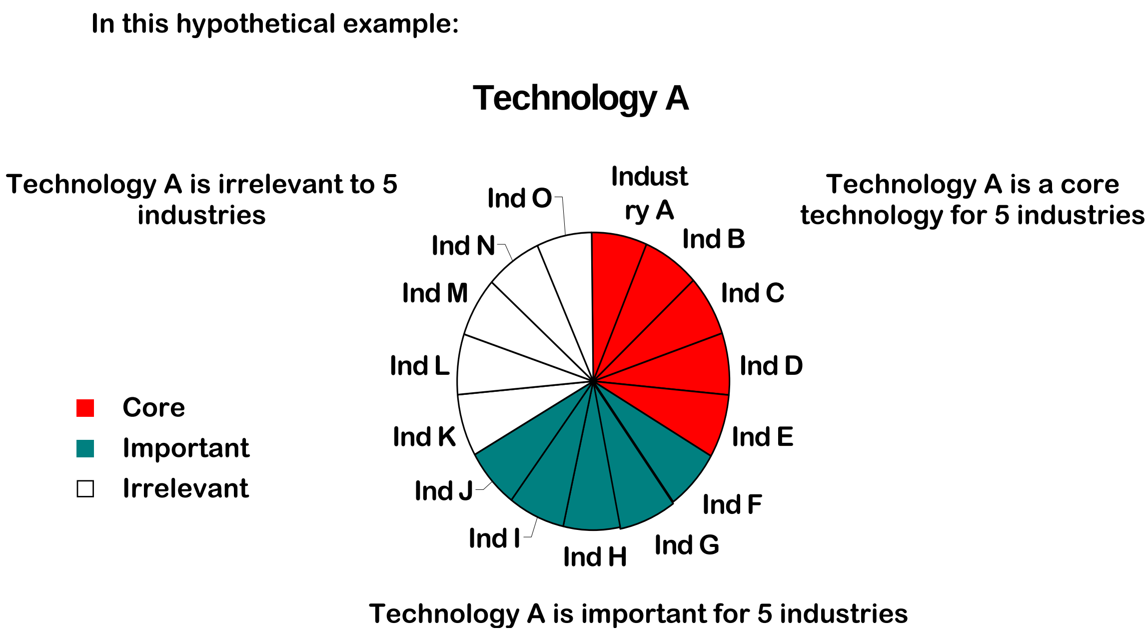
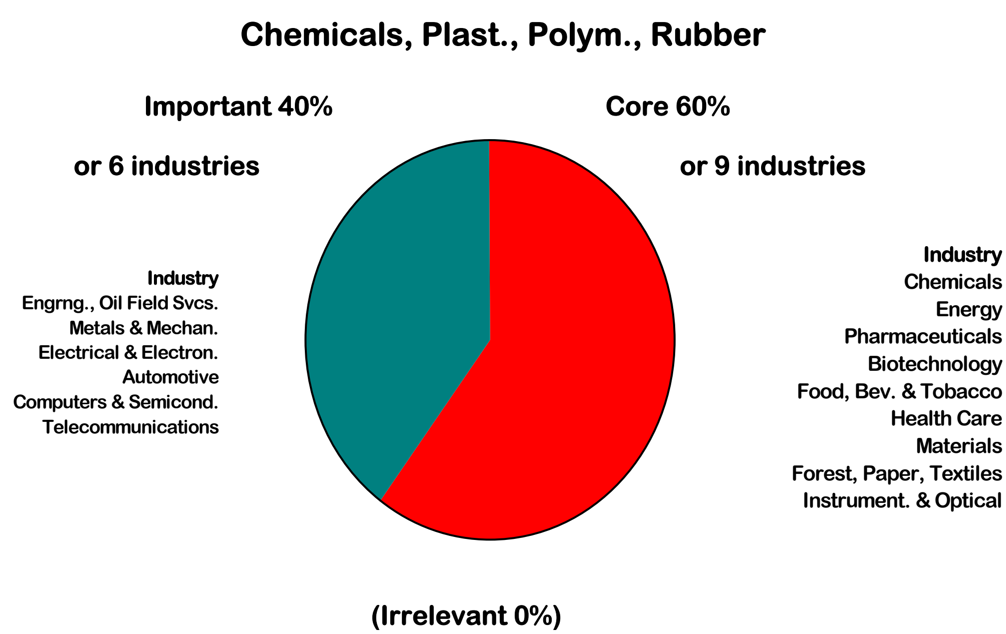
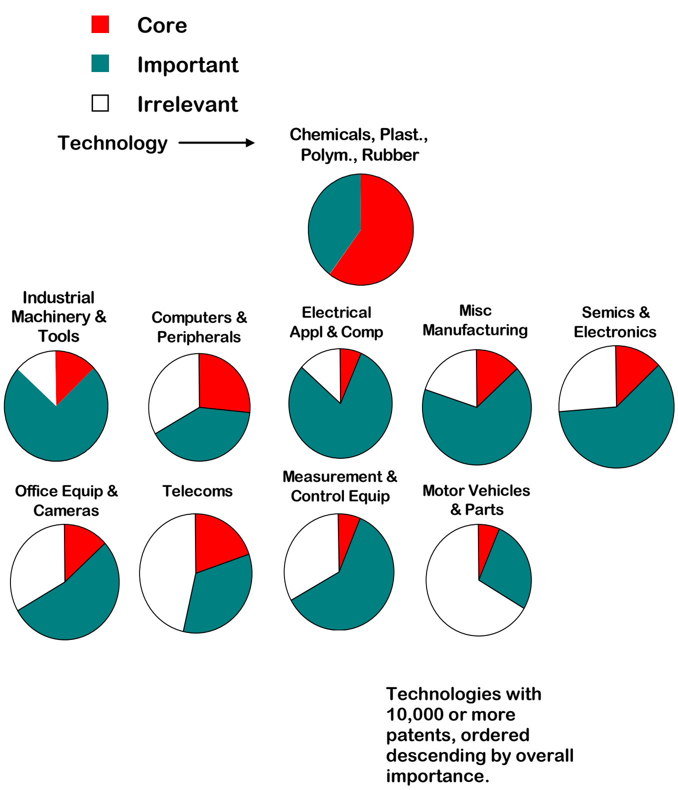


Figure 7
Chemical Technology Creation is Core or Important in All 15 of The Industries



But what about the other technologies? Pie charts for the top 10 technologies are compared in **Figure 8**.[4] We see that no other technology comes close to the breadth and intensity of chemical technology patenting across industries. For example, industrial machinery and tools is core in just 2 industries and important in 11, computers and peripherals is core in 4 and important in 6, and electrical appliances and components is core in just 1 and important in 12 industries.

Figure 8
Technology Creation Across Industries: Chemical Technology Ranks First



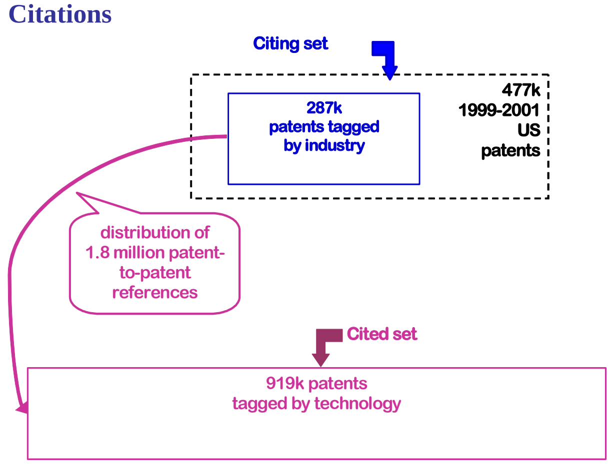
Summarizing our examination of technology creation, our finding is that all industries create chemical technology, and the evidence for this shows up in the patenting activity within each industry. In fact, we see that there is significant chemical technology patenting going on in all industries, and that chemical technology is core or important across a much broader range of industries than any other technology.

INDUSTRY TECHNOLOGY BASE

The second approach we take to quantify the extent to which chemical science and technology is enabling examines the distribution of underlying or base technology, specifically, the prior art references upon which each industry's patents are building. In the U.S. patent system, when patents are applied for, the applicants are bound to provide relevant prior art they are aware of; and, in the course of examining patent applications examiners may provide additional prior art references. When a patent issues, a list of all the prior art "examiner" references is included on the front page of the patent. The intent of these references is to define the bounds of the allowed patent claims.

We call the cited patents the "technology base." In **Figure 9** we again note the 477,000 1999-2001 U.S. utility patents, and the subset of 287,000 patents that can be matched to an industry. These 287,000 patents (the citing set) contain 1.8 million citations to 919,000 U.S. patents (the cited set). It is the distribution by cited patent technology of these 1.8 million patent-to-patent citations that we use to quantify the industry-to-technology base linkages.

Figure 9
Industry Technology Base Using Patent-to-Patent Citations



The average citation frequency among all cited patents is approximately 2 per patent, but is very

---
[4] In the figure technology areas are arranged in descending order based on a composite score, where 3 points are awarded for each core industry, 2 for each important one and 1 for irrelevant ones. The other 19 technologies, which are not shown, have less than 10,000 granted 1999-2001 patents, and are largely irrelevant across most industries.

skewed; while the vast majority of the cited patents are cited just once, a very small number of the cited patents are cited many times. **Figure 10** provides a list of the 20 most highly cited chemical technology patents and shows the cite count breakout by citing industry for each.[5]

The distribution across technologies of citations is not to be confused with the distribution across technologies of the 919,000 cited patents themselves. We look at the distribution of the citations to the cited patents, and not at the distribution of the cited patents themselves, because many of the top-cited chemistry patents are enabling in more than one citing industry, and only by looking at the citation distribution do we see this. For example, the 1993 Dow Chemical patent number 5,272,236, "Elastic substantially linear olefin polymers," is cited a total of 73 times from the citing set; 47 of these cites come from chemical industry patents, 10 from forest and paper products industry patents, and 7 each from energy industry and from metals and mechanical industry patents. A second reason to count citations, rather than cited patents, has to do with a given cited patent having been cited multiple times. Highly cited patents should be given more weight in determining the nature of the cited prior art. This can only be done by counting citations.

Figure 11 plots the number of industries in which a given technology is cited first, second or third as prior art.[6] Chemical technology is among the top three cited technologies in 10 of the 15 industries, while no other technology is among the top three in more than 4 of the 15.

Looking deeper, at the level of citations coming from each industry, let us define three levels of citation intensity, that is, citations to core, important and irrelevant base technology:

- Core base technology: Technology accounts for at least 10 percent of citations from an industry's patents.
- Important base technology: Technology accounts for between one and ten percent of citations from an industry's patents.
- Irrelevant technology: Technology accounts for less than one percent of citations from an industry's patents.

We use the pie chart method of visualizing the data as before. **Figure 12** shows that no other technology comes close to matching chemical technology[7]. As a base technology, it technology is core in 9 of 15 industries, and important in the other six. By comparison, miscellaneous manufacturing technology, which includes construction and layered products, is a small technology area that appears to be of generic importance; it is important as a core technology in just two and is an important base technology in 12 industries. Computers and peripherals and telecommunications, two technology areas with more patents and more total cites each than chemical technology, also do not have the same broad enabling presence. Computers and peripherals is core in just 4 and important in 8 industries, while telecommunications technology is only core in 4 and important in 4 industries.

Our industry technology base finding then is that chemical technology is a significant part of the underpinning or base of all industries' technology. The evidence is found in industry-to-technology patent citations, that is, the degree to which the patents generated in each industry build on chemical technology as prior art.

Cross Industry Spillovers

Our third approach to the question of whether chemistry is an enabling science / technology looks at cross-industry spillovers, most specifically, how many different industries build upon all the technology produced by the industry, as compared to all the technology produced by the other industries. The method is the same as before, except that this time we look at high, medium and low spillover, rather than core, important or irrelevant technology.

[5] Refer to Appendix Figure A3 for a list showing the same information for the 100 most highly cited chemical technology patents.

[6] See Appendix Figures A4 and A5 for detailed citation counts and percentage distributions by citing industry and by cited patent technology.

[7] In the figure technology areas are arranged in descending citation share order, based on a composite score, similar to that used in Figure 8. Technologies receiving less than 60,000 citations are not shown.

Figure 10
Most Highly Cited Chemical Technology Base Patents

Ranked by number of cites received from 1999-2001 industry patents — Citation counts broken out by industry of citing patent:

U.S. patent number	Title	Issue Date	Assignee	Main IPC Subclass	Cites recd from all years all pats.	Cites from '99-'01 industry pats.	Forest, Paper, Textiles	Chemicals	Pharmaceuticals	Biotechnology	Instruments & Optical	Computers & Semiconductors	Metals & Mechanical	Energy	Electrical & Electronics	Health Care	Food, Bevg & Tobacco	Materials	Telecommunications	Automotive
3953566	PROCESS FOR PRODUCING POROUS PRODUCTS	4/27/1976	GORE (W. L.) & ASSOC INC	B29D	632	116	88	7	1		1	1	10		3	3		1		1
4340563	Method for forming nonwoven webs	7/20/1982	KIMBERLY-CLARK WORLDWIDE INC	B29J	429	90	80	4			1		4	1						
5272236	Elastic substantially linear olefin polymers	12/21/1993	DOW CHEMICAL CO.	C08F	379	73	10	47			1		7	7		1				
4133814	2-PHENYL-3-AROYLBENZOTHIOPHENES USEFUL AS ANTIFERTILITY AGENTS	1/9/1979	LILLY (ELI) & CO.	C07D	356	72			71							1				
5278272	Elastic substantialy linear olefin polymers	1/11/1994	DOW CHEMICAL CO.	C08F	309	69	19	37					8	2		1		2		
5085698	Aqueous pigmented inks for ink jet printers	2/4/1992	DU PONT (E.I.) DE NEMOURS & CO.	C09D	221	63	18	10			19	15			1					
5143854	Large scale photolithographic solid phase synthesis of polypeptides and receptor binding screening thereof	9/1/1992	AFFYMAX TECHNOLOGIES N.V.	G01N	438	61	4		7	46	3	1								
4491628	POSITIVE- AND NEGATIVE-WORKING RESIST COMPOSITIONS WITH ACID GENERATING PHOTOINITIATOR AND POLYMER WITH ACID LABILE GROUPS PENDANT FROM POLYMER BACKBONE	1/1/1985	IBM CORP.	G03C	275	55		24				21			8				2	
5055438	Olefin polymerization catalysts	10/8/1991	ECPI/EXXON CHEMICAL PATENTS INC	C08F	240	55		33			1			20				1		
4597794	RECORDING PROCESS AND A RECORDING LIQUID THEREOF	7/1/1986	CANON KK	C09D	189	53	1	27			15	7	2		1					
4576850	SHAPED PLASTIC ARTICLES HAVING REPLICATED MICROSTRUCTURE SURFACES	3/18/1986	MINNESOTA MINING & MFG. CO.	C08G	194	49		5			38		4	1				1		
4380635	Synthesis of acylated benzothiophenes	4/19/1983	LILLY (ELI) & CO.	C07D	242	46			46											
5126022	Method and device for moving molecules by the application of a plurality of electrical fields	6/30/1992	SOANE TECHNOLOGIES, INC.	G01N	202	46				38			7		1					
4816567	RECOMBINANT IMMUNOGLOBIN PREPARATIONS	3/28/1989	GENENTECH, INC.	C07K	283	45			28	12						1	4			
5498392	Mesoscale polynucleotide amplification device and method	3/12/1996	UNIV PENNSYLVANIA, TRUSTEES OF	G01N	201	45			3	39	3									
4482516	Process for producing a high strength porous polytetrafluoroethylene product having a coarse microstructure	11/13/1984	GORE ENTERPRISE HOLDINGS, INC.	B29C	116	44	35	1				1	3			4				
5064802	Metal complex compounds	11/12/1991	DOW CHEMICAL CO.	C08F	264	44	4	28			1			11						
5540853	Personal treatment compositions and/or cosmetic compositions containing enduring perfume	7/30/1996	PROCTER & GAMBLE CO., THE	C11D	88	44		28						1		10	5			
4230862	Antifertility compounds	10/28/1980	LILLY (ELI) & CO.	C07D	111	43			43											
5215680	Method for the production of medical-grade lipid-coated microbubbles, paramagnetic labeling of such microbubbles and therapeutic uses of microbubbles	6/1/1993	CAVITATION-CONTROL TECHNOLOGY, INC.	B01J	125	43		2	24						17					
			Total Cites			1156	259	253	223	135	83	46	45	43	31	21	9	5	2	1
			Percentage Share			100%	22%	22%	19%	12%	7%	4%	4%	4%	3%	2%	1%	0%	0%	0%

ut by industry of c
ut by industry of c
5055438 Olefin polymerization catalysts 10/8/1991 ECPI/EXXON CHEMICAL PATENTS INC C08F 240 55 33 1 20 1
4597794 RECORDING PROCESS AND A RECORDING LIQUID THEREOF 7/1/1986 CANON KK C09D 189 53 1 27 15 7 2 1
4576850 SHAPED PLASTIC ARTICLES HAVING REPLICATED MICROSTRUCTURE SURFACES 3/18/1986 MINNESOTA MINING & MFG. CO. C08G 194 49 5 38 4 1
4380635 Synthesis of acylated benzothiophenes 4/19/1983 LILLY (ELI) & CO. C07D 242 46 46
5126022 Method and device for moving molecules by the application of a plurality of electrical fields 6/30/1992 SOANE TECHNOLOGIES, INC. G01N 202 46 38 7 1
4816567 RECOMBINANT IMMUNOGLOBIN PREPARATIONS 3/28/1989 GENENTECH, INC. C07K 283 45 28 12
5498392 Mesoscale polynucleotide amplification device and method 3/12/1996 UNIV PENNSYLVANIA, TRUSTEES OF G01N 201 45 3 39 3
4482516 Process for producing a high strength porous polytetrafluoroethylene product having a coarse microstructure 11/13/1984 GORE ENTERPRISE HOLDINGS, INC. B29C 116 44 35 1 1 3

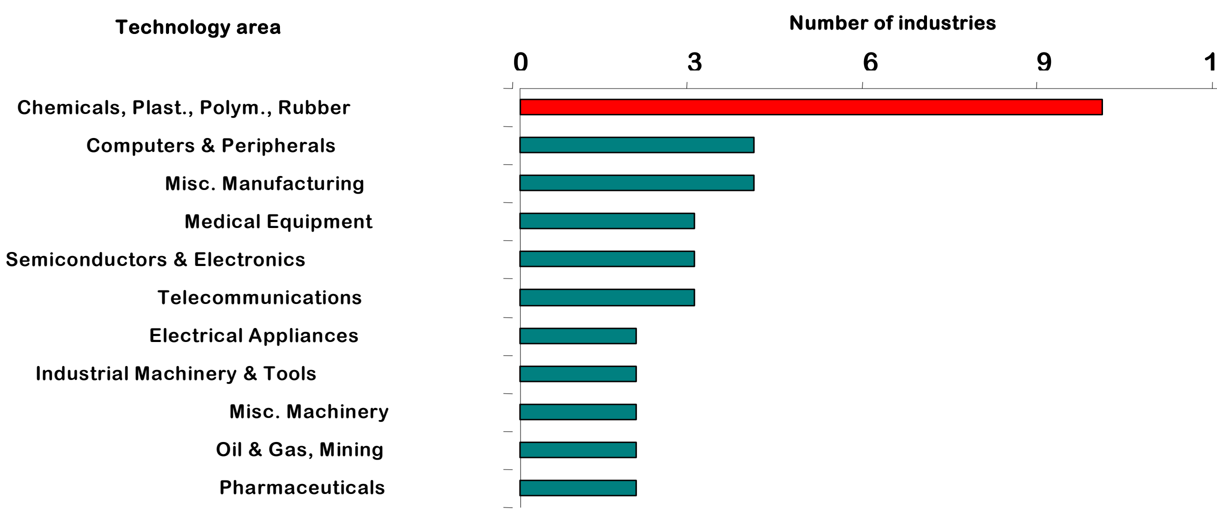


Figure 12
Technology Base Across Industries: Again Chemical Technology Ranks First

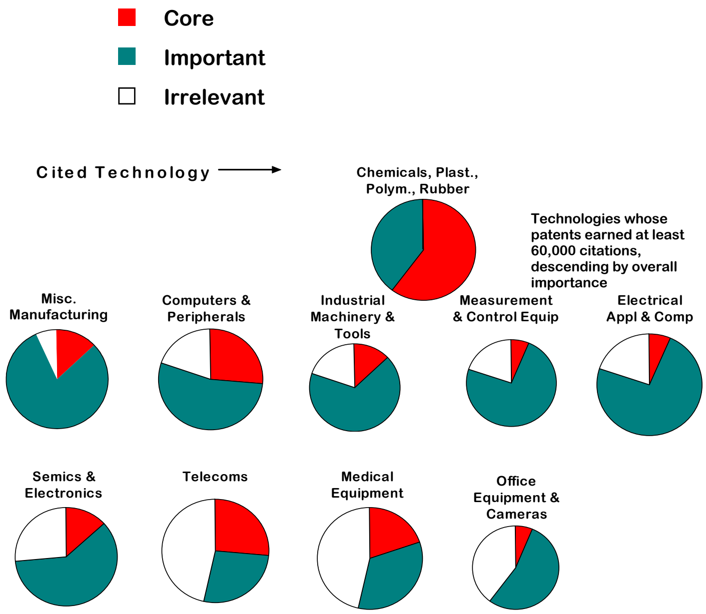
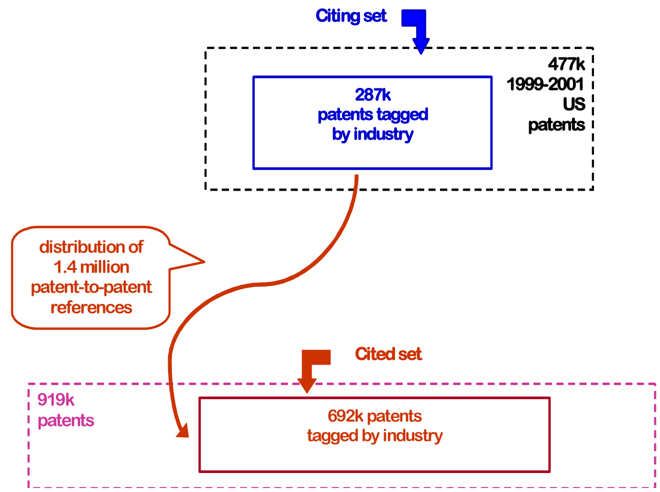


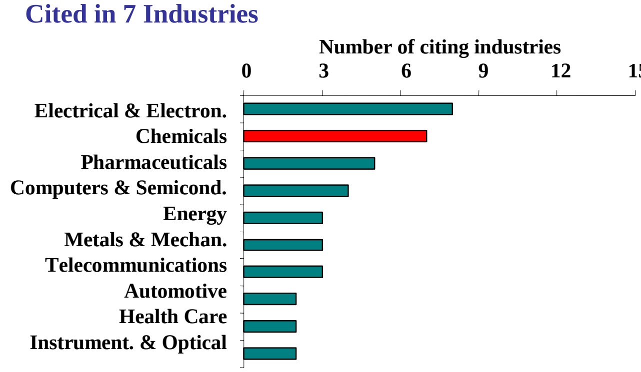
Figure 13 is a diagram that shows how the citing set of industry-tagged patents links to the cited set of industry-tagged patents. The 287,000 industry-tagged citing patents contain 1.4 million patent-to-patent references or citations to 692,000 patents that can be tagged by industry, because these cited patents, which comprise a subset of the 919,000 total cited patents, belong to companies that are identifiable by industry. It is the distribution of these 1.4 million industry-to-industry references that we use to quantify the spillovers.[8]

Figure 13
How Many Industries Build Upon Technology Produced By The Chemical Industry?



In **Figure 14**, for each cited industry, we plot the number of industries that reference its patents first, second or third most often. In this case, the chemical industry, which ranks among the top three in 7 industries, comes in second, behind the electrical and electronics industry, which is among the top three in 8 industries.[9] The pharmaceuticals industry is next; it is among the top three cited in 5, followed by the computers and semiconductors industry, the energy industry, and so on.

Figure 14
Chemical Industry Patenting is Among The Top 3 Cited in 7 Industries



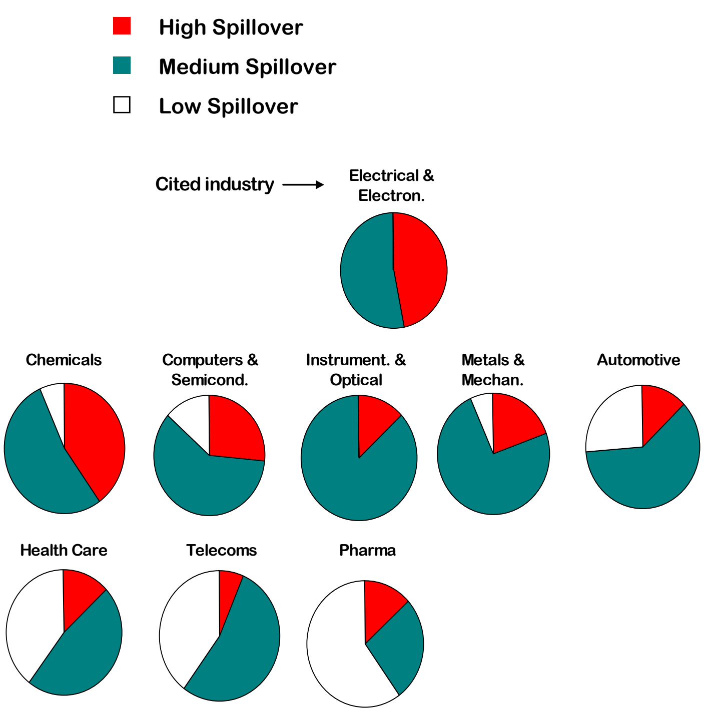
---

[8] In addition to the 15 industries, in this case the cited "industries" also include government agencies, universities, research labs, etc. However, in no case does any of these additional "industries" come up as significant.

[9] See Appendix Figure A6 and A7, respectively, for detailed citation count data and percentage distributions by citing industry and by cited industry.

In the pie charts in **Figure 15** we assess the technology spillover from cited industries on our high, medium and low scale.[10] A spillover into an industry is considered high if the cited industry accounts for at least 10% of the citing industry's citations; medium spillover is 1-10% of citations and low spillover is less than 1%. The electrical and electronics industry has the strongest breadth and depth, with high spillover into 7 industries and medium spillover into 8. The chemical industry comes in second behind electrical and electronics, with high spillover into 6 industries, medium spillover into 8 industries, and low spillover into just 1 industry. The two industries that are ranked next below the chemical industry are the computer and semiconductor industry (high spillover into 4, medium spillover into 9, and low spillover into 2 industries) and the instrument and optical industry (medium and high spillover, respectively, into 13 and just 2 industries).

Figure 15
Chemical Industry Spillover Ranks Second Only to Electrical & Electronics



[10] In the figure industries are arranged in descending spillover order based on a composite score like the one used in Figure 8. Only the 9 industries whose patents obtained at least 40,000 citations are shown in the figure.

In summary, instead of chemical industry technology coming out far ahead, we find that cross-industry technology spillovers are highest from the electrical and electronic industry with the chemical industry a close second. The evidence is in industry-to-industry patent citation counts; patents granted to companies in all industries cite foremost to patents granted to electrical and electronics industry and then to chemical industry companies.

INDUSTRY SCIENCE BASE

The last approach we take to examining chemistry as an enabling technology is to measure the importance of chemistry as a science base, compared to other science. We do this by counting the direct citations from the patents in each industry to published papers in chemistry and other scientific fields.

In addition to prior art "examiner" references on the front pages of U.S. patents that cite to earlier patents, patents also contain examiner references to non-patent prior art. While some of these non-patent references are to textbooks, industrial catalogues, newspaper stories, and so on, here we are interested in the subset of these non-patent references which is made up of peer-reviewed science papers, principally papers published in scientific journals. Basically, the question here is to what extent does the technology created by each industry cite to peer-reviewed chemistry science papers as prior art, compared to papers in other fields.

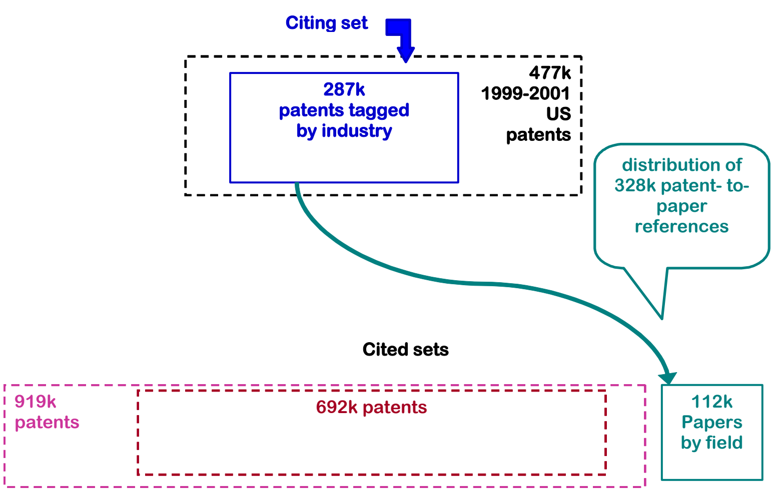
Based on the journal in which each has been published, all scientific papers can be categorized into one of eight fields: biomedical research, biology, chemistry, clinical medicine, earth & space, engineering & technology, mathematics, and physics. **Figure 16** defines each of these fields by listing all the "subfields" that make up each. This CHI Research field classification has been used in the US-congressionally-mandated, biennial *Science and Engineering Indicators* reports published by the National Science Board.

Figure 16
Science Paper Fields and Their Respective Subfields

Field	Subfields
Chemistry	Analytical Chemistry Organic Chemistry Inorganic & Nucl Chm Applied Chemistry General Chemistry Polymers Physical Chemistry
Biomedical Research	Physiology Anatomy & Morphology Embryology Genetics & Heredity Nutrition & Dietet Biochem & Molec Biol Biophysics Cell Biol Cyt & Hist Microbiology Virology Parasitology Biomedical Enginrng Microscopy Misc Biomedical Res Genrl Biomedical Res
Biology	General Biology General Zoology Entomology Misc Zoology Marine Bio & Hydrobi Botany Ecology Agricult & Food Sci Dairy & Animal Sci Misc Biology
Clinical Medicine	General & Internal Med Allergy Anesthesiology Cancer Cardiovascular Systm Dentistry Dermat & Venerl Dis Endocrinology Fertility Gastroenterology Geriatrics Hematology Immunology Obstetrics & Gynecol Neurol & Neurosurg Ophthalmology Orthopedics Arthritis & Rheumat Otorhinolaryngology Pathology Pediatrics Pharmacology Pharmacy Psychiatry Radiology & Nucl Med Respiratory System Surgery Tropical Medicine Urology Nephrology Veterinary Medicine Addictive Diseases Envir & Occup Hlth Misc Clinical Med
Earth & Space	Astronmy & Astrophys Meteorol & Atmos Sci Geology Environmental Sci Earth & Plantry Sci Oceanography & Limno
Engineering & Tech	Chemical Engineering Mechanical Engineer Civil Engineering Electr Eng & Elctron Misc Eng & Technol Industrial Engineer General Engineering Metals & Metallurgy Materials Science Nuclear Technology Aerospace Technology Computers Operations Research
Physics	Chemical Physics Solid State Physics Fluids & Plasmas Applied Physics Acoustics Optics General Physics Nucl & Particle Phys Misc Physics
Mathematics	Probablty & Statist Applied Mathematics General Mathematics Misc Mathematics

We call the cited papers the science base. In **Figure 17** we see that the 287,000 industry-tagged set of patents contain 328,000 patent-to-paper references to 112,000 different papers. It is the distribution of the 328,000 references by scientific paper field, rather than the distribution by field of the papers themselves, that we use to measure the industry-to-science base linkages.[11]

Figure 17
Industry Science Base – Industry-to-Science Field Patent-to-Paper Citations



[11] It is important to recognize that we are certainly not restricting our analysis to cited papers turned out by each industry itself, although, of course, some industry self citing is likely to exist.

The average citation frequency among the all cited papers is nearly 3 (actually 328,000 / 112,000 or 2.92). Just as with the cited patents, the citation distribution has a very long tail; the vast majority of the cited papers are cited just once and only a small minority are cited many times. **Figure 18** is a list of the 10 most highly cited <u>chemistry</u> papers. (For a list of the 100 most highly cited chemistry papers, see Appendix, Figure A8.) The table is arranged in descending order by total number of citations received, and citing industries are ordered descending by number of references to chemistry papers. For example, the most highly cited paper, Uhlmann et al (Hoechst AG), "Antisense Oligonucleotides..," Chemical Reviews (1990), is cited a total of 131 times. Of these cites 94 are from the pharmaceutical industry, 24 from biotechnology, and so on, and just 3 of the cites are from chemical industry company patents.

Figure 19 plots, for each scientific field, the number of industries that reference its papers first, second or third. Chemistry ranks first; it is among the top three cited fields in 13 of the industries, followed by physics, which is among the top three in 10 industries, and engineering and technology, which is in the top three in 9 industries.[12] Citations to clinical medicine, to biomedical research, and to the remaining fields shown, are in the top three in a much narrower fraction of the industries.

In this figure "chemistry" is actually a combination of the field of chemistry and the chemical engineering subfield of the engineering and technology field (and the engineering and technology data exclude chemical engineering). However, the impact of the inclusion of chemical engineering literature with chemistry is not really all that significant. Even without including chemical

[12] Appendix Figures A9 and A10, respectively, provide detailed citation counts and percentage distributions by citing industry and by cited paper field, where chemical engineering papers are in with chemistry papers, and are excluded as a subfield of the engineering and technology field. The corresponding data, where the chemical engineering papers remain in the engineering and technology field and are NOT combined with chemistry papers, are given in Appendix Figures A11 and A12.

Figure 18

Chemistry Papers Most Highly Cited by Patents Ranked by number of cites received from 1999-2001 industry patents

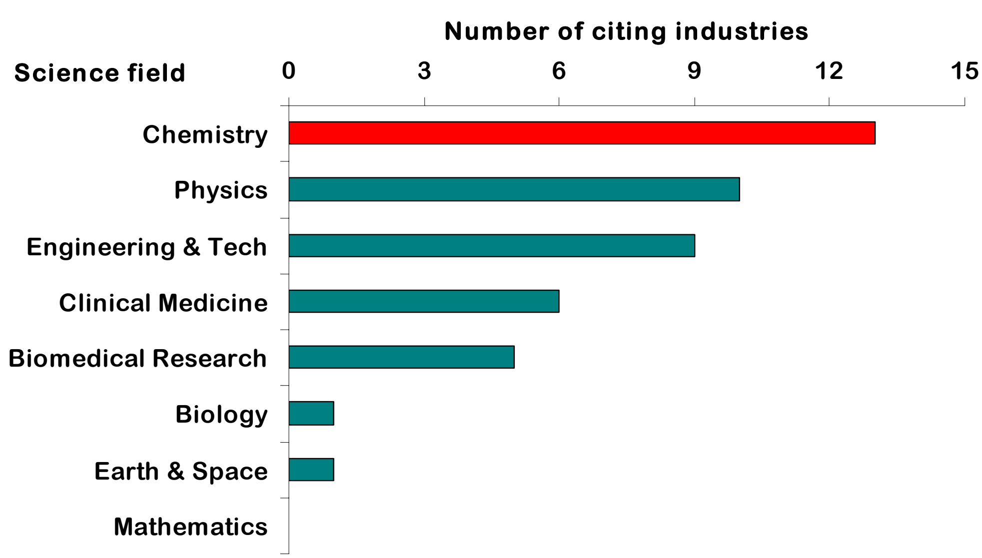
Citation counts broken out by industry of citing patent*:

Paper Reference	Addresses	Funding Source	Cites from '99-'01 industry pats	Biotechnology	Pharmaceuticals	Instruments & Optical	Chemicals	Metals & Mechanical	Health Care	Computers & Semiconductors	Food, Bevg. & Tobacco	Electrical & Electronics
Uhlmann, Eugen, et al., 1990, "Antisense Oligonucleotides: A New Therapeutic Principle," Chemical Reviews, vol. 90, no. 4, 543-562.	Hoechst	None mentioned	131	24	94	6	3		2		2	
Dasgupta, P. et al., 1994, "Electroosmosis: A Reliable Fluid Propulsion System for Flow Injection Analysis", Analytical Chemistry, vol. 66, no. 11, (June 1) pp. 1792-1798.	Texas Tech U	None mentioned	77	58		14		5				
Seiler, Kurt et al, 1993, "Planar Glass Chips for Capillary Electrophoresis: Repetitive Sample Injection, Quantitation, and Separation Efficiency," Analytical Chemistry, vol. 65, no. 10 (May 15) 1481-1488.	U of Alberta, Ciba-Geigy	Foreign govt & univ. & company	63	56		2		5				
Beaucage, S.L., and M.H. Caruthers, 1981, "Deoxynucleoside Phosphoramidites-A New Class of Key Intermediates for Deoxypolynucleotide Synthesis," Tetrahedron Letters, vol. 22, no. 20, pp. 1859-1862.	U of Colorado	NIH - NIGMS & foreign govt	58	22	27		5		4			
Jacobson, Stephen C. et al, 1995, "Fused Quartz Substrates for Microchip Electrophoresis" Analytical Chemistry, vol. 67, no. 13, (July 15) 2059-2063.	Oak Ridge Natl Lab	DOE	58	56		1						1
Beaucage, S.L. et al., 1992, "Advances in the Synthesis of Oligonucleotides by the Phosphoramidite Approach", Tetrahedron, 48, no. 12 (March 12) 2223-2311	FDA	None mentioned	54	1	47	3	2		1			
Seiler, Kurt et al, 1994, "Electroosmotic Pumping and Valveless Control of Fluid Flow within a Manifold of Capillaries on a Glass Chip", Analytical Chemistry, vol. 66, no. 20 (Oct. 1) 3485-3491.	U of Alberta	Foreign govt. & company	53	53								
Martin P., 1995, "A New Access to 2 -0-Alkylated Ribonuclesides and Properties of 2 -0-Alkylated Oligoribonucleotides," Helvetica Chimica Acta, vol. 78, pp. 486-504. Article in German with English Abstract.	Ciba-Geigy	None mentioned	48		48							
Englisch, U. et al., 1991, "Chemically Modified Oligonucleotides as Probes and Inhibitors", Angew. Chem. Int. Ed. Eng., vol. 30, no. 6, (June) pp. 613-629.	Max-Plank Inst.	None mentioned	47		46		1					
Holt, Dennis A. et al., 1994, "Structure-Activity Studies of Synthetic FKBP Ligands as Prptidyl-Prolyl Isomerase Inhibitors," Bioorganic & Medicinal Chemistry Letters, vol. 4, no. 2, pp. 315-320.	SmithKline	None mentioned	44	40	1					3		
Total Cites			633	310	263	26	11	10	7	3	2	1
Share of cites			100%	49%	42%	4%	2%	2%	1%	0%	0%	0%

* Zero cites to top-cited papers from Automotive, Energy, Engineering & Oil Field Svcs., Forest, Paper & Textiles, Materials and Telecommunications industries' patents

Figure 19

Chemistry is Among The Top 3 Cited Fields in 13 Industries

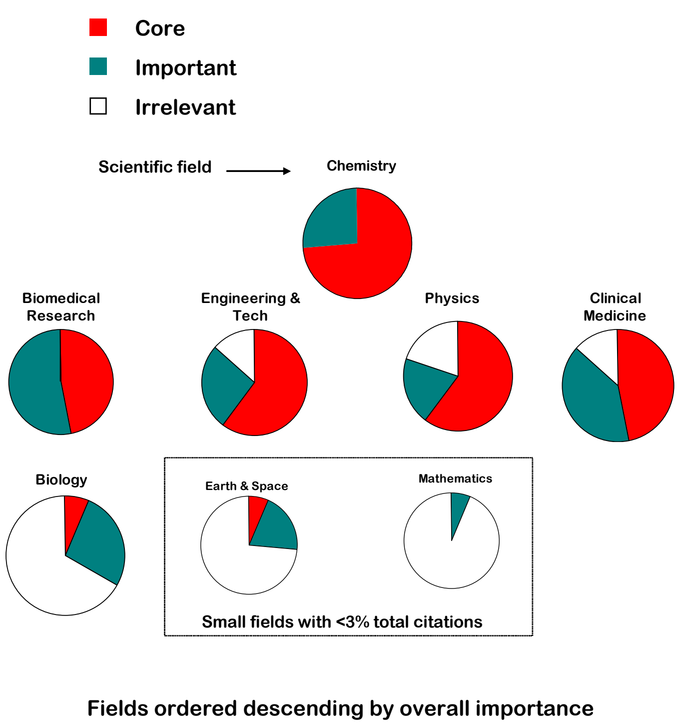


engineering, chemistry still ranks ahead of all the other fields. Then, chemistry is among the top 3 cited fields in 12 of 15 industries, not 13 of 15 industries, and engineering and technology ties with physics as being among the top 3 cited fields in 10 citing industries.

And finally, **Figure 20** compares pie charts for each of the scientific paper fields, and shows in how many industries each field is core, important or irrelevant. All paper fields are shown. Only chemistry and biomedical research are either core or important across all industries, but chemistry is core in more industries than biomedical research (chemistry is core in 11, versus 7 for biomedical research). And, chemistry is also core in more industries than any of the other fields as well; engineering and technology and also physics are core in 9 industries, and clinical medicine is core in 7.

Figure 20

Science Base Across Industries: Chemistry Ranks First



If chemical engineering papers are not combined with chemistry papers, the results are still basically the same. Then chemistry is core in 10, not 11, industries, and engineering and technology is core in 10, rather than 9, industries.

Thus, in this final approach to our question, we find that chemistry is an important part of the science base of all industries. The evidence is found in patent-to-paper citations; patents granted to companies in all industries cite chemistry papers as prior art.

CONCLUSIONS

We have taken four different approaches to examining the question of whether chemistry is an enabling science / technology, and in all four we found strong evidence to support a very positive finding.

First, looking at technology creation within each of the industries, as measured by patenting activity, we find significant chemical technology patenting going on in all industries, and no other technology comes close the breadth exhibited in chemical technology patenting.

Second, based on industry-to-technology patent citations, that is, the degree to which the patents generated in each industry build on chemical technology as prior art, our findings are that chemical technology underpins technology development in all industries and no other technology comes close to having as broad an enabling presence.

Third, based on industry-to-industry patent citation data, we find that the technology spillovers to other industries are greatest from the electrical industry, and second greatest from the chemical industry. In other words, patents granted to companies in all industries build foremost on patents granted to electrical industry and then to chemical industry companies.

And fourth, based on patent-to-paper citations, that is, the extent to which patents granted to companies in all industries build on the chemistry science literature as prior art, our finding is that chemistry is a core part of the science base of more industries than any other scientific field.

Together, these four patent and citation analyses conclusively establish broad application of chemical science and technology. Because chemical science and technology is used so broadly, it underpins innovation across the economy. And the fact that no other science / technology is used as broadly and intensely leads us to conclude that chemistry is the most enabling science / technology.

Phase II Task 3:
"Tracing the Timeline from Government Funding to Industrial Impact"

Prepared by:
Peter Kroll, ipIQ

INTRODUCTION

ipIQ (formerly CHI Research, Inc) is pleased to present to the Council for Chemical Research the results of its analysis of the timeline from government funding of research, through to industrial impact. This segment of the CCR project is designed to complement previous phases of the project, and to contribute to its overall objective of developing a greater understanding of the role and value of chemical research. Previous segments of the CCR project have used patent and citation indicators to examine the relationship between research and development expenditures and operating revenues for chemical companies, and how chemistry is an enabling technology—a technology upon which many other technologies build extensively. We also analyzed the financial benefits of investing in high quality science and technology.

This segment of the study examines the length of time from the initiation of the supported research to the resulting patented technology, in order to establish the length of time to achieve the payoff to the chemical industry of investing in public science.

The basic hypothesis, supported by the evidence that we have already generated– such as our finding that 75 percent of the science cited by patents from all US industries is from the public sector (Narin et al., 1997)—is that there is a traceable path from research and grant support acknowledgements on papers, to the patents that cite the papers.

METHODOLOGY

ipIQ examined a large subset of the US patent database and used our citation analysis techniques to identify the links from funding of basic science literature through time to the patents invented that cite that science. We did this by tracing the process of bringing an innovative concept to market by identifying landmarks along the way. This could be done because patents build upon and acknowledge prior art in technology and science. In turn, published scientific results acknowledge funding support sources. This identification is not theoretical or predictive, but rather tracks historical evidence.

Patent Database and Patent Citation Analysis

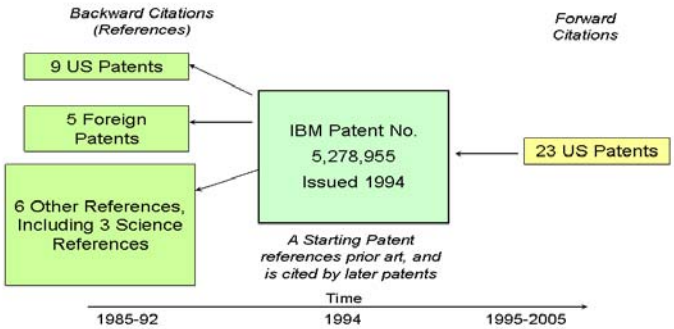
When a US patent is issued, it must satisfy three criteria: it must be useful, it must be novel, and it must not be obvious. The references cited on the front page of the patent are related mainly to the question of novelty—to demonstrate that the patent as issued is different from and improves upon the cited 'prior art.'

There are three major classes of citations on the front page of a US patent: to earlier US patents; to earlier foreign patents; and to a set of nonpatent references, the majority of which are scientific papers reporting the results of original research. A typical US patent issued today cites 13 earlier US patents, two or three foreign patents, and three or four non-patent sources.

The fundamental idea of patent citation analysis is that when an earlier patent is cited in many later patents, then that earlier patent is likely to contain a significant advance. Citation distributions are highly skewed, with the average patent cited 4 or 5 times in the first five or so years after it is issued, and a relatively small number of patents cited 10, 15, 20 or more times. It is those highly cited patents that have been shown in numerous studies to contain technological advances of far more than passing importance (Narin, 2000; Albert et al., 1991).

Figure 1 shows an example of the citation relationships around one 1994 patent issued to IBM. The patent document indicates that it cited nine US patents as prior art. It also cited five foreign patents. Six other prior art references were made to literature other than patents; three of those were to scientific literature. That prior art represents an earlier state of knowledge that the IBM invention improved upon. Since the issuance of that patent, 23 later US patents have cited it.

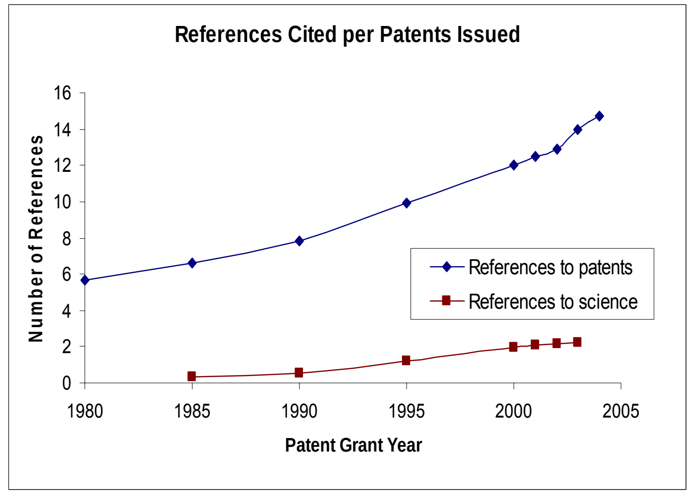
Figure 1 A Patent Must Cite the Prior Art: An Example



ipIQ maintains a database of the information contained on the front page of all patents issued by the US Patent and Trademark Office from 1975 to the present. Upon weekly receipt of the newly issued patents, we determine—for the major patenting organizations—which corporate family contains each patent's assignee, standardize nonpatent references by parsing their free text format as it arrives from the Patent Office and characterize whether they are to scientific or other sources, and determine the technology area of the patent, based on our proprietary classification scheme. We also construct a set of technology indicators from these data for individual patents, organizations, and technologies, based on citation patterns, and normalize them based on overall patent system measures, within industries, technologies, and years.

Figure 2 shows the trends over the past several decades of the increasing number of references by newly issued patents both to earlier patents and to earlier scientific papers. From 1980 to 2004, the average number of references to a US patent rose from 5.7 to 14, almost 150%. The relative increase in science references was even greater, from 0.31 per citing patent in 1985 (the first year we have those data available) to 2.24 in 2003, an increase of more than 600%.

Figure 2 Average Number of Cited Patents and Science Has Increased Over Time

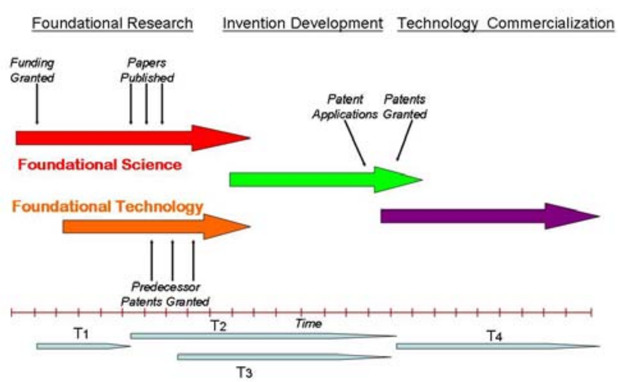


Time Intervals to Determine

Figure 3 shows a simplified schematic timeline of the genesis of an invention from conception to market. Of course, no model can fully represent the complex iterative multi-layered knowledge development that is the process of innovation. This timeline serves as

means of measuring the mile markers along that path. We recognize that there is overlap between the stages.

Figure 3 Timeline from Conception to Market



We begin with our focus in the middle of the diagram, with the *development of the invention*, marked by the application and grant date of the patent. The *technology commercialization* stage follows, leading to the actual production of the final product. Moving backward to the stage preceding the invention, we refer to the *foundational research* representing the scientific research and technology precedents that the invention under consideration is built upon.[13] The *foundational technology* is represented by the predecessor patents cited by the invention's patents. The *foundational science* is represented by the predecessor science papers cited by the invention's patents. The dates of the cited patents and papers can be determined. In its early stages, the scientific research is supported by funding grants, which are traditionally acknowledged in the papers reporting the research results. The dates of the initial funding can often be determined.

Thus, we want to determine the following parameters:

T1 = time from grant funding to paper publication

T2 = time from paper publication to citing patent grant date (Science-to-Technology Cycle Time)

T3 = time from predecessor patent issuance to patent grant date (Technology Cycle Time)

T4 = time from patent issuance to product commercialization

Patent Set Selected

The patents selected were a subset of all US patents issued in the years 2001-2003.

For studies such as this, we categorize each patent into a single Technology Area. The classification is based on the main invention art International Patent Classification (IPC) given to each patent by the patent examiners. Typically, patents are given several IPCs, but for simplicity's sake, we only work with the "main classification." For this study, we have focused on patents falling into two of our Technology Areas: (1) Chemicals; and (2) Plastics, Polymers, and Rubber. For the rest of this report, we will simply refer to this combined set of 47,631 patents as "Chemical Technology."

Figure 4 shows that over the three study years, the absolute number of Chemical Technology patents in the US patent system has remained relatively steady.

[13] The observation has been made that two years of unfunded research may ensue before the initial funding is granted.

Figure 5 shows that, as a percentage of all US-issued patents, a relatively level pattern is also exhibited.

Figure 4 Chemical Patenting has Remained Steady in Absolute Numbers

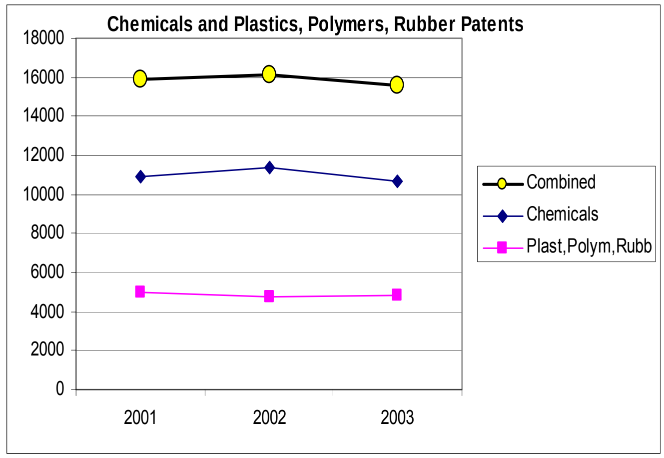
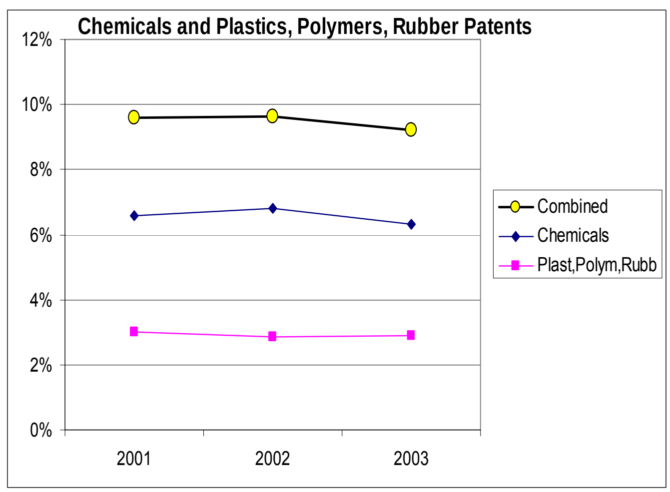


Figure 5 Chemical Patenting has Remained Steady as a Percentage of All patents



Our internal Tech-Line® database tracks almost 2000 parent organizations that have received the most US patents over the past five years. In Tech-Line we also designate a primary "industry group" for each parent company, based on a variety of sources such as industrial directories, company web pages, and reported primary Standard Industrial Classification (SIC) data. This industry group designation is used here to place each company in an industry. In this study, we restricted the set to patents granted only to assignees in the Chemical Industry. This is distinct from the Chemical Technology Area categorization. A technology is a way of characterizing patents by the art of their inventions, which is something quite different from characterizing the patents by the nature of the companies that own them. IBM, a computer industry company, owns patents in many technology areas, not only the obvious ones such as computers and semiconductors, but also less obvious technologies such as food, biotechnology, industrial machinery, and, of course, chemicals. In our tracking of the major patenting organizations in the US system, we categorize each of those companies by industry, and from those selected the companies that are in the Chemicals Industry. We also created a separate combined category of "Public Organizations," those in our Tech-Line categories of Government, Universities, and Research Institutions. The patent counts for these two sets are 12,900 and 3,783, respectively.

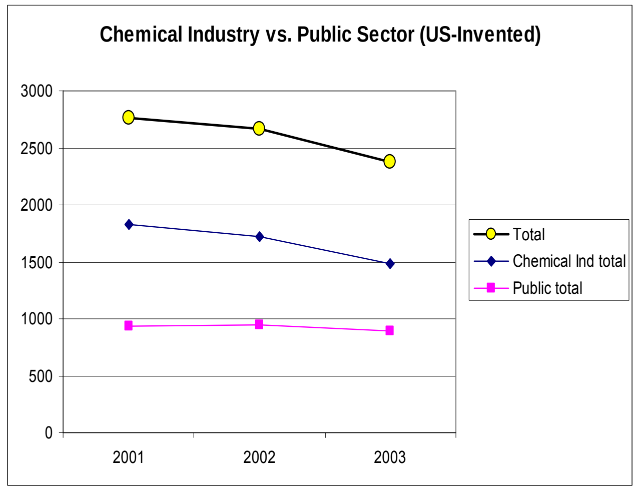
Our final restriction on inclusion in the set was to select only patents having at least one inventor with a US address. This reduced the set of patents to 7,762, consisting of 5,029 from the Chemical Industry and 2,770 from the Public Sector (including 37 falling into both sets due to patents having coassignees in each sector).

To summarize, the patents in this study phase are a subset of all 2001-2003 patents granted in the US system:

- Chemistry Technology Area; and
- Assigned only to major patenting organizations in two industry categories
    - Chemical Companies (115)
    - Public Organizations (159), consisting of
        - Government (26)
        - Universities (102)
        - Research Institutions (31); and
- Issued to US inventors only.

This subset of patents—that is, US-invented Chemical Technology Patents in the Chemical Industry and Public Sectors—is shown in Figure 6. It shows a decline over the three years.

Figure 6 For this Subset, Chemical Patenting Declined



This three-year set of 7,762 unique patents *reference* prior patents 100,812 times (76,961 by Chemical Industry patents and 23,851 by Public Sector patents). Because multiple patents may cite the same prior art, the set consists of 56,305 unique patents (40,583 cited by the Chemical Industry and 17,106 cited by the Public Sector, including 1,384 in both sets).

Looking at references to nonpatent publications, the 7,762 patents in our base set cite 73,692 nonpatent references. Of these, we classify 60,718 as references to science (papers appearing in journals or research that could result in a refereed journal). Of these, 58,359 are in standard journals. We observe that the Public Sector patents cite many more science references than do the Chemical Industry's (11,749 cited by the Chemical Industry vs. 46,852 cited by the Public Sector's patents, including 242 cited by both in patents coassigned to both sectors). In identifying a paper sufficiently to have enough information to find it in the library, we need at least the year, journal, author, and page (they are reported in a nonstandard free format on the patent document itself, often omitting one or more of these pieces of information). These could be determined for 41,401 unique papers (7,585 cited by Chemical Industry patents and 34,363 cited by Public Sector patents, including 597 cited by both sets). It is these references that are evaluated in the remainder of this report.

Analysis

Time from Patent Issuance to Commercialization

Empirically determining the time from invention date to product commercialization is a difficult task and beyond the scope of this study. We know, for example that in the pharmaceutical industry, it is often relatively easy to establish this time lag, because the patents underlying specific pharmaceuticals are often listed in the various drug delivery and description documents. This public disclosure is not usually the case in the chemical industry, where new, complex products are often built based on a portfolio of patents.

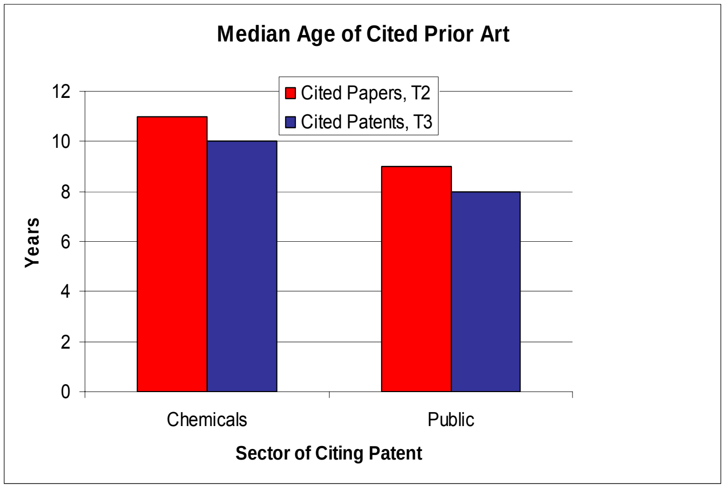
Perhaps surprisingly, according to Griffin (2002) studies on product development times have focused mainly on methods of reducing them (Griffin, 1997), or anecdotal data on particular projects. Absolute numbers, in general or in specific industries such as chemicals, are elusive in the literature. So, for this study, we rely on anecdotal evidence and general observation to put the average time (T4) to scale up the production process from invention at least five years for significant innovations.

Age of Cited Prior Art

We first determined the age of the cited prior art represented by patents and papers. Although patent grant dates are known to the precise day of issuance, the publication dates of the cited scientific papers are usually known only to the year, so all age calculations were based on an annual basis. Furthermore, because references many decades old occasionally appear, they would tend to skew a calculation based on means, so the median is the statistic used in this study.

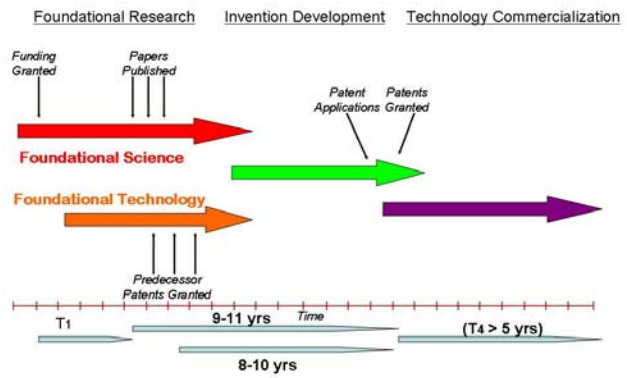
Figure 7 shows the median age of the cited patents and papers in our set, separated between the citing Chemical Industry Patents and the citing Public Sector patents. The Chemical Technology patents cited by Chemical companies have a median age of 10 years between issuing date of citing and cited patents. The age of cited papers is even older—11 years. Public sector Chemical Technology patents build on prior art (patents and papers) that is two years newer than for Chemical Industry patents, on average—8 and 9 years, respectively.

Figure 7 Age of Cited Prior Art



With this information, we can now fill in two elements, T2 and T3, of our timeline, as shown in Figure 8.

Figure 8 Timeline from Conception to Market



At this point, we will also put in a number for T4. Although it is beyond the scope of this study, anecdotal evidence and general observation would put the average time to scale up the production process at least five years for significant innovations.

Time Between Funding and Scientific Paper Publication

In order to determine the value of T1, the time from the initiation of scientific research to the publication of results, we used the milepost of funding grant date. This information is not reported in the patent data received from the Patent Office, since it is associated with the cited paper, rather than the citing patent. Because the patent identifies the papers cited by the patents, we could determine the grant identifiers from the paper's funding acknowledgments to grants, and therefore potentially the grant dates. Because this process involved sending staff to research libraries to physically find the cited paper, record the funding acknowledgment information, and then research the grant date, we selected a random sample of 500 papers cited by Chemical Industry patents and 500 papers cited by Public Sector patents.

Of these, 355 cited by the Chemical Industry and 395 cited by the Public Sector were found in the library. They made acknowledgements to 613 and 970 grants respectively. Table 1 shows the top funding sources for scientific research papers for both industrial and public sector patents that were cited in our sample. For comparison, we also list the funding acknowledgement distribution for the papers most highly cited by patents in our full study dataset.[14] NIH and NSF are the prominent individual granting organizations.

Table 1 Top Funding Sources for Scientific Research Cited in Chemical Patents

For Sample of Cited Papers			For 23 Highly Cited Papers	
Funding Source	Number of Acknowledged Grants*		Funding Source	Number of Acknowledged Grants*
Natl Inst of Health	361		Private Companies	10
Foreign Nonprofit	223		Natl Science Foundation	8
Foreign Government	156		Natl Inst of Health	6
Private Companies	105		Foreign Government	4
All other US private non-profit	103		Foreign Nonprofit	3
Natl Science Foundation	69		Dept of Energy	3
All other federal government	68		All other US private non-profit	3
All other US private non-profit	47		American Cancer Soc	1
Dept of Energy	27		Howard Hughes Medical Institute	1
Foreign univ, med, tech schools	26		Public Health Service	1
American Cancer Soc	25		State or local government	1
US univ & med schools	27			
Howard Hughes Medical Institute	17			
Petroleum Research Fdn	13			
State or local government	8			
Counts are for those papers found in library. Some acknowledged multiple grants. Some that were found acknowledged no funding sources.				
Funded, not sure by whom	10		* No Information *	8
* No Information *	270			
* Article Not Found *	26			

At this point, the grant identifiers were recorded in cases where funding was acknowledged, as were the sectors of the authors' institutions. Because the date of the grant is rarely a component of the acknowledged grant number, and access to individual granting organizations' individual grant data is ordinarily restricted at best, we limited our grant date lookup to only the NIH and NSF online databases. Of the 361 NIH + 69 NSF funding acknowledgements by these found papers, we were able to identify the initial grant date of 63 of the grants acknowledged in papers cited by Chemical Industry patents and 256 of the grants acknowledged in papers cited by the Public Sector patents. These represent, respectively, 92 and 390 combinations of patent-to-cited paper-to-acknowledged grant. From these results, we calculated the number of years from grant issuance to paper publication.

Figure 9 displays the results of that compilation. The median time from grant to publication is 4 years for papers cited by Chemical Industry patents; for papers cited by Public Sector patents, the median age is 5 years.[15] This completes the timeline, shown in Figure 10.

[14] The most highly cited papers in the set are listed in Table 2.

[15] The values range from 0 to 22 years, with a mean (standard deviation) of 6.68 (5.75) for Chemical Industry patent-paper-funding combinations, and 6.29 (4.59) for Public Sector combinations.

Figure 9 Time from Grant to Paper

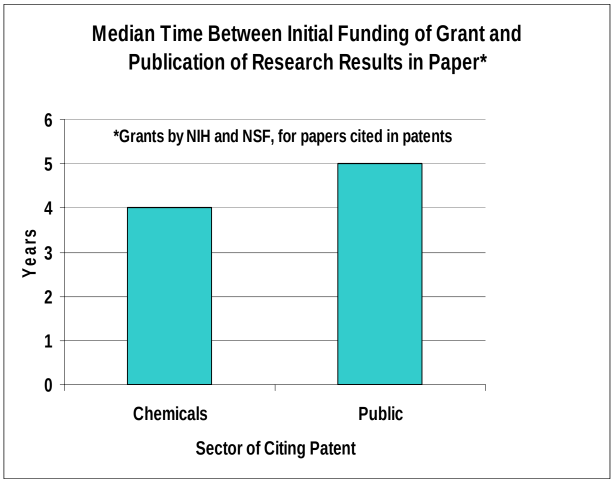


Figure 10 Timeline from Conception to Market Total Time between Funding and Commercialization

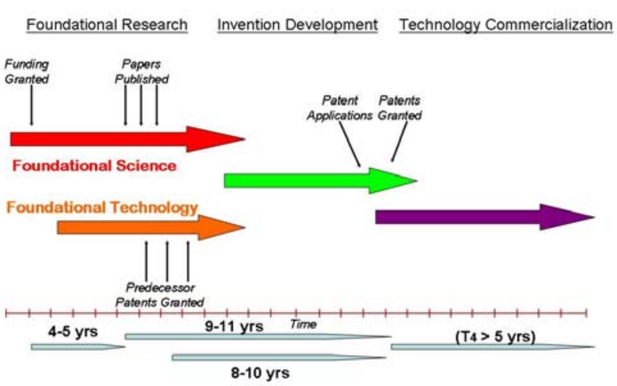


Figure 10 shows the resulting figures for the timeline from beginning to end. **The complete cycle time is then 13 to 16 years from initial funding to patent issuance, plus another five or more years before a technology reaches the market.**

A Note on Collaboration Between Sectors

With the sample of cited papers having been looked up at the library and the author institutions identified, we now turn to the collaboration between sectors. For this analysis, we grouped a paper's authors into the public sector, the industry sector, or both. Figure 11 shows the distribution of author sectors for this sample. As might be expected, the public sector (universities, research institutions, and government entities) publishes the majority of papers that provide the foundation of the chemical patents. In fact, in Figure 12 we can see that 86% of the cited papers are published by the public sector. Industry authors alone represent 7% of the cited papers, and collaborative efforts between industry and the public sector account for the remaining 7%. Recall that based on the timeline determined earlier, these are vintage 1990s papers cited by the 2001-2003 patents.

Figure 11 Universities and Nonprofits Lead in Authorship of Cited Scientific Papers

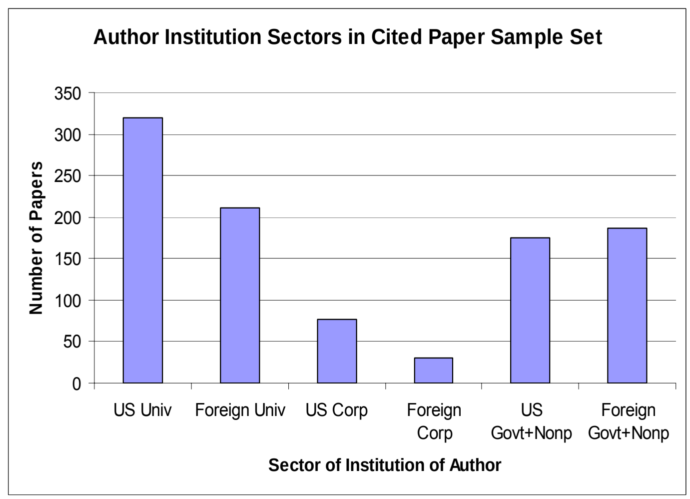
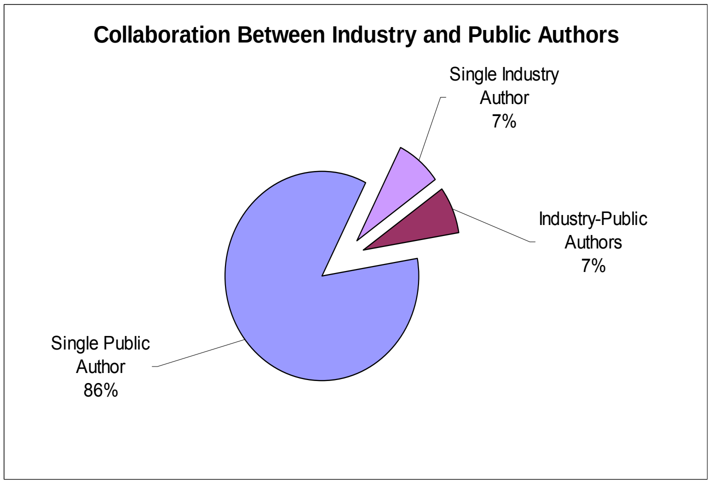


Figure 12 Sectors Collaborate in Cited Papers



CONCLUSIONS

This segment of the study examined the length of time from the initiation of the supported research to the resulting patented technology, in order to establish the length of time to achieve the payoff to the chemical industry of investing in public science.

The basic hypothesis was that there is a traceable path from research and grant support acknowledgements on papers, to the patents that cite the papers.

In tracing the science cited in patents back to its funding source, we found that

1. Scientific research cited by chemical industry chemical technology patents has a median age of 11 years; scientific research cited by public sector chemicals patents has a median age of 9 years;

2. Predecessor technology (in the form of patents) cited by chemical industry chemicals patents has a median age of 10 years; predecessor technology cited by public sector chemicals patents has a median age of 8 years;

3. Scientific papers cited by chemical industry chemicals patents acknowledge grants from NIH and NSF with a median age of 4 years; scientific papers cited by public sector chemicals patents (also based on NIH and NSF grants) have a median age of 5 years;

4. The time for the results of basic research to reach the stage of patented invention may typically take 13-16 years from the time funding is provided by a support agency;

5. Both the chemical industry and the public sector rely on public research; and

6. Evidence of collaboration was found between industry and public sector authors in papers cited by patents.

REFERENCES

Albert, M.B., D. Avery, P. McAllister, and F. Narin, “Direct Validation of Citation Counts as Indicators of Industrially Important Patents,” *Research Policy*, *20*, 251–259, 1991.

Griffin, A., “Modeling and Measuring Product Development Cycle Time Across Industries,” *Journal of Engineering and Technology Management*, *14*, 1, 1997.

Griffin, A., “Product Development Cycle Time for Business-to-Business Products,” *Industrial Marketing Management*, *31*, 291-304, 2002.

Narin, F., K. Hamilton, and D. Olivastro. "The Increasing Linkage between U.S. Technology and Public Science," *Research Policy, 26*, 3, 317-330, 1997.

Narin, F., “Tech-Line® Background Paper,” in *Measuring Strategic Competence*, Imperial College Press, Technology Management Series, Joe Tidd, editor, 2000.

Table 2 Scientific Papers Cited Most Highly in Chemical Patents Set

Cites Received	Reference as Appears in Sample Patent
44	Bowie, J.U., et al., "Deciphering the Message in Protein Sequences: Tolerance to Amino Acid Substitutions", Science vol.247:1306-1310 (Mar. 1990).
27	L. K. Johnson et al, J. Am. Chem. Soc., 1995, 117, 6414.
27	Lazar, E., et al. "Transforming Growth Factor .alpha.: Mutation of Aspartic Acid 47 and Leucin 48 Results in Different Biological Activities". Molecular and Cellular Biology. Mar. 1988. 1247-1252.
25	Kohler and Milstein, "Continuous culture of fussed cells screting antibody of predefined specificity," Nature 256:495-497 (1975).
20	Burgess, W.H. et al. "Possible Dissociation of the Heparin-binding and Mitogenic Activities of Heparin-binding (Acidic Fibroblast) Growth Factor-1 from Its Receptor-binding Activities by Site-directed Mutagenesis of a Single Lysine Residue". J. Cell Biolo
19	J. Am. Chem. Soc., Scollard et al., vol. 118, pp. 10008-10009 (1996).
17	J. Chem. Soc. Dalton Trans. , Cloke et al., pp. 25-30 (1995).
17	Fields et al., "A Novel Genetic System to Detect Protein-Protein Interactions", Nature 340:245-246 (1989).
17	Macromolecules, Repo, vol. 30, pp. 171-175 (1997).
16	V. M. Mohring, et al, Angew, Chem. Int. Ed. Eng., 1985, 24, 1001.
16	J. Am. Chem. Soc., Baumann et al., vol. 119, pp. 3830-3831 (1997).
16	D.J. Greenland, "Adsorption Of Polyvinyl Alcohols By Montmorillonite", Journal of Colloid Science, 18, (1963) pp. 647-664.
16	Organometallics, Bei et al., vol. 16, pp. 3282-3302 (1997).
15	Copolymerization of Ethylene and Propylene with Functionalized Vinyl Monomers by Palladium(II)-Catalysts; J. Am. Chem. Soc., vol. 118, No. 1, 1996, p. 267-268. L.K. Johnson et al.
15	Branch, A.D. et al., "A Good Antisense Molecule is Hard to Find," TIBS, Feb. 1998, 23, 45-50.
15	Wells Ja. Additivity of mutational effects in proteins, Biochemistry 29:37(8509-8517)Sep. 1990.
15	Organometallics, Horton et al., vol. 15, pp. 2672-2674 (1996).
14	Maneck, Heterogeneous Carbonylation of Methanol on Rhodium Introduced into Faujasite-Type Zeolites, Catalysis Today, (1988), 421-429, 3, Elsevier Science Publishers B.V., Amsterdam.
14	M. J. Howard, M. D. Jones, M. S. Roberts and S. A. Taylor, "C1 to Acetyls: Catalysis and Process", Catalysis Today, 18 (1993) pp. 325-354, Amsterdam.
14	Merrifield, R.B., "Solid Phase Peptide Synthesis. I. The Synthesis of a Tetrapeptide", J. Am. Chem. Soc., 1963, 15, 2149-2154.
14	Spevak, W., et al., J. Am. Chem. Soc. 115:1146-1147 (1993).
14	Altschul, et al., "Basic Local Alignment Search Tool" J. Mol. Biol. 215:403-410 (1990).
14	Gelin, Coordination Chemistry of Rhodium and Iridium in Constrained Zeolite Cavities: Methanol Carbonylation, Pure & Appl. Chem., (1988), 1315-1320, 60, Great Britain.
14	Journal of Organometallic Chemistry, Clark et al., vol. 501, pp. 333-340 (1995).
14	Organometallics, Guerin et al., vol. 17 (23), pp. 5172-5177 (1998).
14	Organometallics, Guerin et al., vol. 15, pp. 5085-5089 (1996).
14	W. Keim et al., Angew, Chem. Int. Ed. Eng., 1981, 20, 116.
14	Skolnick et al., Trends in Biotechnology, 18(1):34-39, Jan. 2000.*
14	Krzywicki, Formation and Evolution of the Active Site for Methanol Carbonylation on Oxide Catalysts Containing RhCl3, Journal of Molecular Catalysts, (1979), 431-440, 6, Elsevier Sequoia S.A., Lausanne, The Netherlands.
14	Cuny et al., J. Am. Chem. Soc., 115, 2066, 1993.

Appendices for report available upon request to CCR

Acknowledgement

This material is based upon work supported by the National Science Foundation under Grant No. 0329872. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

The Council for Chemical Research
1730 Rhode Island Ave., NW, Suite 302
Washington, DC 20036
202-429-3971
202-429-3976 (fax)
ccrmail@ccrhq.org (email)
http://www.ccrhq.org