Human Resources for Science and Technology: How the U.S. Meets National Needs

A Report to the Japan Research Institute

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Preface

This report was commissioned by the Japan Research Institute (JRI) in 2003 to examine the system by which the U.S. produces and deploys science and technology personnel to meet its national needs. It is intended as input to analysis now being undertaken by the National Institute of Science and Technology Policy (NISTEP) to evaluate Japan's First and Second National Plans for Science and Technology. Undertaken by the authors as independent consultants in the firm of Technology Policy International[*], the work and its findings derive in significant part from their experience in government, the private sector and academic life. The opinions herein do not necessarily reflect the views of JRI, NISTEP or the institutions with which the authors are affiliated.

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1. INTRODUCTION: HUMAN RESOURCES FOR SCIENCE AND TECHNOLOGY IN THE U.S.: A SYSTEM OF "OPPORTUNITY-TROPISM"

This report focuses on the question of how the U.S. meets its human resources needs in science and technology. Of critical importance to the U.S. – as to all nations that rely on technical sophistication – this issue is especially germane to the science and technology planning process now underway in Japan. Japan, unlike the U.S., has long engaged in deliberate planning exercises to chart its national directions; the extension of this process to science and technology is of more recent vintage.[1] Again unlike the U.S., Japan has avidly sought to understand the experiences of other countries, on the assumption that inferences drawn from comparative analysis would prove useful in its domestic policy. This report has been commissioned from exactly this perspective: as a study of international experience that will serve as input to an evaluation of science and technology policies under the First and Second Plans.[2]

The overall thrust of the report is to elucidate the "system" by which the U.S. produces and deploys professionals engaged in work in science and technology, particularly in "priority" fields at the forefront, such as nanotechnology and bioinformatics (the two case studies herein). The use of the word "system" here must be approached cautiously, as the degree to which it describes the American reality is open to question. The U.S. has never had a comprehensive planning process for either human resources or science and technology. Nor do its policy-making institutions address the connection between human resources and science and technology in any systematic way. Indeed, the very notion of identifying "priorities" to which a supply of technical professionals can be allocated hardly fits into the American policy mindset.

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[1] The first Science and Technology Basic Plan covered the years 1996 –2000, and the Second Plan, 2001-2005. A Third Plan is now being contemplated.

If the U.S. has neither a system nor a plan, what it clearly has is a vibrant "market" for science and technology human resources. The principal actors in this market include industrial employers, universities (who function both as employers and producers of human resources), government programs that need and demand technical expertise, and the technically trained individuals who by and large chart their own academic and professional destinies. The context for the market is set not only by the preferences and practices of institutions, but also by public policies, coupled with a social tradition that expects technical people to exercise individual choice within a market framework.

We have coined the word "opportunity-tropism" to describe the essential nature of the U.S. system in which three principal elements are connected: science and technology policy; human resources; and societal norms. The term derives from the biological phenomenon (e.g., hydrotropism; heliotropism) by which plants grow in the direction of an attractive force (water, sun). The fundamental point it suggests by is that actors in the U.S. system are strongly motivated by the search for new opportunities and the rewards they present, and that this "opportunity-tropism" is the mechanism through which national needs are met.

The U.S. system of science and technology policy-making is well known for its decentralization. There is no national plan or preordained budget. Rather, a host of actors – many government agencies and programs, various industrial interests, diverse academic institutions, professional societies, numerous think tanks and individual members of a wide science and technology policy community – all compete for precedence and influence. All are habituated to responding to new opportunities. The currency of opportunity is often money: new public programs to support research. But opportunities to participate, to influence and to be heard are as eagerly sought. In other

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[2] As noted in the Preface, this report was prepared under contract to the Japan Research Institute and has been developed in cooperation with the National Institute for Science and Technology Policy (NISTEP),

work, we have characterized this policy system as "entrepreneurial," highly reliant on creative individuals who champion new policy concepts and public opportunities.[3] In essence, they are displaying "opportunity-tropism."

The human resource context for technical professionals in the U.S displays personal choice as one of its most pervasive characteristics. By the end of secondary school, young people have learned to develop a portfolio of options in the higher education "market." University curricula, both in liberal arts and engineering, are designed to offer an exceptionally wide range of choices. In the professional context, career mobility is a given. Not only is it assumed that technical professionals are likely to change employers, but frequently as well, that they will move into a new field. Often, these movements are in response to changes in public funding patterns, which mark new areas as national priorities. Rarely do such new public initiatives contain explicit human resource program elements. Thus, the scientists and engineers who migrate in new directions are responding to their perceptions of exciting new opportunities through the mechanism of personal career choice.

Always an immigrant-based society, the U.S. has long been accustomed to the acceptance of new individuals into its institutions, and has been highly attuned to the need to develop policies and norms that promote personal mobility and flexibility. The degree of reliance on foreign-born technical professionals in American industry and academe is one obvious example of this tendency. But a host of legal and societal institutions also contribute to a fluid milieu for technical employment and technological innovation. Portable pensions and individual savings and educational accounts offer a few examples of policies that impart great flexibility to the careers of technical

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who is responsible for the evaluation referred to in text.

[3] "Policy Innovation: The Initiation and Formulation of New Science and Technology Policies in the U.S. During the 1980s,"with D. Cheney, C. Hill with T. Suzuki, a Report to JETRO-New York and NEDO-DC, March 2000.

professionals, and rest on the acceptance of a high degree of personal responsibility. The reliance that many technical professional now place on informal professional and "affinity" networks further demonstrates a societal context in the U.S. that increasingly emphasizes opportunity and eschews secure life-patterns.

In the report that follows, the themes sketched above – mobility, flexibility, choice, and "opportunity-tropism" – are developed in more detail and particularity. In the following chapter, the domestic human resources context is explored, addressing the distribution of personnel across fields, trends in university employment, in employment mobility and of female and minority entrants into science and technology. In Chapter 3, geographic mobility of technically trained individuals into the U.S. is the main focus, with data on both migration patters and the public policy context explored. Chapter 4 focuses on the long American tradition of a "liberal education," explaining its origin and contours and considering its relationship to national needs in science and technology. Chapters 5 and 6 offer two case studies of how human resources issues are addressed in two priority areas in science and technology: nanotechnology and bioinformatics. A set of general conclusions is presented in Chapter 7.

2. RELATIONSHIP BETWEEN S&T PRIORITIES AND THE MOBILITY OF HUMAN RESOURCES IN THE UNITED STATES

2.1 Background

This chapter focuses on the mobility of scientists and engineers in the United States and how this mobility relates to changes in U.S. science and technology priorities. The United States has a relatively mobile population of scientists and engineers, who are able to change, to some degree, both their institutional affiliations and their fields of work in response to changing S&T priorities. This responsiveness enables the U.S. science and technology system to move rapidly in new directions in response to new technological opportunities or social needs.

To understand the mobility of scientists and engineers in the United States, it is important to understand two more general characteristics of the United States. One is the general high degree of mobility in the United States, which has historical and cultural origins. The other is the general reliance on market mechanisms and individual choice, rather than planning, to make career choices and set salaries for professionals.

2.1.1 Historical and Cultural Aspects of U.S. Labor Mobility

The United States has always been characterized by a high degree of human resources mobility relative to most other countries. This mobility is geographic, occupational and institutional. Part of this mobility may be due to the fact that the United States was largely populated by immigrants. Nearly everyone in the United States is related to someone who moved to the United States within a few generations. As a result, people’s ties to geographic regions, to communities, or to a particular way of life are weaker than in most nations. U.S. history has been filled by major movements of people, as immigrants have come in waves from other countries around the world, as early settlers on the east coast moved west, and more recently, as people have moved from the Midwest to the "sunbelt" states of the Southwest and Florida.

There is a tradition of people being able to start over, or "reinvent" themselves – moving to a new city, perhaps a new career, and changing their life in a major way. The United States is filled with people who have changed careers or started new lives. This has a long history. Early immigrants came to the US to start over, and early settlers in the American West were often moving to get a new start in life. In addition to culture, a variety of laws and practice reinforce this. For example, bankruptcy laws in the United States make it relatively easy for some who has failed in one business to start another. Housing markets are also relatively liquid compared to most countries, making it easier to move.

People's ties to institutions are also weaker in the United States than in Japan. Japanese sociologist Nakane Chie describes the U.S. as a horizontal society, where people's stronger affiliations are with their profession, compared to Japan, where people's stronger affiliations are with their institutions.

2.1.2. Market-Based Approach to Labor in the United States

A second general U.S. characteristic that affects the mobility of scientists and engineering is the reliance on market mechanisms, rather than non-market mechanisms such as planning. The United States relies relatively heavily on supply and demand in the labor market to set salaries and to allocate human resources.[4] Shortages in a particular field are assumed to lead to employers to bid against each other to hire people in the field, leading to wage increases. Wage increases are assumed to encourage more people to enter the field, until the demand is met. There is generally

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[4] As in other countries, wages are also guided by norms and traditions and various institutional features, such as government pay grades, modulate changes in wages due to market forces. But market forces play a greater role in allocating human resources and setting wages than they do in many countries.

broad acceptance of market results in the United States, even when the market produces results that seem less than ideal (such as very high salaries for CEOs and stockbrokers and poor salaries for teachers). People, of course, are not entirely or even largely motivated by salary. Many people, perhaps scientists and engineers to a greater extent than many others, want to do interesting and enjoyable work and contribute to society, and accept lower salaries to have careers with these characteristics. But the salaries are generally set by the supply and demand for people who can do certain jobs, and everything else being equal, workers will move to jobs that offer higher salaries.

Although the United States generally relies on the labor markets, as with other area of U.S. policy, it is often recognized that markets do not always provide the optimum results for society at large, and these shortcomings provide a justification for policy intervention. Many people hold the belief that the United States as a whole would be better off if there were more people trained as scientists and engineers,[5] and there have been, for more than 50 years, programs to increase the numbers of people trained as scientists and engineers. In addition, a problem with the science and engineering labor market is that there is time lag between the time when an increased demand scientists and engineer arises and when new scientist and engineers can enter the labor market. As a result of these time lags, the science and engineering labor market is characterized by cyclical shortages and surpluses of scientists and engineers. When shortages occur, there is often political pressure for government action.

For these reasons, and because the government itself needs scientists and engineers, government policy is more involved in the science and technology labor markets than in most other labor markets. The main framework for allocating science and technology related human resources, however, remains the market rather than

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[5] Scientist and engineers are viewed as essential for national defense, which has been increasingly technological, and are essential for conducting R&D that to technological innovation that provide broad benefits to society at large.

planning. The following sections of this report describe aspects of the S&T labor market, and then discuss specifically S&T labor mobility.

2.2. S&T Labor Market Features

2.2.1. Supply and Demand for S&T Personnel

In the science and technology labor market, demand for scientists and engineers comes primarily from industry, academia, and government. Table 2-1 Shows the sector of employment for science and engineering doctorates.[6] About equal numbers are employed in business and education, with a smaller number, less than 10 percent of the total, employed in government. The general pattern is that more engineering doctorates are employed in business while more science doctorates are employed in academia.

Table 2-1. Individuals with S&E doctorates by broad field of highest degree and employment sector: 1999

Field of highest degree	Employed S&Es, total	Business/ industry	Educational	Government
All S&E degree fields	614,600	274,700	283,000	56,800
Sciences	509,000	207,300	253,000	48,700
Computer and math sciences	40,600	15,800	22,400	2,300
Life and related sciences	176,200	62,400	96,600	17,200
Physical and related sciences	125,900	65,700	47,500	12,700
Social and related sciences	166,400	63,500	86,500	16,400
Engineering	105,600	67,400	30,100	8,100

Source: *Science and Engineering Indicators -2002*, Appendix table 3-18

Industrial demand depends largely on the overall state of the economy, as well as the competitiveness of U.S. industry in specific sectors. Industrial demand for scientists and engineers also depends in part on government-funded R&D, because, especially in defense-related areas, a significant amount of government-funded R&D is performed by industry.

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[6] This analysis focuses most extensively on science and engineering doctorates, because they are the degree category that does most of the science and engineering research.

Academic demand for scientists and engineers depends strongly on government funding of R&D, as well as on demographics, including changes in the size of the student population and faculty retirements. Because many universities are state-funded, hiring also depends on state budgets for universities.

Government demand for scientists and engineers depends both on the amount and direction of government R&D. In some areas, such as such as defense and space, a greater portion of government-funded R&D is performed by government scientists than in other areas, such as biomedical or energy research.

The supply of scientist and engineers is determined by the numbers new scientists and engineers coming out of academia, the conversion of persons trained in other fields, and by the number of foreign scientists coming to work in the United States. The number of new scientists and engineers coming out of academia in turn depends largely on student choices but is influenced by government funding for research assistantships and fellowships, and by student's perceptions of the job opportunities in each field. The number of foreign scientists and engineers depends both on the U.S. job market for scientists and on U.S. visa policy. When unemployment is high, there is more resistance to hiring non-U.S. citizens. In addition, certain types of S&T jobs, especially national security-related or U.S. government jobs, require U.S. citizenship or permanent resident status.

Students and researchers respond to opportunities in the job market. When there is an expansion in demand, due to economic growth in a sector (such as for information technology workers in the late 1990s) or due to government R&D funding (such as currently is the case in areas such as bioterrorism or cybersecurity research), employers find it harder to hire enough people, and wages or other job benefits in that area tend to increase. Students who are choosing their technical field and researchers who are working in related fields tend to move into the expanding area in response to the perception of greater opportunities. The greater opportunity may include factors other than wages. For academic researchers, the incentives may include funding to start a lab, the ability to hire post-docs, a lighter teaching load, or an endowed chair.

In response to the perception of greater opportunities, some researchers will reposition themselves to work in the new field. Mobility in this way is typically somewhat limited to movement between closely related fields. For example, a physicist usually will not try to become a biologist, but might become a biophysicist or a nanotechnologist. A scientist working on infectious disease or microbiology might shift his or her focus to work on bioterrorism.

Students will also tend to migrate towards fields where job opportunities and research assistantships are perceived to be the greatest. There is a time lag, however, typically 2-6 years, from the time a student chooses their field and when they reach the job market. During this period, market conditions often change. There have been numerous cases when there have been shortages or predicted shortages of scientists or engineers, either as whole or in specific subfields, that resulted in an increase of people going into those field. By the time students had completed their degrees, the job markets had changed and there were few jobs. This occurred with aerospace engineering after the end of the Apollo space program in the 1970s, with chemical engineers and geologists in the 1980s after the energy crisis had passed, in the late 1980s and early 1990s for scientists and engineers in general, and in the 2001-2002 period for information technology specialists.

Table 2-2 shows median annual salaries for science and engineering doctorates in various occupations in 1999. These variations in salary largely reflect supply and demand in the labor market.[7] This shows that there is considerable variation in salaries

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[7] They may also reflect other factors, such as differences in the median age of individuals in different categories.

for doctorates in different occupations. Some of these differences persist over long periods of time – engineers generally earn more than sociologists – but the magnitude of the differences and the rankings change over time in response to market conditions. Note that the table shows median wages. The wages for individuals vary much more widely, depending on the skills of a specific individual, location, the sector of employment and other factors.

Table 2-2. Median annual salaries of U.S. doctorates in S&E occupations, by occupation -- 1999

Occupation	Median Salary (dollars)
S&E occupations	68,000
Scientists	65,000
Computer and math scientists	71,200
Computer and information scientists	81,000
Mathematical scientists	74,400
Postsecondary teachers	60,000
Life and related scientists	62,000
Agriculture and food scientists	64,000
Biological scientists	61,300
Environmental life scientists	61,000
Postsecondary teachers	62,000
Physical and related scientists	70,000
Chemistry, except biochemistry	75,000
Earth scientists, geologists, and oceanographers	72,000
Physicists and astronomers	80,000
Other physical and related scientists	68,800
Postsecondary teachers	59,600
Social and related scientists	60,000
Economists	92,000
Political and related scientists	65,000
Psychologists	60,000
Sociologists and anthropologists	56,000
Other social and related scientists	62,000
Postsecondary teachers	55,000
Engineers	79,000
Aerospace and related engineers	83,600
Chemical engineers	80,000
Civil and architectural engineers	68,900
Electrical and related engineers	86,000
Industrial engineers	84,800
Mechanical engineers	75,000
Other engineers	77,000
Postsecondary teachers	72,800

S = suppressed for reasons of confidentiality and/or data reliability.
SOURCE: National Science Foundation, Science and Engineering Indicators 2002.

2.2.2. Distribution of Human Resources Across S&T Fields

Compared to Japan, a somewhat higher percentage of the U.S. population obtains a university degree (see table 2-3). A substantially higher percentage of the U.S. population receives degrees in natural science (4.2 percent in the U.S. versus 1.8 percent in Japan), whereas a substantially higher percentage of Japanese receive degrees in engineering (5.8 percent in Japan versus 1.8 percent in the U.S.).

Table 2-3. Proportion of the 24 year old population in the United States, Japan and Europe that have received first university degrees in various fields.

Region/location	First univ. Degrees	Natural science degrees	Engineering degrees
Japan	30.1	1.8	5.8
European Union	22.4	3.7	2.7
United States	35.3	4.2	1.8

Notes: Source: National Science Foundation, *Science & Engineering Indicators – 2002.* Data come from several sources, and degree fields may not be strictly comparable. First university degrees in different countries are of different duration and may not be academically equivalent. Natural science includes physics, chemistry, astronomy, and earth, atmospheric, ocean, biological, and agricultural sciences, and mathematics and computer sciences.

Table 2-4 shows the distribution of degrees by type of degree and by field in the United States. The most degrees, of course, are awarded at the bachelor's level, which is a prerequisite for more advanced degrees. Among the natural sciences and engineering, the most degrees are awarded in the biological and agricultural sciences, followed by engineering, mathematical and computers sciences, and the physical sciences.

At the master's level, the largest number of degrees awarded are in engineering. At the doctoral level, the most degrees are awarded in the biological and agricultural sciences. The ratio of doctoral degrees to bachelor's degree is highest in the physical sciences. The ratio between doctoral degrees and bachelors degrees is about 1:4 in the physical sciences, compared to about 1:10 in engineering and 1:12 in the biological and agricultural sciences.

Table 2-4 Degrees awarded by major field group, type of degree 2000

Degree	All fields	Science & engineering fields								Non-S&E fields
		Total	Engineering	Physical sciences	Earth, atmos., & ocean sciences	Mathematical/ computer sciences	Biological/ agricultural sciences	Psychology	Social sciences	
Bachelors	1,253,121	398,622	59,536	14,580	4,047	49,123	83,148	74,654	113,534	854,499
Masters	456,260	95,683	25,736	3,512	1,345	17,824	10,183	13,708	23,375	360,577
Doctoral	41,368	25,979	5,330	3,411	757	1,909	6,798	3,623	4,151	15,389

SOURCE: Tabulated by National Science Foundation/Division of Science Resources Statistics; data from Department of Education/National Center for Education Statistics: Integrated Postsecondary Education Data System Completions Survey

Table 2-5 shows trends in doctoral degrees. The United States produces about twice as many PhDs in natural sciences as in engineering, a pattern that has remained fairly consistent over the last 30 years. Biology and agricultural doctorates account for more than half of the natural science doctorates, and exceed those of all fields of engineering. Social science doctorates account for about 30 percent of U.S. science and engineering PhDs.

Most fields show fairly steady increases over the last three decades, but there are also some sharp increases and decreases that reflect changes in the job market. Engineering and mathematics doctorates decreased from 1970 to 1980, coinciding with the end of the Vietnam War and declining defense funding. Engineering degrees, which are more closely tied to the industrial job market, show more variation than other fields. In some cases, doctoral degrees decrease in a field when the economy is good, because the job market for bachelor's and master's degree holder is lucrative. For example, computer science and electrical engineering PhDs declined between 1995 and 1999, in the midst of the information technology boom, in part because the IT job market was so lucrative that many people elected to enter the job market rather than continue studies.

Table 2 - 5 Earned doctoral degrees, by field: 1970–99 (selected years)

Field	1970	1975	1980	1985	1990	1995	1999
All degrees	29,498	32,952	31,020	31,297	36,067	41,743	41,140
S&E	18,052	18,799	17,775	18,935	22,868	26,535	25,953
Natural sciences	8,556	8,103	7,864	8,436	9,763	11,024	10,954
Physical	3,893	3,076	2,521	2,934	3,524	3,841	3,582
Earth/atmospheric/ocean sciences	498	625	628	599	738	780	807
Biological and agricultural Sciences	4,165	4,402	4,715	4,903	5,502	6,412	6,565
Mathematics and computer Sciences	1,332	1,360	962	998	1,597	2,187	1,935
Mathematics	1,225	1,147	744	688	892	1,190	1,085
Computer sciences	107	213	218	310	705	997	850
Social and behavioral Sciences	4,825	6,538	6,470	6,335	6,613	7,307	7,727
Psychology	1,890	2,751	3,098	3,118	3,281	3,429	3,667
Social sciences	2,935	3,787	3,372	3,217	3,332	3,878	4,060
Engineering	3,446	3,011	2,479	3,166	4,894	6,008	5,337
Chemical	457	396	316	504	658	708	678
Civil	366	361	306	391	553	656	585
Electrical	857	714	540	716	1,276	1,731	1,477
Mechanical	635	487	384	513	884	1,025	853
Materials	303	272	273	303	440	588	470
Other	828	781	660	739	1,083	1,300	1,274

Source: Science and Engineering Indicators 2002. Appendix table 2-24.

2.2.3. Trend on Utilizing More Female and Minority Groups

Over the last 20 years, the composition of the science and engineering workforce has changed considerably as more female and minority scientists and engineers have entered the workforce. Figure 2-1 shows that the percentage of women in the non-academic science and engineering has doubled from 12 percent in 1980 to 25 percent in 2000. The percentage of blacks increased from less than three percent to almost 7 percent during the same period, while the percentage of foreign born scientists and engineers increased from 11 to 19 percent. The percentages of males, whites, and U.S. citizens have decreased by comparison.

Figure 2-1. College graduates in nonacademic S&E occupations: women and minorities

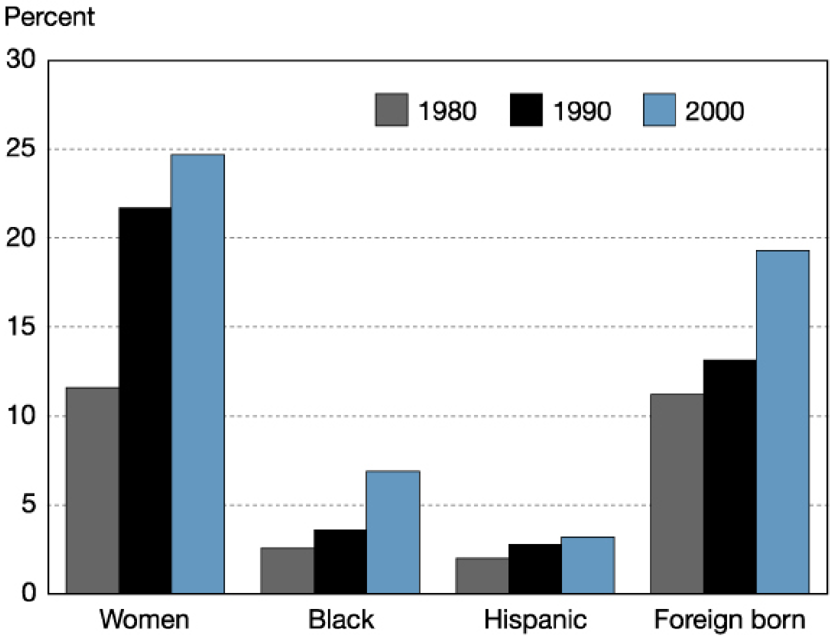
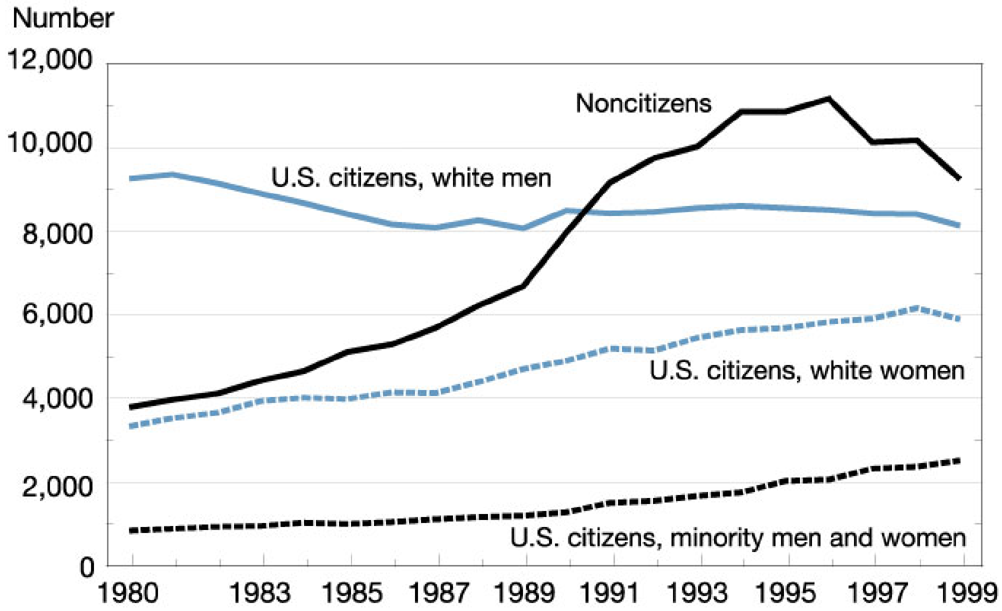


Figure 2-2 shows the trends for doctoral degrees. Doctoral degrees granted to white males have declined, while doctoral degrees for white women and minority men and women have increased. Non-citizen doctorates have declined sharply from 1996 to 1999, primarily reflecting the earlier drop in enrollments of Chinese students in the years after Tiananmen Square, as well as decreases in other Asian countries as they developed their own university systems. Although enrollments had begun to increase again, it remains to be seen what the long term effects of post-September 11, 2001 security related changes will have on non-citizen degrees.

Figure 2-2 Trends in Science and Engineering Doctoral Degrees



Source: National Science Board, *Science and Engineering Indicators-2002*

The percentage increase in females and minorities in science and engineering reflects broad social changes in the U.S. since the 1960s. There have been efforts throughout society to reduce discrimination against women and minorities in the workplace, and there have been programs to provide college scholarships for minority science and engineer students. Many government agencies, companies, and universities have made conscious efforts to increase the hiring of women and minority applicants. It is these broad trends, rather than any changes in the demand for scientists and engineers, that appears to be responsible for increases in women and minority scientists and engineers.

2.2.4. S&T Priorities and Labor Markets

Changes in government R&D priorities affect both the supply and the demand for scientists and engineers. An increase in government R&D in a particular field, such as information technology, nanotechnology, or bioterrorism, immediately increases the demand for researchers in that field. It also initiates shifts in the supply of researchers, as students and researchers shift to the new priority field. The supply of researchers tends to lag behind the demand, because it takes time for people to shift fields. Some researchers in related fields, such as infectious disease specialists who decide to move to bioterrorism, may be able to shift field quite rapidly. The ability to make this shift is aided by the relatively broad training that many scientists and engineers receive, especially at the undergraduate level, as discussed in chapter 3. It takes longer, typically several years, for students to receive training in the new field. It is common for there to be a temporary increase in salaries or benefits when government R&D priorities shift because the limited numbers of people who are specialized in the field are in very high demand until others can enter the field. Economists say that the short-run demand curve is inelastic but the long-run curve is elastic.

Government R&D initiatives that fund work though the National Science Foundation and National Institutes of Health tend to automatically increase the supply of researchers in the long-run. This is because NSF and NIH conduct most of their work through academic institutions, and much of the R&D funding pays for the training of scientists through research assistantships and post-doctoral training. An increase in funding increases the number of graduate students that can be supported.

S&T initiatives that are focused in NASA, the Department of Defense, or Department of Energy, however, do not automatically increase the supply of scientists and engineers in to the same extent, because these agencies fund more of their research in government laboratories or in industry. NASA, DOE, and DOD support some university research and provide some fellowships for scientists and engineers, but this support is not integral to the research programs, as it is for NIH and NSF.

Today many initiatives, such as nanotechnology discussed in chapter 5 have a workforce component. Generally, however, it is not a major part of the initiative. More importantly, many initiatives are designed so that a substantial amount of their funding goes to universities, where it pays for the research assistantships of graduate students, and results in the training of people with skill relevant to the initiative.

In the past, there were more broad based Federal initiatives to develop S&T human resources. These have had decidedly mixed results, as often by the time the scientists and engineers received their doctorates, labor market conditions had changed and there were few jobs. Following World War II, returning soldiers were given funding for college, known as the GI Bill. This enabled many returning soldiers to pursue careers in science and engineering. In the late 1950s and early 1960s, following the Soviet launch of Sputnik, there were major efforts to increase the numbers of people going into the math, science, and engineering. During the 1950s and 60s, people pursuing advanced studies in science and engineering were able to avoid being drafted in to the military.[8] This was a powerful incentive for many people to continue their studies to the doctoral level. Later, in the mid-1980s, the National Science Foundation published studies that suggested there soon would be shortages of scientists and engineers. These studies led to budget increases for NSF. Soon, however, there was an excess of scientists and engineers instead of the predicted shortage, in part because the cold war ended and defense budgets declined. Leaders of the scientific community sometimes call for slowing the production of new scientists and engineers, to avoid soft job markets, but these calls are rarely effective.

Another feature of science and technology labor markets is that not only does government R&D increase the demand for scientists, but also scientists can increase the demand for R&D. If there are a surplus of scientists in a field relative to R&D funding, then the scientific community complains that it is too hard to get grants and that too many good ideas are going unfunded. This often contributes to initiatives, such as the NIH doubling initiative or the NSF doubling initiative, to increase R&D funding.

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[8] In 1969 the draft was changed to a lottery system, and student exemptions were ended. The draft was abolished in 1973.

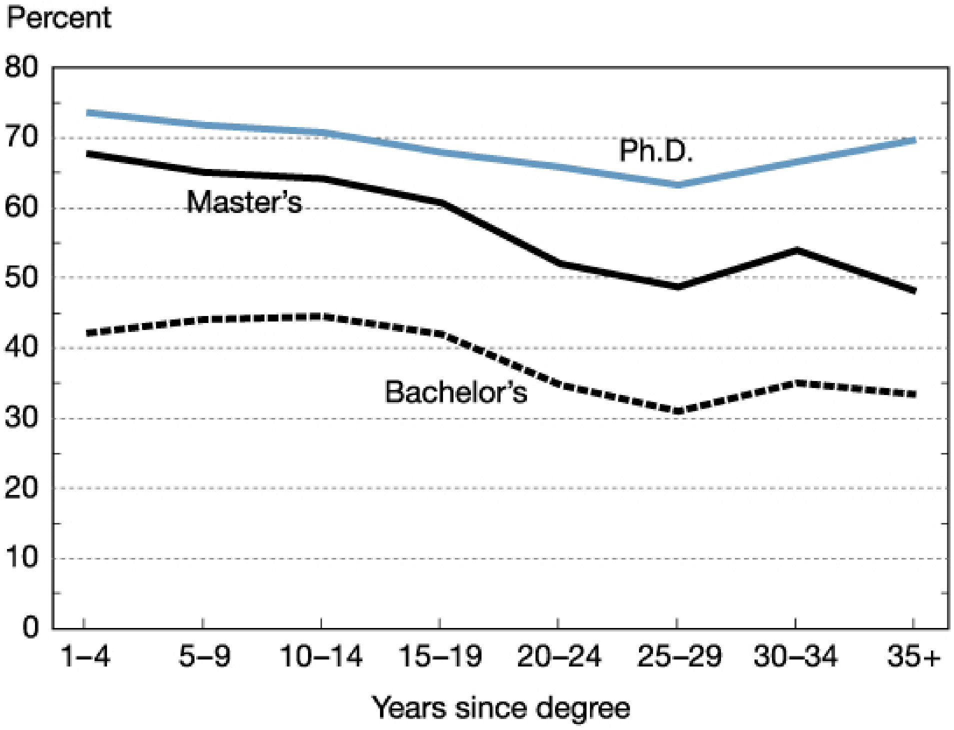
2.3. S&T Labor Mobility

This section discusses the data, trends, and factors that relate to the mobility of the science and technology workforce.

2.3.1. Data on Mobility

One measure of mobility is the extent to which people work in the same field as that in which they were trained. Figure 2-3 shows the percentage people who say they hold jobs closely related to their highest degree. Two trends are evident in these data. First, people tend to move away from their degree field over time. Second, the higher the degree level, the more likely people are to be working in a job related to their degree. Masters degrees and PhDs are more specialized, and degree holders are more likely to work in those fields. A final observation is that most people at the bachelor's and master's degree level eventually move to jobs that are not closely related to their degree. This may be a move into a different field, or it could be a movement into management.

Figure 2-3. Employed S&E degree holders in jobs closely related to their highest degree: 1999



Source: *Science and Engineering Indicators – 2002*

Table 2-6 shows the relationship between the science and engineering doctoral degrees and occupational categories. It shows that there is some movement between fields, but that most of the movement is between related fields. It shows that there is substantial movement to non-S&E occupations – 25 percent of all S&E doctorates work in non S&E fields. There is substantial migration into information technology from engineering and physical sciences: 11 percent of engineering doctorates and 13 percent of physics and astronomy doctorates work as computer and math scientists. In addition, 12 percent of physics and astronomy doctorates work as engineers.

Table 2-6. Occupational distribution of employed doctoral U.S. scientists and engineers by field of highest degree: 1999

		Total	Computer and math scientists	Life and related scientists	Physical and related scientists	Social and related scientists	Engineers	Non-S&E occupations
Field of highest degree	Number				Percent			
All degree fields	736,700	100	9.1	16.4	11.5	17.2	11.4	34.3
S&E degree fields	614,600	100	9.6	19.2	13.7	18.8	13.4	25.2
Sciences	509,000	100	9.4	22.9	16	22.6	2.3	26.7
Computer and math sciences	40,600	100	76.4	0.9	0.8	0.4	3.5	17.9
Computer and information sciences	12,100	100	72.4	S	S	S	4.7	22.1
Mathematical sciences	28,500	100	78.1	1.2	1.1	0.5	2.9	16.2
Life and related sciences	176,200	100	2.3	60	3	1	0.7	33
Agricultural and food sciences	18,100	100	2.1	68.8	3.9	1.8	0.7	22.6
Biological sciences	153,100	100	2.3	59.4	2.5	0.8	0.5	34.4
Environmental life sciences	5,000	100	3	46.6	14.3	3.3	7.1	25.7
Physical and related sciences	125,900	100	6.4	6.1	59.2	0.3	6.9	21
Chemistry, except biochemistry	63,600	100	2.9	9.3	58.7	S	4.6	24.3
Earth science, geology, and oceanography	16,500	100	4.1	2.3	77.5	S	2.4	13.6
Physics and astronomy	43,800	100	12.6	2.4	53.9	0.5	11.4	19.1
Other	1,800	100	S	20	45	S	13.9	17.2
Social and related sciences	166,400	100	2.8	1.7	0.6	67.9	0.4	26.5
Economics	22,500	100	2.8	1.6	S	71.1	S	24.1
Political and related sciences	16,700	100	2.3	S	S	61.5	S	35.4
Psychology	88,800	100	2.1	2.2	S	75.6	0.4	19.7
Sociology and anthropology	23,100	100	2.4	0.9	0.5	63.6	S	32.3
Other	15,300	100	8.5	2.1	4.6	32.1	S	51.6
Engineering	105,600	100	10.7	1.5	3	0.2	66.4	18.2
Aerospace and related	4,900	100	9.4	S	S	S	72.7	14.9
Chemical	13,600	100	4.8	2.6	2.4	S	68.5	21.7
Civil and architectural	9,900	100	3.9	S	1.8	S	80.4	13.8
Electrical and related	28,300	100	18.1	0.2	2.1	S	60.4	18.9
Industrial	3,300	100	16.1	S	S	S	47.8	34.4
Mechanical	13,500	100	7.5	0.7	1.5	S	75.2	15.1
Other	32,100	100	9.7	3.2	5.3	0.4	63.8	17.6
Non-S&E degree fields	122,100	100	6.4	2.3	S	9.4	1.7	79.8
Business and management	12,600	100	S	S	S	15.3	S	80.5
Education	S	S	S	S	S	S	S	S
Health	45,700	100	10.4	2.9	S	10.4	S	75.2
Other	63,800	100	4.4	2.3	S	7.5	2.9	82

S = suppressed for reasons of confidentiality and/or data reliability
SOURCE: National Science Foundation, Division of Science Resources Statistics (NSF/SRS), Science and Engineers Statistical Data System (SESTAT), 1999. *Science & Engineering Indicators – 2002*

Another measure of mobility is mobility between employers. Table 2-7 shows the median years of employment with the current employer for workers (16 years of age and older) in various categories. Several points are important. First, most scientists and engineers, mobility between employers is actually less than in U.S. occupations as a whole. Median tenure for engineers and natural scientists is 4.8 and 4.6 years respectively, which is longer than 3.7 years for all occupations and the 4.3 years for all professional specialty occupations. The median tenure of math and computer scientists, however, was only 3.3 years, which reflects a very high rate of labor mobility in information technology industries. Second, mobility for science and engineering occupations appears to be increasing. Although mobility for each occupation varies over time, depending on current labor market conditions, the overall trend is towards increased mobility. This is in contrast to the pattern for all occupations. Finally, the overall mobility level is fairly high. The majority of scientists and engineers have been with their current employer for less than 5 years.

Table 2-7. Median years of tenure with current employer for employed wage and salary workers by occupation, selected years, 1983-2002

Occupation	1983	1987	1991	1996	1998	2000	2002
Total, 16 years and over	3.5	3.4	3.6	3.8	3.6	3.5	3.7
Professional specialty	4.5	5.0	4.9	4.8	4.4	4.6	4.3
Engineers	6.3	6.1	6.7	6.6	5.3	4.8	4.8
Math and computer scientists	3.8	5.0	4.2	4.5	3.3	3.3	3.3
Natural scientists	4.7	6.0	5.6	4.4	5.0	5.2	4.6
Teachers, col. and university	4.4	7.2	5.5	4.4	4.2	4.7	3.8

Source: Bureau of Labor Statistics. http://www.bls.gov/news.release/tenure.t06.htm

Table 2-8 show labor mobility by degree level and age (note that these categories are not limited to scientists and engineers). This shows that mobility decreases with age – older people are likely to have been in their current job longer than younger people. It also shows that people with doctorates and other professional degrees tend to have somewhat less mobility, especially late in their careers, than other categories. Most people move several times in their career, most frequently in the earlier stages of their careers.

Table 2-8. Median years of tenure with current employer for employed wage and salary workers 25 years and over by educational attainment, and age, January 2002

Educational attainment	**Total**	**25 to 34**	**35 to 44**	**45 to 54**	**55 to 64**	**65 years**
Total	4.7	2.7	4.6	7.6	9.9	8.7
Less than a high school diploma	3.9	2.3	3.5	5.2	8.4	7.4
High school graduates, no college	5.1	2.9	4.9	7.8	10.1	8.5
Some college, no degree	4.6	2.6	4.6	7.8	9.5	8.4
Associate degree	4.6	2.9	4.5	6.7	8.1	8.0
College graduates	4.7	2.6	4.9	8.4	10.7	9.6
Bachelor's degree	4.4	2.7	5.1	7.7	9.8	8.0
Master's degree	5.6	2.7	4.9	9.6	11.8	9.1
Doctoral or professional degree	4.8	1.9	3.8	8.6	13.6	15.9

Bureau of Labor Statistics based on Current Population Survey (CPS)
http://www.bls.gov/news.release/tenure.t04.htm

2.3.2. Trends and Factors Increasing Mobility

Several trends in industry are also likely contributors to increased mobility:

- Industrial positions have become less secure due to higher rates of mergers, acquisitions, and bankruptcies. Companies increasingly resort to downsizing and restructuring to maintain profitability. The average lifespan of companies believed to be decreasing. Companies in high technology areas, such as information technology, grow and contract at especially high rates.

- Companies (as well as government) have relied more on outsourcing, such as for contract research or for specialized services. Competition is no longer between companies but is between teams of companies, such as supply chains in manufacturing. These teams come together and disband and employees often move between companies.

- In industry as well as in government, there have been trends towards more portable pension systems. Increasingly, employers put money into retirement funds that the employees control, and can take with them as they change jobs, rather than pensions that the employers control.[9] Most significantly, the Federal

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[9] Examples of portable retirement funds are Individual Retirement Accounts, Keogh Plans and "401k" plans. There are provisions in the US tax code that allow all taxes to be paid when funds are disbursed (usually after retirement) rather than when the income is earned.

government began a move toward portable retirement funds in the mid-1980s. This made it easier for people to move in and out of government employment.

There are also factors that contribute to increased mobility in academia, although good data is not available on this mobility. One factor is the increased use of postdoctoral appointees ("postdocs") in research universities over the last 20-30 years. Postdoctoral positions are generally temporary research positions that provide additional training to researchers. Historically, they have been a stepping stone to tenure track faculty positions, but in recent years the percentage of postdocs who have been able to move to tenure track positions has declined. Postdocs have traditionally been one or two year positions, but the duration of postdocs appointments have increased, and some people have remained in postdoc positions indefinitely.

Postdoc positions are advantageous to universities because they offer a lower salary and often fewer benefits that faculty positions, and the postdocs are usually willing to work long hours to improve their publication record and get recommendations that will give them a better chance of getting a regular faculty position.

The number of science and engineer postdocs has increased from 25,695 in 1994 to 29,971 in 2001.[10] The biological sciences and physics have been the heaviest users of postdocs. The biological sciences account for about two-thirds of all postdocs, and about 60 percent of biological science doctorates are in postdoc positions a year after receiving their degree.

A second factor has also been a general weakening of the tenure system, as universities rely increasingly on instructors and lecturers, adjunct professors, and

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[10] National Science Foundation/Division of Science Resources Statistics, Survey of Graduate Students and Postdoctorates in Science and Engineering.

professor on short term contracts. There are two related trends. First, there has been an increase in the use of part-time faculty, from 33.1 percent of instructional faculty in 1987 to 42 percent in 1998. Only 5.3 percent of part-time faculty were tenured or in tenure track position in 1998.[11] Second, fewer full-time faculty are tenured or are in tenure-track positions. The percentage of full-time faculty that are tenured or are in a tenure track position declined from 82.4 percent in 1987 to 71.9 percent in 1998. These two trends have resulted in a significant erosion of the tenure system over the past thirty years.

Another new type of mobility that has developed in the last 20 years is mobility between universities and start-up companies. U.S. universities have always had flexible policies about leave, providing for professors to take sabbaticals (paid leave) or to take visiting professorships at other universities.[12] Many universities now allow their faculty to take "entrepreneurial leave" to temporarily join a company on a full time basis. For example, at the University of Pittsburgh, the pursuit of entrepreneurial endeavors is a considered a valid reason for application for a faculty leave of absence. Similarly, Ohio States university allows for an entrepreneurial unpaid leave of absence, not to exceed two years.[13] Entrepreneurial leave policies are in addition to long-standing policies at many universities that allow faculty members approximately one day a week for consulting. Entrepreneurial leave, however, is still relatively rare, and is much smaller component of mobility in academia than traditional sabbaticals and visiting professorship arrangements.

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[11] U.S. Department of Education, National Center for Education Statistics (2002). Tenure Status of Postsecondary Instructional Faculty and Staff: 1992–98, (NCES 2002–210), by Basmat Parsad and Denise Glover. Washington, DC: 2002. http://nces.ed.gov/pubs2002/2002210.pdf

[12] Often it is financially advantageous for universities to allow their faculty to take a leave of absence. The university can usually find a temporary or part-time person to teach the courses at lower pay than the professor who is going on leave. The replacement faculty, however, generally do not replace the full scope of the absent member's work, including research, departmental guidance, student guidance, curriculum renewal, etc. For this reason, the absence of such faculty is also a burden to colleagues , and many institutions limit its term, usually to two years.

Some national laboratories have similar policies. Sandia National Laboratories, for example, offers an entrepreneurial leave program that lets inventors take several years off (without pay) to launch a business.[14]

2.4. Key Factors Influencing Mobility of S&T Personnel and S&T Priorities

The mobility of U.S. S&T personnel, while high by international standards, is not particularly high compared to other professional occupations in the United States. The mobility of S&T personnel is related less to any specific policies to promote mobility of S&T personnel, and is related more to the relatively high degree of labor mobility of in the United States and the relatively flexible U.S. labor markets. The United States relies on a relatively efficient labor market to allocate S&T personnel to industrial and national needs. A variety of policies and systems, ranging from portable pension systems, entrepreneurial leave policies in universities, bankruptcy laws and relatively liquid housing markets also facilitate movement of people to new jobs.

Changes in S&T priorities, as well as changing economic conditions, create new opportunities (as well as risks) for scientists and engineers. S&T personnel reposition themselves to respond to opportunities. Broad based training, as discussed in chapter 4 contributes to this.

New S&T initiatives increase the demand for people with specific skills. In the short run, specialists in the field are often in very high demand, and leading to an increase in wages or other benefits. In the longer run, other researchers and students

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[13] For examples of these policies, see http://www.pitt.edu/HOME/PP/policies/11/11-02-03.html and http://www.oaa.admin.ohio-state.edu/Handbook/ix_loaentrepren.html.

[14] Candace Stuart. High Tech's Hatcheries. *Small Times.* http://www.smalltimes.com/document_display.cfm?document_id=6476

move to the field, and supply and demand returns to balance. Many S&T initiatives, by concentrating funds in universities, automatically train people in the new priority areas.

Several factors in industry and in academia contribute to increases in overall mobility of S&T personnel in the United States. Overall increases in mobility, however, are long-term and gradual, and mobility goes up and down in each field with changing economic conditions.

3. GEOGRAPHICAL MOBILITY OF HUMAN RESOURCES TO THE U.S. FROM ABROAD: THE POSSIBLE IMPACT ON S&T PRIORITY FIELDS

3.1. Section Introduction

The United States benefits enormously from foreign-born scientists and engineers. In 1999, for example, 27 percent of doctorate-holders in science and engineering (S&E) in the United States were foreign born, and almost one-fifth (19.9 percent) of those with master's degrees were foreign born.[15] These professionals make major contributions as university faculty members, corporate researchers, high-tech entrepreneurs, and government scientists and engineers.

But will the United States continue to receive and retain the numbers and types of foreign-born scientists and engineers it needs for the future, including the researchers needed to keep America at the cutting edge in priority fields such as nanotechnology, biotechnology, and computer science? This section of the paper will discuss several trends that are beginning to affect both the supply of foreign-born scientists and engineers and the U.S. demand for these professionals.

Two main trends are now affecting the *supply* and economic contributions of these people from abroad:

- First, since the attacks of September 11, 2001, the U.S. Government has installed new procedures and restrictions regarding the admission of foreign nationals into the United States. Interviews and sometimes extensive background checks are now required. University officials and others in the U.S. worry that these new restrictions will prevent or deter foreign students from studying in America, denying the country an important source of new scientists and engineers.
- Second, some foreign-born scientists and engineers working in the United States are returning to their native countries. We do not have exact numbers,

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[15] National Science Board, *Science and Engineering Indicators –2002*, NSB 02-01, Arlington, VA: National Science Foundation, 2002, Volume 1, page 3-39. *Indicators—2000* is available at http://www.nsf.gov/sbe/srs/seind02/start.htm.

but Taiwan and now China are examples of countries that actively recruit their nationals to return home, either to start new companies or help existing ones. These returnees are part of a larger trend, one which some analysts call "brain circulation." Instead of the old "brain drain," in which gifted young people from abroad come to America and stayed, in the newly emerging pattern many foreign-born professionals to circulate back and forth between the U.S. and their native countries.

In addition to these factors affecting supply, other factors will affect the *U.S. demand* for foreign-born S&E professionals. The picture here is complex, however, since some trends may increase the demand for foreign-born professionals while other trends may reduce that demand.

- If the U.S. economy grows as it has over the past 20 years, then the demand for scientists and engineers will grow, as well. According to the National Science Foundation (NSF), from 1980-2000 the growth rate of S&E jobs greatly exceeded the overall rate of job growth – a trend that may continue into the future as the U.S. becomes a more advanced technological society. But two trends will lower the native-born supply to meet this expanded demand: the large "baby-boom generation" will retire, and the supply of new native-born scientists and engineers is not expected to grow significantly. As a result, there *might* be an expanding demand for foreign-born S&E professionals. At a minimum, U.S. universities will need new S&E professors as the current generation begins to retire.
- However, past trends in job growth may not apply in the future. First, the U.S. Government and some defense companies may hire fewer foreign scientists and engineers, given new security requirements put into place after September 11, 2001. Second, non-defense companies may begin to hire fewer scientists and engineers within the United States. Companies are now moving more and more of their engineering and research operations to other countries, either by "outsourcing" (hiring overseas contractors to handle the work) or by "offshoring" (moving their own corporate operations to other nations, such as China and India). We lack detailed statistics on the offshoring and outsourcing of S&E-related activities, but anecdotal evidence suggests that they are major tends in certain U.S. industrial sectors, especially electronics and software.

This mixture of trends – some suggesting increased demand for scientists and engineers and some suggesting reduced demand – makes it very hard to predict the future. But we do expect that that the demand for foreign-born scientists and engineers will continue and may in fact expand, although not as much as some analysts earlier predicted.

This section of the paper also examines the possible impact that these trends may have on the ability of the U.S. to succeed in priority fields of science and technology. It concludes that while there is no immediate problem, in the future the U.S. university system, more than the corporate sector, may have difficulty recruiting and retaining the top researchers it needs to stay at the cutting edge of science and technology.

3.2. Scientists and Engineers in the U.S. from Abroad

3.2.1. Recent Numbers of Foreign-Born Scientists and Engineers

In 1999, the U.S. workforce included 11 million college-educated individuals either with S&E degrees or otherwise working in S&E occupations. The vast majority (10.5 million) held at least one college degree in a science or engineering field.[16]

That year, 12.2 percent of scientists and engineers in the United States were foreign born, and 27.0 of those with doctoral degrees were foreign born. Table 3-1, taken from NSF data and included in *Science and Engineering Indicators—2002*, provides details.

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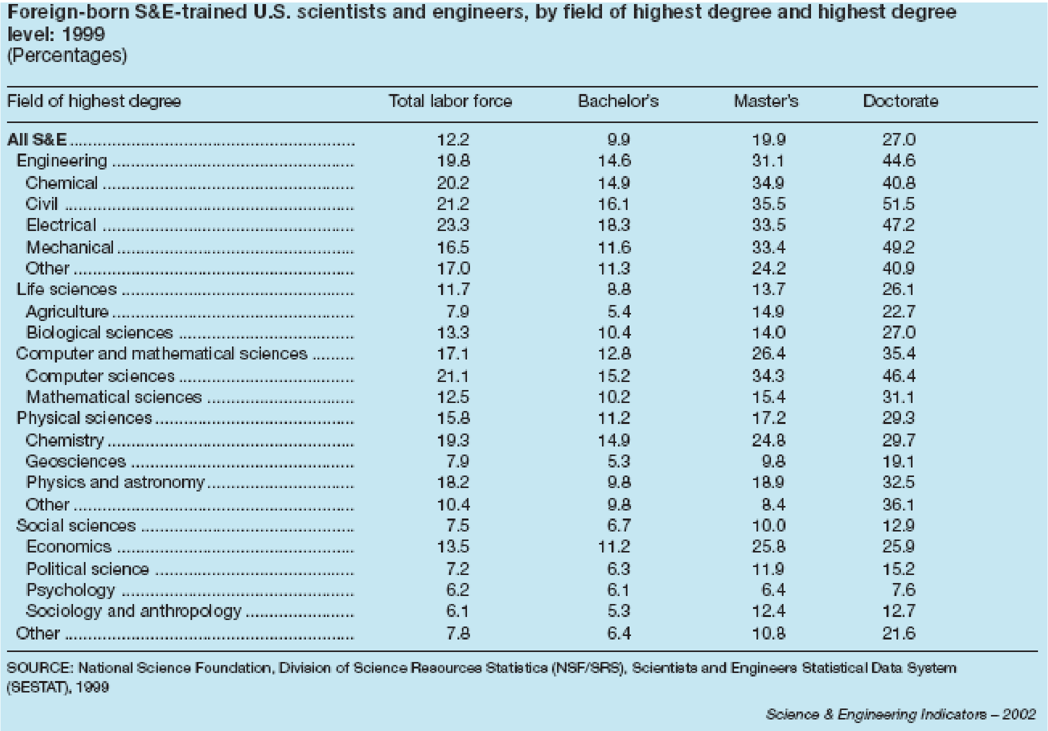
[16] *Science and Engineering Indicators—2002*, Volume 1, page 3-3.

Table 3-1



Foreign-born S&E-trained U.S. scientists and engineers, by field of highest degree and highest degree level: 1999
(Percentages)

Field of highest degree	Total labor force	Bachelor's	Master's	Doctorate
All S&E	12.2	9.9	19.9	27.0
Engineering	19.8	14.6	31.1	44.6
Chemical	20.2	14.9	34.9	40.8
Civil	21.2	16.1	35.5	51.5
Electrical	23.3	18.3	33.5	47.2
Mechanical	16.5	11.6	33.4	49.2
Other	17.0	11.3	24.2	40.9
Life sciences	11.7	8.8	13.7	26.1
Agriculture	7.9	5.4	14.9	22.7
Biological sciences	13.3	10.4	14.0	27.0
Computer and mathematical sciences	17.1	12.8	26.4	35.4
Computer sciences	21.1	15.2	34.3	46.4
Mathematical sciences	12.5	10.2	15.4	31.1
Physical sciences	15.8	11.2	17.2	29.3
Chemistry	19.3	14.9	24.8	29.7
Geosciences	7.9	5.3	9.8	19.1
Physics and astronomy	18.2	9.8	18.9	32.5
Other	10.4	9.8	8.4	36.1
Social sciences	7.5	6.7	10.0	12.9
Economics	13.5	11.2	25.8	25.9
Political science	7.2	6.3	11.9	15.2
Psychology	6.2	6.1	6.4	7.6
Sociology and anthropology	6.1	5.3	12.4	12.7
Other	7.8	6.4	10.8	21.6

SOURCE: National Science Foundation, Division of Science Resources Statistics (NSF/SRS), Scientists and Engineers Statistical Data System (SESTAT), 1999

Science & Engineering Indicators – 2002

This table shows just how dependent the U.S. has become on foreign-born scientists and engineers. And that dependence has grown sharply since 1990. Another report, from NSF's National Science Board, finds that for all degree levels, the share of U.S. science and engineering occupations filled by scientists and engineers who were born abroad increased from 14 to 22 percent between 1990 and 2000; for doctoral degrees, the share went from 24 percent in 1990 to 38 percent 10 years later.[17] The U.S. benefits greatly from the willingness of these individuals to come and work in America.

Figure 3-1, also from NSF, provides details on the home countries of foreign-born individuals in the United States whose highest degrees were in science and engineering.

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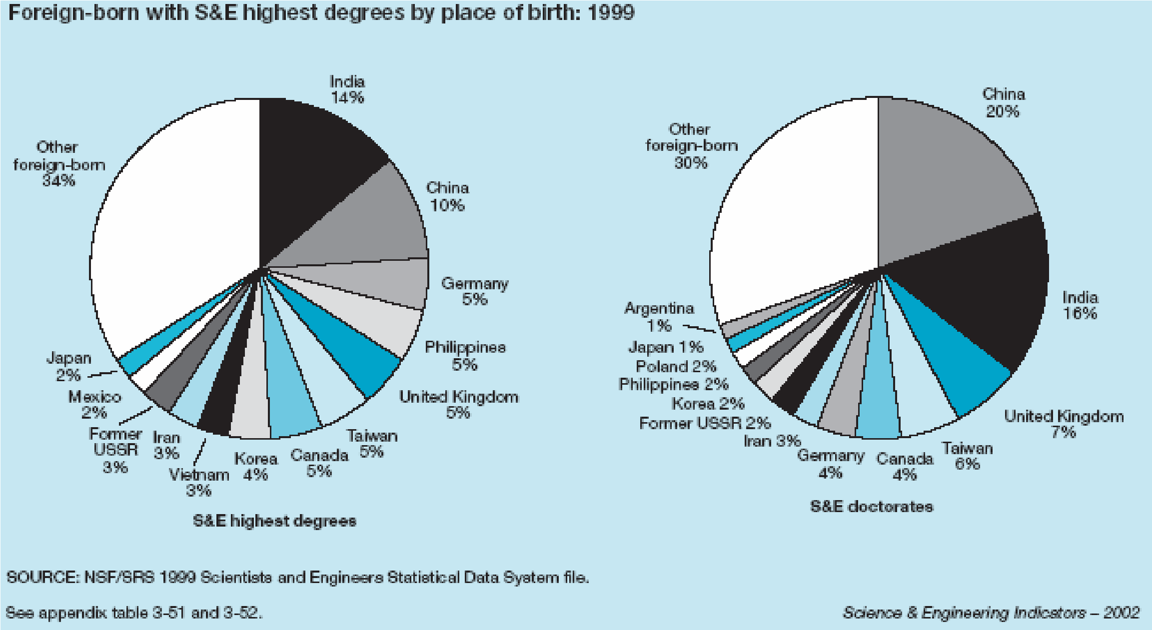
[17] National Science Board, *The Science and Engineering Workforce: Realizing America's Potential*, NSB 03-69 (Arlington, VA: National Science Foundation, August 14, 2003), page 9. The report is available at: http://www.nsf.gov/nsb/documents/2003/nsb0369/nsb0369.pdf.

Figure 3-1



Foreign-born with S&E highest degrees by place of birth: 1999

SOURCE: NSF/SRS 1999 Scientists and Engineers Statistical Data System file.

See appendix table 3-51 and 3-52.

Science & Engineering Indicators – 2002

NSF has recently released data on 2002 science and engineering doctoral degrees awarded, by citizenship status of recipients. The following table uses that NSF data. It shows that non-U.S. citizens remain particularly important in engineering.

Table 3-2. Doctorates Awarded, by Citizenship Status of Recipients: 2002

	Total S&E Doctorates	Engineering Doctorates	Science Doctorates
Total numbers of doctorates (all citizenships)	23,558	5,073	19,485
Citizenship known	23,152	4,806	18,346
U.S. citizens	14,313	1,890	12,423
Non-U.S. citizens	8,839	2,916	5,923
Non-U.S. citizens with permanent visas	1,166	271	895
Non-U.S. citizens with temporary visas	7,674	2,645	5,028
Citizenship unknown	1,406	267	1,139

Source: National Science Foundation, *Science and Engineering Doctorate Awards: 2002*, Table 4. The report is available at www.nsf.gov/sbe/srs/nsfo4303/htmstart.htm.

Foreign-born individuals typically take one of three routes into the U.S. science and engineering community:

- They came to the United States as children, with immigrant parents, and then received their education in the U.S.
- They came to the United States as undergraduate or graduate students in science and engineering, and after completing their education they stayed in the U.S.
- They received their education in their native countries but came to the United States after school, either as immigrants or under temporary visas (including H-1B visas).

The second route is particularly important. The U.S. has succeeded in attracting some foreign-born undergraduate students and many foreign-born graduate students.

At the undergraduate level, foreign students have earned only a small percentage (3.6 percent) of all S&E bachelor's degrees awarded in the U.S. in recent years, although foreign students in U.S. institutions earn approximately 7-8 percent of bachelor's degrees in mathematics, computer science, and engineering.[18]

At the doctoral level, NSF's *Science and Engineering Indicators – 2002* provides this analysis regarding foreign students receiving U.S. Ph.D. degrees:

> Each year from 1986 to 1996, the number of foreign students earning S&E doctoral degrees at universities in the United States increased; after that, this number of earned degrees dropped off…. [T]he number of foreign students earning doctoral degrees in S&E increased from 5,000 in 1986 to almost 11,000 in the peak year of 1996…. During the peak 1986-1999 period, foreign students earned 120,000 doctoral degrees in S&E fields. China is the top country of origin of these foreign students; almost 24,000 Chinese students earned S&E doctoral degrees at universities in the United States during this period….
>
> The decline in S&E doctoral degrees earned by foreign students mirrors their declining enrollment in graduate S&E programs from 1993 through 1996 [e.g., after Tiananmen Square]. After this four-year drop-off in enrollment, the

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[18] National Science Board, *Science and Engineering Indicators—2002*, Volume 1, page 2-21.

> number of foreign graduate students stabilized in 1997 and increased in 1998 and 1999….
>
> Foreign students earn a larger proportion of degrees at the doctoral level than any other degree level, more than one-third of all S&E doctoral degrees awarded…. Their proportion in some fields is considerably higher: in 1999, foreign students earned 47 percent of all doctoral degrees awarded in mathematics and computer sciences and 49 percent of those awarded in engineering….
>
> Historically, approximately 50 percent of foreign students who earned S&E degrees at universities in the United States reported that they planned to stay in the United States, and a smaller proportion had firm offers to do so….
>
> Foreign doctoral students' plans to stay in the United States differ from region of origin. Those from East and South Asia receive the highest number of doctoral degrees by far and constitute the highest percentage of students who plan to stay in the United States.[19]

The following figure, also from NSF, shows both the numbers of doctoral degrees awarded to students from several foreign countries and the percentages of those students who plan to stay in the United States.

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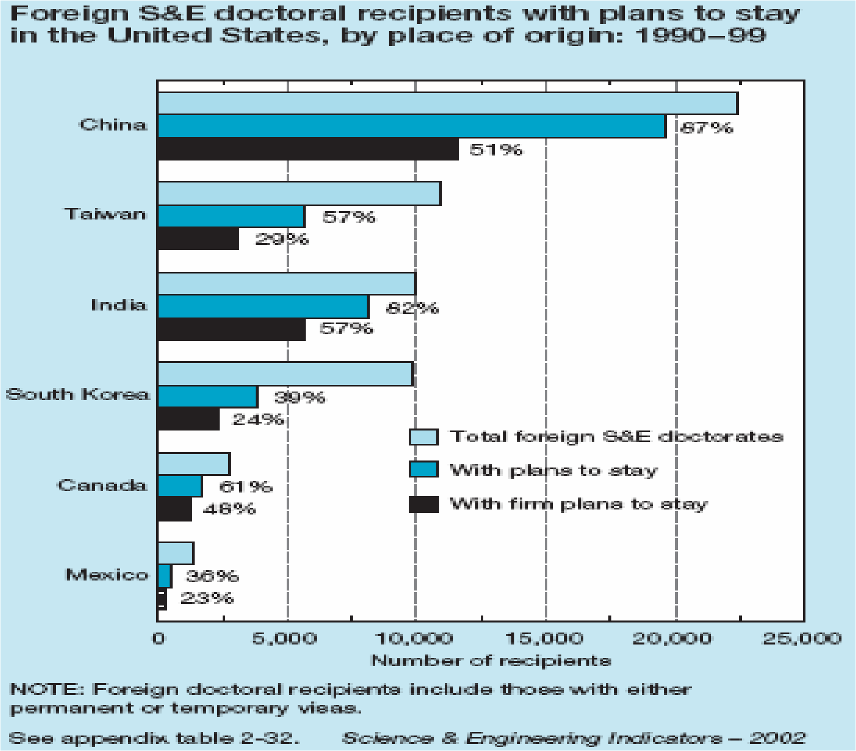
[19] National Science Board, *Science and Engineering Indicators—2002*, Volume 1, pages 2-30 to 2-31 and 2-33 to 2-34.

Figure 3-2



NOTE: Foreign doctoral recipients include those with either permanent or temporary visas.

See appendix table 2-32. *Science & Engineering Indicators – 2002*

In short, large numbers of foreign students come to the United States to earn their doctoral degrees, and many of them stay – something that greatly benefits the U.S.

There is no evidence so far that Chinese, Taiwanese, and Indian students awarded doctoral degrees in the U.S. show any increasing tendency to go home rather than stay in America. In 1999 the proportion planning to stay in the U.S. actually increased. But it is possible that in the future more students will go home because of greater opportunities in their native countries.

Foreign students without permanent visas enter the U.S. with temporary papers (F-1 visas) that expire when they finish their degrees.[20] However, these individuals can

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[20] A built-in tension (or contradiction) exists in the F-1 visa process. Even before September 11, 2001, U.S. Government policy stated that F-1 visas were only to be granted to students who have “binding ties” to their home countries and who intend to return home rather than try to stay in the U.S. In short, foreign students are not supposed to become immigrants. Chinese students, in particular, often have trouble convincing U.S. consular officials that they have binding ties and intend to return to China. But of course

then apply either for immigrant status (numbers here are limited) or try to remain in the United States under one of several types of temporary work visas (see Box 1). Exact figures on how many foreign-born, American-educated scientists and engineers actually stay in the United States (as opposed to plan on staying) are not available. However, *Science and Engineering Indicators – 2002* quotes a study by Michael Finn. He found that 51 percent of 1994-95 U.S. S&E doctorate recipients were still in the United States in 1999.[21]

Box 1. Types of U.S. Temporary (Non-Immigrant) Work Visas

The U.S. Government issues a wide range of temporary (non-immigrant) visas. Some of the major types of temporary work visas are the following:

- B-1. Temporary Visitor for Business. Short-term visa.
- H-1B. Specialty Occupations (for professionals). These visas are for three years and renewable for an additional three. U.S. companies, not foreign individuals, apply for H-1B visas.
- Other H visas (for nurses, temporary agricultural workers, temporary non-agricultural workers, and trainees).
- J-1. Exchange Visitors. Many foreign post-doctoral fellows, visiting professors, and other visiting professionals use this type of visa.
- L-1. Intracompany Transferee. Foreign employees of a company can use this type of visa.
- O-1. Temporary Worker of Extraordinary Ability.
- TN. NAFTA Professionals. For Canadian and Mexican professionals, entering under the North American Free Trade Agreement.

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many Americans are pleased when foreign students do decide to stay, because of the contributions they make to the U.S. economy. This is one example of conflicting goals within U.S. immigration policy.

[21] National Science Board, *Science and Engineering Indicators—2002*, Volume 1, page 3-30.

Scientists and engineers educated in their native countries also can enter the United States, either as immigrants[22] or as temporary workers (particularly under J-1 or H-1B visas). Workers in the U.S. under temporary visas may apply for permanent immigration status, although there are not enough immigration slots for all of them.

In recent years, the H-1B category has been an important source of foreign scientists and engineers, especially for the information technology and life science sectors. Under this program, U.S. companies – not the individuals themselves – petition the U.S. Government for a visa. The U.S. Bureau of Citizenship and Immigration Services (USCIS), a branch of the Department of Homeland Security and formerly the U.S. Immigration and Naturalization Service, decides whether to grant H-1B petitions.[23]

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[22] The following useful summary of immigrant visas comes from the Web page of True, Walsh & Miller, a law firm (see www.twmlaw.com/site/resources/general1cont.htm):

> An immigrant (or lawful permanent resident, "LPR") is someone admitted to the United States permanently. To obtain immigrant status, an applicant must meet both the substantive and numerical requirements of the law. Substantively, one must qualify as a specified close relative of a U.S. citizen or other LPR, as an employee of a sponsoring employer or prospective employer [thus receiving an employment-based, "EB", immigrant visa], or as a "diversity immigrant" under a visa "lottery" program. Further, the potential immigrant must not fall within any of the general categories of inadmissible aliens specified in the law, as criminality, mental defect, Communist party affiliation, drug trafficking, or terrorism.
>
> In addition to substantive requirements, there are also country-specific and world-wide statutory quota limits imposed on most categories of family and employment-based immigrant visas. These quota limitations can result in extended waiting periods before immigrant status may be obtained. Currently, about 670,000 immigrant visas are available each year.

[23] USCIS has provided the following summary of the H-1B program:

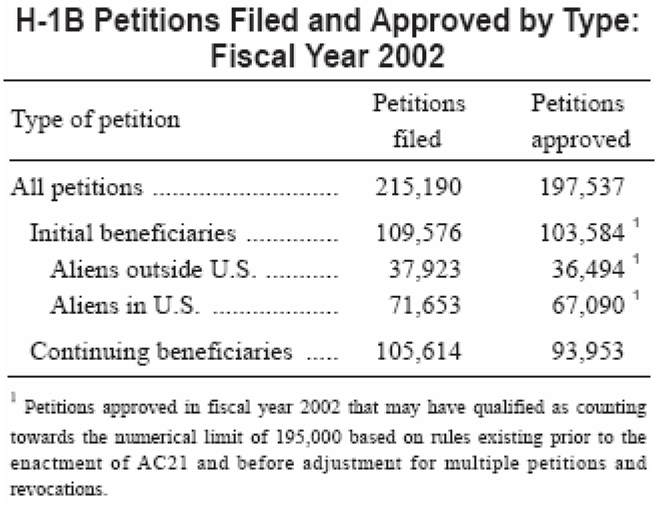
> An H-1B temporary worker is an alien admitted to the United States to perform services in "specialty occupations," based on professional education, skills, and/or equivalent experience…. The H-1B nonimmigrant classification permits foreign professionals to enter the United States on a temporary basis to work in their field of expertise.
>
> Under the H-1B program, specialty workers are permitted to be employed for as long as three years initially with extensions not exceeding six years. The maximum stay is six years…. Specialty occupations include computer systems analysts and programmers, physicians, professors, engineers, and accountants.

Source: USCIS, "Temporary Admissions," Chapter 6 of *2002 Yearbook of Immigrations Statistics*, Washington, DC: USCIS, 2003, page 94. Chapter 6 is available at: http://uscis.gov/graphics/shared/aboutus/statistics/TEMP02yrbk/Temp2002.pdf.

Through most of the 1990s, the government could grant up to 65,000 H-1B petitions per year. But at the request of the information technology industry, Congress raised that level to 115,000 in each of federal fiscal years (FY) 1999 and 2000 and 195,000 per year for FY 2001, 2002, and 2003. On October 1, 2003 – the first day of FY 2004 – the level dropped again to 65,000 per year.

USCIS collects statistics about the visas it grants, and the following tables present some of those statistics. Table 3-3 presents data from federal fiscal year (FY) 2002 on the number of petitions received and granted.[24] Table 3-4 identifies H-1B beneficiaries by countries of birth. Table 3-5 identifies H1-B beneficiaries by occupation.[25]

Table 3-3



H-1B Petitions Filed and Approved by Type: Fiscal Year 2002

Type of petition	Petitions filed	Petitions approved
All petitions	215,190	197,537
Initial beneficiaries	109,576	103,584 [1]
Aliens outside U.S.	37,923	36,494 [1]
Aliens in U.S.	71,653	67,090 [1]
Continuing beneficiaries	105,614	93,953

[1] Petitions approved in fiscal year 2002 that may have qualified as counting towards the numerical limit of 195,000 based on rules existing prior to the enactment of AC21 and before adjustment for multiple petitions and revocations.

Source: U.S. Bureau of Citizenship and Immigration Services

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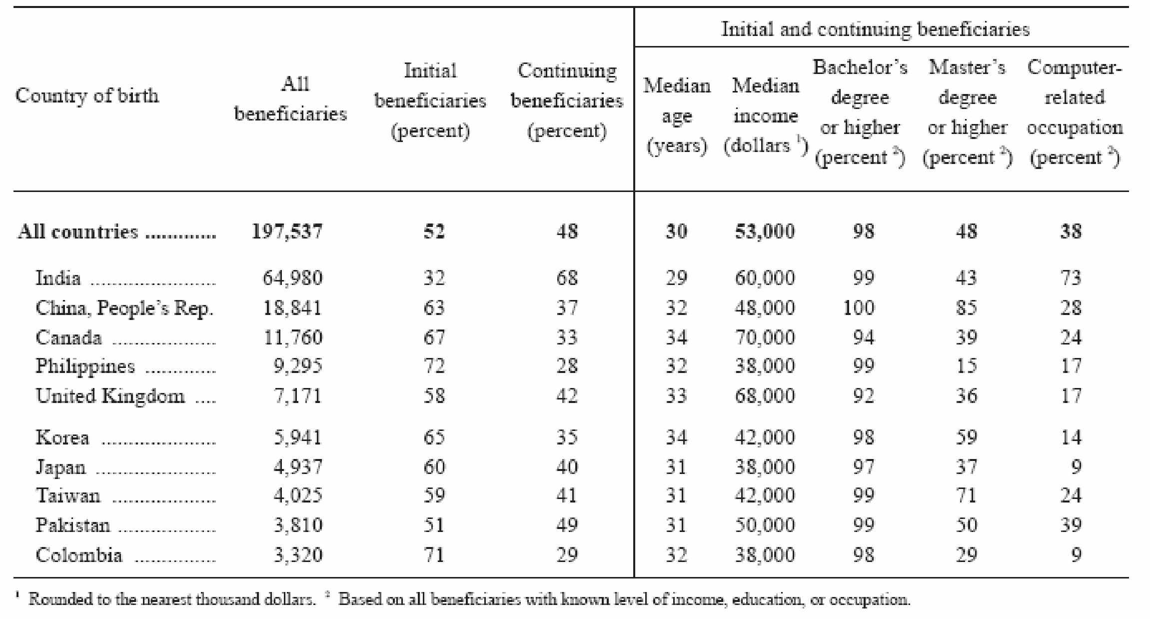
[24] Inn at least some years Japan has accepted more highly skilled temporary workers than has the United States. In 1999, 240,936 workers entered Japan in high-skill visa categories – an increase of 75 percent since 1992. National Science Board, *Science and Engineering Indicators—2002*, Volume 1, page 3-3.

[25] These three tables come from USCIS, "Temporary Admissions," Chapter 6 of *2002 Yearbook of Immigrations Statistics*, Washington, DC: USCIS, 2003, pages 94-96.

Table 3-4

Profile of H-1B Beneficiaries by Top 10 Countries of Birth: Fiscal Year 2002

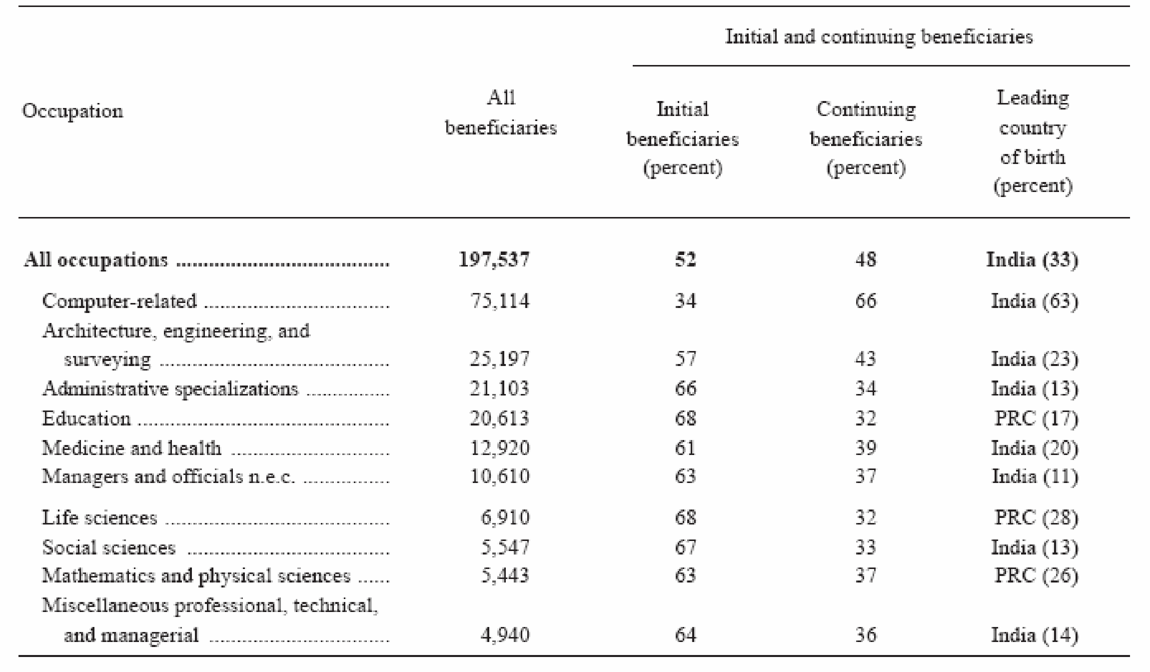


Country of birth	All beneficiaries	Initial beneficiaries (percent)	Continuing beneficiaries (percent)	Initial and continuing beneficiaries: Median age (years)	Median income (dollars [1])	Bachelor's degree or higher (percent [2])	Master's degree or higher (percent [2])	Computer-related occupation (percent [2])
All countries	**197,537**	**52**	**48**	**30**	**53,000**	**98**	**48**	**38**
India	64,980	32	68	29	60,000	99	43	73
China, People's Rep.	18,841	63	37	32	48,000	100	85	28
Canada	11,760	67	33	34	70,000	94	39	24
Philippines	9,295	72	28	32	38,000	99	15	17
United Kingdom	7,171	58	42	33	68,000	92	36	17
Korea	5,941	65	35	34	42,000	98	59	14
Japan	4,937	60	40	31	38,000	97	37	9
Taiwan	4,025	59	41	31	42,000	99	71	24
Pakistan	3,810	51	49	31	50,000	99	50	39
Colombia	3,320	71	29	32	38,000	98	29	9

[1] Rounded to the nearest thousand dollars. [2] Based on all beneficiaries with known level of income, education, or occupation.

Source: U.S. Bureau of Citizenship and Immigration Services

Table 3-5 Profile of H-1B Beneficiaries by Top 10 Occupations: Fiscal Year 2002



Occupation	All beneficiaries	Initial and continuing beneficiaries: Initial beneficiaries (percent)	Continuing beneficiaries (percent)	Leading country of birth (percent)
All occupations	**197,537**	**52**	**48**	**India (33)**
Computer-related	75,114	34	66	India (63)
Architecture, engineering, and surveying	25,197	57	43	India (23)
Administrative specializations	21,103	66	34	India (13)
Education	20,613	68	32	PRC (17)
Medicine and health	12,920	61	39	India (20)
Managers and officials n.e.c.	10,610	63	37	India (11)
Life sciences	6,910	68	32	PRC (28)
Social sciences	5,547	67	33	India (13)
Mathematics and physical sciences	5,443	63	37	PRC (26)
Miscellaneous professional, technical, and managerial	4,940	64	36	India (14)

Source: U.S. Bureau of Citizenship and Immigration Services

In 1999, the total U.S. S&E workforce totaled 11 million people. Assuming a workforce of similar size in 2002, H-1B visa beneficiaries constituted approximately 1.8 percent of the total S&E workforce.

However, the beneficiaries were particularly important in the information technology industry and life sciences sectors. For example, Table 3-5 shows that, in 2002, 75,114 H-1B beneficiaries were in computer-related occupations. NSF's data on total S&E workforces by sector do not fit exactly with the USCIS categories, but in 1999 the total U.S. S&E workforce in computer and information sciences plus all of electrical and related engineering totaled 1,173,500.[26] The 75,114 number constitutes 7.4 percent of the 1,173,500 number. And these foreign-born professionals on H-1B visas were of course in addition to other foreign-born scientists and engineers in the United States.[27]

The H-1B program has undoubtedly contributed to the U.S. economy, but it is also controversial. Critics argue that the program depresses salaries in those fields with large numbers of H-1B individuals, such as electrical engineering and computer programming. Foreigners are willing to work for lower amounts of money. Critics further argue that if it were not for the H-1B visas, companies would pay higher salaries and do more to retrain Americans to do new technical jobs. It is possible, as well, that the resulting lower salaries discourage some American students from pursuing careers

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[26] National Science Board, *Science and Engineering Indicators—2002*, Volume 2, Appendix table 3-6.

[27] While individuals working under H-1B visas are important to both the U.S. information technology and life sciences sectors, there is an important distinction between these two fields. In information technology, many of the individuals entering the U.S. under H-1B visas have received university degrees in their home countries. This largely reflects the quality of electrical engineering and computer science programs in India and China. However, in the life sciences – especially the biotechnology industry – most people under H-1B visas have received U.S. degrees. According to Sevier and Dahms, "80% percent of biotechnology H-1Bs are from US universities, and 85% of those eventually will acquire permanent residency in the United States." See E. Dale Sevier and A. Stephen Dahms, "The role of foreign worker scientists in the US biotechnology industry, *Nature,* September 2002, Volume 20, Number 9, pages 955-956. http://www.nature.com/cgi-taf/DynaPage.taf?file=/nbt/journal/v20/n9/full/nbt0902-955.html. This high reliance on U.S.-trained life sciences professionals may reflect both the importance of Ph.D. degrees in biotechnology and the fact that the U.S. trains a high percentage of the world's total life sciences Ph.D.s.

in science and engineering. Instead, these students may become lawyers or investment bankers, careers that often offer high salaries and less competition from immigrants.

Company executives sometimes admit privately that they are looking for ways to lower costs, but add that if salaries in the U.S. rise the companies then have an added reason to move R&D activities – and jobs – overseas. Lower salaries may help keep jobs in the United States.

3.2.2. Contributions of Foreign-Born Scientists and Engineers

In the 19th and early 20th centuries, many Americans saw immigrants as primarily a source of low-skilled, low-cost labor. The data mentioned above, however, are striking; they show that many very highly skilled professionals have chosen to come to the United States.

Foreign-born scientists and engineers contribute greatly to America, and have done so for a long time. [28] Recently, they have become increasingly important as high-tech entrepreneurs. AnnaLee Saxenian, a professor at the University of California, Berkeley, has conducted a pioneering study of immigrant entrepreneurs – that is, how much foreign-born scientists, engineers, and technology business executives contribute to the creation and growth of new companies in the United States. She has focused on immigrant professionals from Greater China (especially Taiwan) and India and their contributions to the Silicon Valley region of California.

In a 1999 report, *Silicon Valley's New Immigrant Entrepreneurs*, Saxenian found that in the late 1990s more than one-third of the engineers and scientists in Silicon Valley's

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[28] There are many examples. Russian immigrant scientist Vladimir Zworykin helped invent television. Numerous immigrants from Europe helped the United States develop atomic energy. Erich Bloch, a refugee from Germany, led the IBM team that developed the modern mainframe computer. Many of the Americans who have won Nobel prizes in science originally came from Europe and Asia. Thousands of scientists and engineers from overseas have become professors and industrial researchers. In addition, immigrants are increasing important as entrepreneurs and creators of important new technology companies. For example, Andy Grove, from Hungary, helped start Intel Corporation.

technology workforce were foreign-born, mostly of Asian descent. They also were creating businesses, jobs, and wealth. She calculated that in 1996 (the most recent year for which she had data) Indian or Greater Chinese executives ran 1,786 Silicon Valley technology companies with $12.6 billion in sales and 46,000 employees. And they were running 27 percent of the more than 4,000 total Silicon Valley businesses started between 1991 and 1996.[29] Clearly, the United States has benefited from both foreign-born S&E professionals and foreign-born high-tech entrepreneurs.

But are these benefits likely to continue into the future, especially since (1) the U.S. Government has imposed new visa restrictions since September 11, 2001, and (2) it appears that many American-trained foreign-born scientists and engineers are returning to their home countries?

3.3. Two Trends That Affect the Supply of Foreign-Born Scientists and Engineers

3.3.1. Visa Restrictions and Other Changes in U.S. Immigration Policy

Since the attacks of September 11, 2001, the U.S. Government has changed its visa policies. Some observers, including officials at American universities, are concerned that the new practices will block or deter foreign students from attending American universities – hindering research in U.S. university laboratories and ultimately leading to fewer foreign-born scientists and engineers to help the American economy.

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[29] AnnaLee Saxenian, *Silicon Valley's New Immigrant Entrepreneurs*, San Francisco: Public Policy Institute of California, 1999. For a summary of her findings, see her commentary entitled "A Valley Asset: Chinese, Indians Creating Businesses, Jobs, Wealth As Successful Entrepreneurs," at http://www.ppic.org/main/commentary.asp?i=206.

The numbers seem to support this view. In FY 2003, the U.S. State Department (which processes visa applications, after consulting other U.S. agencies) received about 24 percent, or 93,000, fewer applications for F-1 student visas than two years earlier.[30]

University data confirm a continuing decline in the number of foreign graduate students (from all fields) applying to U.S. universities. *The Chronicle of Higher Education* provides this summary of the results from a survey conducted in February and early March of 2004:

> More than 90 percent of American colleges and universities have seen a drop in applications from international graduate students for the fall 2004 term, and the number of submissions has fallen 32 percent from last year, according to a survey released by the Council of Graduate Schools on Tuesday [March 2, 2004]….
>
> The new study, which focuses on graduate students only, found the largest drop in applications from countries that usually send the most applications. Applications from students in China declined by 76 percent, those from India fell 58 percent. Students in the Middle East sent 31 percent fewer applications, and even Western Europe had a 30-percent decline. The drop crossed all fields of study as well, with an 80-percent plunge in applications to engineering programs [from foreign students] and a 65-percent reduction in those to physical-sciences programs.[31]

It is not clear whether new U.S. visa restrictions have been the main cause of this decline. Other factors may also be responsible, including growing economic opportunities within China and India themselves. However, the perception among U.S. university officials is that foreign students feel that the U.S. is less welcoming today than in earlier years. Today's U.S. visa system is a big reason for this feeling.

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[30] Jean Kumagai, "Problems Persist With U.S. Visas," *IEEE Spectrum Online*, December 2003. http://www.spectrum.ieee.org/WEBONLY/resource/dec03/1203nvisa.html.

[31] Michael Arnone, "New Survey Confirms Sharp Drop in Applications to U.S. Colleges from Foreign Graduate Students," *The Chronicle of Higher Education*, March 4, 2004. A further summary of the survey's results is available from the Council of Graduate School Web site. See: http://www.cgsnet.org/pdf/CGS_PR_IntlSurvey.pdf.

The current visa policy for students and other visitors has both older and newer elements:[32]

- Foreign nationals have always needed to apply to the U.S. State Department for a visa. However, as of August 1, 2003, students and researchers must now have in-person interviews with U.S. consular officers prior to receiving or renewing a visa. Since the number of consular officers did not increase, visa delays are possible.
- Background checks for some foreign nationals are more extensive and longer than in the past. Male applicants and people studying sensitive scientific fields are being subjected to extra checks, which often take longer than past checks and made lead to visa applications being denied.[33]
- Immigration officers now fingerprint, photograph, and sometimes interview individuals arriving in the U.S. from many countries – a process that recently has been expanded under the new US-VISIT program.
- Foreign students in the United States who travel abroad for short visits home or to attend scientific meetings will have their U.S. visas reviewed, which may lead to delays.
- U.S. universities must now track and monitor foreign students at their campuses through the U.S. Government's electronic system known at SEVIS – the Student and Exchange Visitor Information System.

Security officials worry about admitting terrorists to the U.S. and about potential terrorists learning scientific or engineering skills that could be used to harm the United States.

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[32] The following points about the new U.S. visa process and its effects so far on foreign students, researchers, and those attending scholarly meetings are from Jean Kumagai (cited above) and two articles from *Chemical and Engineering News*: Victoria Gilman, The Changing Face of Visa Policy, September 29, 2003 (http://pubs.acs.org/cen/education/8139/print/8139education2.html) and Jean-Francois Tremblay, "Security Measures Impede U.S. Visits," March 17, 2003 (http://pubs.acs.org/cen/education/8111/print/8111education.html).

[33] Michael Arnone's article in The Chronicle of Higher Education (Ibid.) provides a summary of this program, which has the name "Visas Mantis": "The program, a collaboration between the Federal Bureau of Investigation and the State Department, performs security checks on foreign students and scholars who study any of roughly 200 different scientific fields that are on the government's Technology Alert

But as a result of this new policy, visa delays and denials seem to be growing, causing, in the words of Victoria Gilman of *Chemical and Engineering News*, "many international students and scholars to miss classes and conferences, avoid trips back to their home countries, or decide not to come to the U.S. at all." Gilman quotes an official from the Association of American Universities (AAU) who says that delays ranging from two months to almost a year and a half have been reported, and most of the cases involve students who want to study physical sciences and engineering. An October 2002 survey by AAU and NAFSA founds that hundreds of foreign students and scholars had not been able to start the 2002-2003 school year on time because of visa delays. A second survey conducted in the fall of 2003 found similar problems.[34]

The delays do not apply just to university students and scholars. At the chemical industry's Infomex trade show held in New Orleans in February 2003, 70 percent of the Chinese exhibitors were denied visas.[35]

What are some of the effects so far of the new visa policy and associated visa delays and denials?

- As mentioned earlier, in FY 2003 the U.S. State Department (which processes visa applications, after consulting other U.S. agencies) received about 24 percent, or 93,000, fewer applications for F-1 student visas than two years earlier.

- The October 2002 AAU-NAFSA study found an overall drop of eight percent in the 2002-2003 school year in the number of foreign scholars (post-doctoral

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List. The list catalogs disciplines that could threaten U.S. national security if certain knowledge were transported to another country."

[34] AAU and NAFSA, along with the National Association of State Universities and Land-Grant Colleges (NASULGC) conducted the fall 2003 survey of U.S. universities, asking about visa delays at the beginning of the 2003-2004 school year. The universities reported delays similar to those in 2002. For a summary of the 2003 survey, see "Survey Details Impact of Restrictive Government Actions on Flow of International Scholars and Students," http://www.aau.edu/resources/Visa%20Survey%20Press%20Release.pdf. For further information on the survey findings and the recommendations of the three university associations, see: http://www.nafsa.org/content/PublicPolicy/FortheMedia/visasurvey2003.htm.

[35] Jean-Francois Tremblay, "Security Measures Impede U.S. Visits."

fellows, professors, and other non-students) at U.S. universities as compared with 2001-02.

- Other countries that compete with the U.S. for foreign students may gain from the U.S. problems. From 2001 to 2002, Great Britain saw large jumps in the numbers of students coming from China (up 71 percent) and India (55 percent).
- The AAU and NAFSA argue that the visa delays have already delayed or stalled scientific research at American universities, and that these problems are continuing into the 2003-2004 school year.

University officials worry that foreign students will no longer feel welcomed in the U.S. Foreign graduate students in science and engineering now play a major role in university research. If these students do not come, or if their numbers drop significantly, then cutting-edge research in university laboratories could be affected. The U.S. might also have difficulty recruiting foreign-born professors and researchers – problems that also would affect university research.

3.3.2. From "Brain Drain" to "Brain Circulation"

Today, some skilled American-trained professionals are returning home to their native countries. Is there now a significant "reverse brain drain," and, if so, is it hurting or helping the U.S. economy?

Quantitative data on this subject are not available, but there is no doubt that over the past 20 years many skilled Ph.D. researchers and technical managers have returned to their native countries, often in part because their home governments have actively recruited them. But the resulting picture is something much more complex – and much more beneficial to the U.S. – than the image of a reverse brain drain suggests.

AnnaLee Saxenian, who has studied this issue extensively as part of her research on immigrant entrepreneurs, speaks not of brain drains but of "brain circulation."[36] Many ethnic Chinese and Indians who came to Silicon Valley or other parts of the U.S. high-technology community have now either gone back to their native countries to start companies or have started transnational businesses, which may be based in the U.S. but have extensive operations or subcontracts in Asia. These highly skilled entrepreneurs literally live in two worlds and move easily between them, circulating between the U.S. and Asia.

This process primarily started with Taiwanese, in the 1980s. The Taiwanese government wanted to encourage new high-tech industries, and it made an active effort to recruit back to the island individuals born in Taiwan who had received advanced degrees in the U.S. and worked for American companies. Many of these early efforts focused on recruiting back experts in semiconductors and other electronics sectors.

The Taiwanese effort succeeded, not only because of the government's incentives but also because of genuine economic opportunities in Taiwan and, related, because of significant changes in the worldwide semiconductor and electronic industries. Until about the late 1970s, semiconductor companies and many electronics manufacturers made all of their own products and often made much of their equipment, as well. But this vertical integration began to break down in the 1970s and 1980s, as many companies found it more efficient and cost-effective to contract out some or all of their manufacturing. Taiwan and its American-trained electronics executives were well poised to take advantage of this change.

In 1979 Taiwan's government-supported Industrial Technology Research Institute (ITRI) spun off United Microelectronics Corporation (UMC), and in 1987 it

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[36] Saxenian, *Silicon Valley's New Immigrant Entrepreneurs*, page vi. See also AnnaLee Saxenian, with Yasuyuki Motoyama and Xiaochong Quan, *Local and Global Networks of Immigrant Professionals in Silicon Valley*, San Francisco: Public Policy Institute of California, 2002.

spun off the Taiwan Semiconductor Manufacturing Company (TSMC).[37] Today, these are two of the world's leading contract chip-making companies. Taiwan is of course also a major manufacturer of personal computers and computer components. China has now begun its own effort to recruit American-trained Chinese and Taiwanese experts to help expand its electronics industry.[38] And India now has its own government programs to encourage overseas Indians to start companies,[39] and some American-trained Indian experts have gone back home to start software service companies.

Box 2 provides several examples of American-trained experts who run major Taiwanese and Chinese electronics companies.

Box 2. Some Examples of American-trained Executives Who Run New Asian Companies

- *Taiwan Semiconductor Manufacturing Company*. Chairman and CEO Morris Chang received his Ph.D. degree from Stanford University and worked at General Instrument Corporation. President and Chief Operating Officer Rick Tsai received his Ph.D. from Cornell University. Senior Vice President, Research and Development, Shang-Yi Chiang received his Ph.D. from Stanford and worked at Hewlett-Packard. Senior Vice President, Worldwide Marketing and Sales, Kenneth Kin, received his Ph.D. from Columbia University and worked at IBM. Other senior TSMC executives received Ph.D. degrees from Yale, Princeton, and the University of California, Berkeley.
- *United Microelectronics Corporation (Taiwan)*. Chief Executive Officer Jackson Hu

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[37] For a brief history of ITRI, see http://www.itri.org.tw/eng/about/history.jsp.

[38] For information about Chinese initiatives, see Jonathan Kaufman, "China Reforms Bring Back Executives Schooled in U.S.," *The Wall Street Journal*, March 6, 2003; and "On their way back," *The Economist*, November 8, 2003. For an interesting critique of China's policy to develop high-tech industries (with either indigenous or expatriate entrepreneurs), see "The allure of low technology, *The Economist*, December 20th, 2003, page 99.

[39] For example, see the Web site of the Indian Business Centre, which describes its services to encourage "non-resident Indians" to invest in India. http://www.indiaserver.com/biz/indian-investment-centre.html. However, the reaction of overseas Indians to these programs is mixed, as illustrated in the following article: Karl Schoenberger, "Luring Tech to India's Coast: State's Development Goal Hampered by Expats Who Don't Want to Return," *San Jose Mercury News*, January 11, 2004. http://www.mercurynews.com/mld/mercurynews/business/7684605.htm.

received his Ph.D. degree from the University of Illinois and worked in Silicon Valley, helping to start several companies there. Chris Chi, another senior executive, received a master's degree from UCLA and worked at Rockwell spin-off Conexant.

- *Semiconductor Manufacturing International Corporation (Shanghai).* CEO and President Richard Chang worked at Texas Instruments for 20 years. He then started a Taiwanese semiconductor company that he subsequently sold to TSMC. After that he joined SMIC.

Source: corporate Web sites

Are these new Asian-based companies good or bad for the American economy? One can argue that they are beneficial for the U.S. In a highly competitive world economy, the close links between customer firms in the United States and efficient Asian suppliers offer the U.S. firms a significant advantage. What Saxenian calls "brain circulation" – two-way flows of skilled people between the U.S. and other nations – creates highly valuable business networks that benefit both U.S. and foreign companies. Of course, however, these professionals who return home are not filling university or corporate jobs in the United States.

3.3.3. *An Additional Point: The Flexibility of the U.S. Immigration System*

The analysis above suggests that a combination of restrictive U.S. visas and increasing number foreign-born professionals returning home may, in the years to come, limit the ability of the United States to recruit and retain scientists and engineers from abroad. This is certainly a possibility. However, there is also an important additional point.

Historically, the United States has altered its immigration policies in response to changing needs and political pressures. In the late 1990s, for example, the information technology industry persuaded Congress and the Clinton Administration to increase the annual number of H-1B visas. If, in the future, the United States faces a critical shortage of scientists and engineers, both universities and industry will probably lobby for new immigration rules that allow more foreign-born S&E students and professionals to enter the U.S. and stay here.

3.4. Trends That May Affect the U.S. Need for Foreign-Born Scientists and Engineers

Several factors are likely to affect the future U.S. demand for foreign-born scientists and engineers. Some of these factors that will increase that demand, and some that probably will reduce it. At the moment, it is impossible to predict which of these factors will be the most significant. But by identifying these factors, we can learn which trends we need to watch closely.

The first set of factors discussed below would, if past trends continue, significantly increase the demand for foreign-born S&E professionals.

3.4.1. "Traditional" Factors That May Increase the U.S. Demand for Scientists and Engineers and for Foreign-born Scientists and Engineers in Particular

According to NSF, the number of S&E jobs in the United States grew rapidly between 1980 and 2000, and that number is therefore likely – if traditional trends continue – to grow rapidly as well between 2000 and 2010.

The following quote about the 1980-2000 period comes from *Science and Engineering Indicators – 2002:*

> Since 1980, nonacademic S&E jobs grew at more than four times the rate of the U.S. labor force as a whole. Nonacademic S&E jobs increased by 159 percent between 1980 and 2000 – an average annual rate of 4.9 percent compared with 1.1 percent for the entire labor force….
>
> Although every broad S&E occupational group grew between 1980 and 2000 (the lowest growth, 81 percent, occurred in physical sciences), the most explosive growth was in mathematics and computer sciences, which experienced a 623 percent increase (177,000 jobs in 1980 to 1,280,000 jobs in 2000).[40]

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[40] *Science and Engineering Indicators-2002*, Volume 1, pages 3-3 and 3-6.

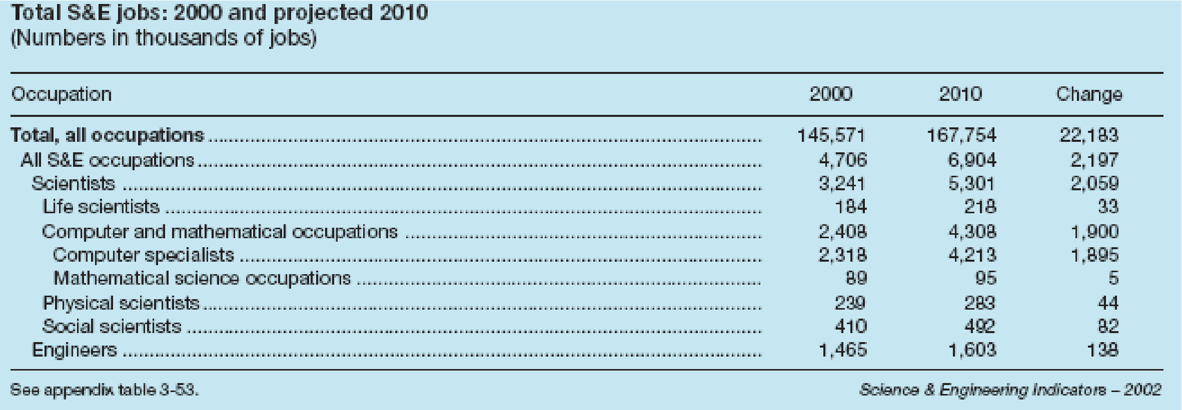
In short, as the U.S. economy becomes more technologically advanced, the demand for scientists and engineers is higher than the demand for other kinds of employees. And as a result the U.S. economy needs more scientists and engineers.

Based on the past trends, NSF projects increased demand in the future:

> During the 2000-2010 period, employment in S&E occupations is expected to increase about three times faster than the rate for all occupations. Although the economy as a whole is expected to provide approximately 15 percent more jobs over this decade, employment opportunities for S&E jobs are expected to increase by about 47 percent (about 2.2 million jobs).
>
> Approximately 86 percent of the increase in S&E jobs will likely occur in computer-related occupations. Overall employment in these occupations across all industries is expected to increase about 82 percent over the 2000-2010 decade, adding almost 1.9 million jobs.[41]

Table 3-6 summarizes NSF's 2002 projections of S&E employment growth between 2000 and 2010.

Table 3-6:



Total S&E jobs: 2000 and projected 2010
(Numbers in thousands of jobs)

Occupation	2000	2010	Change
Total, all occupations	145,571	167,754	22,183
All S&E occupations	4,706	6,904	2,197
Scientists	3,241	5,301	2,059
Life scientists	184	218	33
Computer and mathematical occupations	2,408	4,308	1,900
Computer specialists	2,318	4,213	1,895
Mathematical science occupations	89	95	5
Physical scientists	239	283	44
Social scientists	410	492	82
Engineers	1,465	1,603	138

See appendix table 3-53. *Science & Engineering Indicators – 2002*

If the total number of U.S. S&E jobs does indeed grow this much, the United States will begin to face a significant shortage of scientists and engineers. This would not happen immediately, but rather gradually as the large "baby-boom" generation begins to retire. NSF believes that the total number of retirements among S&E-degreed

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[41] *Science and Engineering Indicators-2002*, Volume 1, page 3-27.

workers in the U.S. will increase dramatically over the next 20 years, unless there is a significant change in retirement rates.[42] In addition, U.S. universities are not training large enough native-born scientists and engineers to replace all of the retirees or to fill all the new vacancies arising from a growing economy.

Science and Engineering Indicators-2002 does not provide quantitative estimates of either expected retirements or likely numbers of new native-born scientists and engineers. Therefore, we cannot estimate how much the domestic supply of scientists and engineers will fall below projected demand in, say, the year 2010 or 2020. But given NSF's projections of a rapidly growing number of American S&E jobs, a significant shortfall is possible. The demand for foreign-born S&E professionals may expand significantly.

However, this type of analysis rests on the assumption that the U.S. demand for scientists and engineers will grow in a traditional way – that is, that this demand will grow in the in the future as it has in the recent past. Yet, this assumption may no longer be valid, for two reasons that we will now discuss.

3.4.2. Possible Effect of New Security Requirements

First, it is possible that in the future the U.S. Government and some American companies, especially firms that sell to the Defense Department, may hire fewer foreign-born scientists and engineers within the United States. The reason is that new security requirements since September 11, 2001, lead to a growing demand in the government and some security-minded areas of industry for professionals who are U.S. citizens or permanent residents. The long-term effect on hiring foreign-born professionals may not be large, but it will exist.

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[42] *Science and Engineering Indicators—2002*, Volume 1, page 3-3.

3.4.3. *"Offshoring" and Overseas Outsourcing*

Second, and more important, many American-based companies are now changing the way that they organize their research and development (R&D), product engineering, technical services, and manufacturing. In the process, they are changing where and how many scientists and engineers they hire to perform these tasks. These new employment practices are beginning to affect the demand for scientists and engineers in the United States – including the demand for foreign-born scientists and engineers.

Two important changes are "offshoring" (moving corporate operations previously in the United States to other countries) and outsourcing overseas (contracting with foreign companies to perform tasks that the U.S. firms once performed themselves).

Contracting with foreign firms for engineering and manufacturing services is common practice now in many U.S. industries, especially electronics. Contract manufacturers in Asia or Mexico such as Solectron or Flextronics now make most personal computers and almost all consumer-electronic products sold in the U.S. The American semiconductor industry also increasingly contracts with foreign manufacturers. This applies not only to small "fabless" chip companies that contract with Asian semiconductor foundries. Intel and other large chip firms now contract with TSMC or SMIC or similar firms to manufacture a large portion of their products. As a result, these U.S. firms need fewer manufacturing engineers in the United States. In some cases, overseas engineers also do the product development and design.

It also appears that the "offshoring" of U.S. R&D, product engineering, and manufacturing is growing. Major American-based multinationals are moving not just manufacturing but also engineering and R&D operations to other nations, particularly to China and India. No precise data are currently available regarding this trend, but press reports suggest that many U.S. companies – particularly electronics and software companies – are establishing R&D and engineering and design centers in China and India. Anecdotal evidence suggests that at least in Silicon Valley, company executives do not expect to expand their local R&D or engineering workforces. Any growth will come overseas, particularly in Asia.[43] One indicator of declining demand for workers in the U.S. is that the demand for H-1B workers – particularly in information technology – is way down.[44] The results in part from recession but also in part from the shift of job growth overseas.

In part, companies move operations overseas or to contractors because of costs: a high-quality engineer in China or India might receive a salary of $10,000 a year, compared with a Silicon Valley engineer whose salary is $100,000 per year. But the moves overseas are also the result of at least two other factors. First, some companies complain that they have trouble finding adequate numbers of high-quality engineers in the U.S. at any price, while the supply of engineers is much larger in China and India. As with any high-tech business activity, the companies go where good people are. And this issue may become more important in the years to come, as many of today's U.S. scientists and engineers retire. Second, Asian markets for electronics and other products are expanding rapidly, causing U.S. companies to establish new research, development, and engineering centers near those important markets.

One does not want to exaggerate this trend, however. For example, if the world's most important academic research in a particular field is conducted in high-wage countries, then companies will establish R&D centers to be near that academic expertise. Not every new corporate R&D investment is in low-wage countries.[45]

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[43] Source: personal conversations.

[44] The number of H-1B visas issued to workers in the U.S. information technology industry dropped nearly 75 percent from 2001 to 2002 (from 105,692 to 27,199). See Margaret Steen, "Tech's use of H-1B visas falls 75% in '02," *The San Jose Mercury News*, September 18, 2003.

[45] NSF has some older data on R&D investments that U.S. firms make in other countries. In the 1990s, little of this investment went to China or India. For example, more than two-thirds of the $17 billion spent abroad in R&D by U.S. majority-owned foreign affiliates in 1999 was in five development countries: Canada, France, Germany, Japan, and the United Kingdom. See National Science Board, *Science and*

Biotechnology R&D is a notable example. For the next few years, at least, most U.S. overseas R&D will continue to be in developed nations. And if U.S. universities remain world leaders in new fields of science and technology, it is likely that American companies will continue to maintain significant research laboratories within the United States – so that they can be close to this cutting-edge research.[46]

Even so, an important new trend is the movement of at least some product development and engineering work from the U.S. to Asia. If this becomes a large trend, it will lower the demand for scientists and engineers in the United States – including foreign-born scientists and engineers.

3.5. The Impact of These Trends on S&T Priority Fields

Given these big trends affecting supply and demand, will the United States continue to need large numbers of foreign-born scientists and engineers in the future? Will the rest of the world continue to supply the United States with the skilled people needed to fill that demand? And will there be a shortage that threatens the ability of the United States to conduct world-class research in priority R&D areas such as nanotechnology, biotechnology, and advanced electronics?

3.5.1. The U.S. Demand for Foreign-Born Scientists and Engineers

With respect to the demand for foreign-born scientists and engineers, one can make a distinction between the needs of R&D organizations whose operations must remain within the United States – particularly universities and government laboratories

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Engineering Indicators—2002, Volume 1, pages 4-61 through 4-63. However, when data become available for the period after 2000, it is likely that we will see an increased percentage of this overseas R&D investment going to areas of Asia outside of Japan.

[46] For further analysis and data about where U.S. firms make overseas R&D investments and why, see the work of Walter Kuemmerle of the Harvard Business School. See, for example, his "Location of R&D Activity—International Data Issues," a presentation to the April 7, 2003, National Academies workshop on R&D data needs. In that presentation, he distinguishes between "home-base-augmenting" R&D investments (that is, R&D to improve a company's technical capabilities and often made near universities

– and those technical organizations, particularly corporations, that can easily move much of their R&D and engineering overseas.

American universities will continue to want the best students and professors they can get, and given the relatively low numbers of native-born Americans going into engineering and the physical sciences one can expect the demand for high-quality foreign-born students and faculty to remain high.

U.S. Government technical agencies (such as the Defense Department, NASA, the Energy Department, and so forth) and their laboratories face a serious problem. Large numbers of government scientists and engineers are or will soon be eligible for retirement. Who will replace them? This problem will be particularly acute in the secret laboratories of the Defense and Energy Departments, where only American citizens may work. Low government salaries and competition from private industry already have led to some shortages in key specialties, such as computer science.

Private U.S. corporations have more flexibility, because they can either move their R&D operations overseas or contract with foreign companies. Of course, in order to stay at the leading edge in new priority R&D fields companies will need both their own world-class researchers and proximity to top academic researchers. But in many cases world-class researchers may be available in other countries, including possibly China.

3.5.2. The Future Supply of Foreign-Born Scientists and Engineers

In the future, will high-quality foreign-born scientists and engineers still be willing and able to come to the United States? In particular, will they want to come if good opportunities exist for them in their native countries? And will they be able to

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in high-wage countries) and "home-base-exploiting" R&D (often made near manufacturing sites in developing countries).

come, given new visa restrictions imposed by the U.S. Government after September 11, 2001?

We have no definitive answers to these questions, but we can offer some observations. First, as long as the U.S. university system remains one of the world's best, and best funded, it is likely to attract bright students and professors from around the world. Anecdotal evidence suggests that even in Greater China, where governments have made major investments in their technical universities, many of the best students still prefer to come to the United States for graduate school. And many of them still stay in the U.S., although we do not yet have data on trends over the past few years. It is possible that in the future, the best students and researchers will find new educational and business opportunities in their own native countries and will therefore not come to the United States. But so far we see no evidence of a significant trend in this direction.

Second, while university officials have expressed concern about new U.S. visa delays and restrictions, it is unlikely that the new visa policies will significantly restrict the number of S&E students and professionals coming to the United States. Visa delays are real, and if they get worse then the consequences of cutting-edge research in American universities would be significant. However, right now the greatest scrutiny and delays apply to applicants from Arab or other Muslim countries, and historically these countries (with the partial exception of Iran) have not been major sources of scientists and engineers for the United States.

Of greater long-term concern is the possibility that Chinese and other foreign students interested in the physical sciences and engineering may gradually be restricted from entering the United States, because of concerns that they might learn skills useful in the making of weapons. But so far we have no data that confirm this type of problem.

As discussed earlier, the number of H1-B visas allowed in the United States recently dropped back to 65,000, from the temporary three-year level of 195,000 per annum. However, given the current recession in the U.S. information technology sector – the main user of H-1B visas – this lower number is not currently a serious problem for U.S. industry. If the U.S. information technology feels the need for more H-1B visas, it may once again lobby Congress for increases, as it did in the late 1990s.

3.5.3. The Impact on S&T Priority Fields

In conclusion, the U.S. continues to draw large numbers of high-quality foreign-born science and engineering students and researchers. In recent years, a significant (but unquantified) number of highly-skilled American-trained technical managers have returned to their home countries to start companies there, but these companies often benefit the U.S. economy by becoming efficient suppliers of critical components or services. In the future, it is possible that fewer top people from abroad will come to the United States, because of new educational or business opportunities in their own countries. But currently we see little evidence of this.

As its economy resumes growth, the United States is likely to need increasing numbers of scientists and engineers, although the growth of corporate outsourcing and offshoring may keep that growth modest.

As a result, while the U.S. remains very dependent on foreign-born researchers, there is little evidence to suggest that the number or quality of these researchers will decline any time soon. If problems do arise, they will most likely arise for U.S. universities more so than for U.S. companies.

4. THE RELATIONSHIP BETWEEN NATIONAL S&T NEEDS AND THE "LIBERAL EDUCATION" TRADITION

4.1 The U.S Liberal Education Tradition and Its Assumptions

The American concept of a "liberal education" consists of a broad set of assumptions about the nature and purpose of education, coupled with a reasonably coherent and widely accepted set of design principles for educational institutions. Sometimes called the "liberal arts tradition," it is a uniquely American model, differing markedly from the English antecedents on which it was based, and fundamentally from the European tradition of specialized educational elites, which it has never emulated. Increasing technical specialization in society does not seem to have cast the liberal education tradition into serious doubt among Americans; on the contrary, there are many who see liberal arts as the best preparation for entry into a world in which the parameters of science and technology will be changing ever-more rapidly.

The essence of the American liberal education is perhaps not so much what one studies as how one studies it. The hallmarks of this approach are breadth and open intellectual inquiry, and its institutions tend to be managed with a great deal of attention to these goals. The following list of adjectives offers an impressionistic characterization of liberal education in the U.S.[47]

- Flexibility
- Mobility
- Personal Choice
- Decentralization
- Diversity
- Competitive
- Non-planned
- Multi-level
- Non-linearity

The above said, there is still a strong sense of an appropriate liberal educational curriculum. This curriculum is often capsulated in the rubric, “arts and sciences.” What this means in practice is that students are obliged to gain familiarity with the basic works and intellectual tools of a number of core disciplines, spanning both technical (“sciences”) and non-technical (“arts”) areas. This approach begins in high school and can proceed through most of university, since it is by no means assumed that bachelor’s degree holders in this tradition will have gained much depth of specialization. But it is assumed that they will “know how to think” in a variety of modes.

The liberal educational tradition is certainly the oldest, and probably still the strongest, in American intellectual life. For example, most of the large, multi-purpose private universities that dominate the nation’s research life today were in fact started in the eighteenth century as undergraduate “colleges” of arts and sciences, and these colleges remain at the core of their identity. The rise of technical schools and their emergence into universities was generally a late-nineteenth century phenomenon. Yet even among technically oriented schools, the deep strength of the American liberal educational tradition is clearly in evidence, in the breadth of curriculum, its experimentation the collegiate life style that is fostered on campus.

It is difficult to determine exactly what proportion of American students are enrolled in a “liberal education.” Certainly, however, the percentage has declined over time, as non-traditional educational institutions (e.g. two-year colleges) have increased greatly in numbers and more students have enrolled in large multi-purpose universities. In 1953, for example, about one-fourth of students in higher education were placed in liberal arts colleges, and about one-half matriculated in traditional universities. By the mid 1990s, the total number of students in higher education had

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[47] From *Educational and Career Paths of American Scientists and Engineers*, a NISTEP Seminar, presented by George R. Heaton, Jr. and Christopher T. Hill, Tokyo, October 21, 2003.

increased about six-fold, but the number in liberal arts schools had only doubled, thus accounting for less than 10% of the total. A full third of students were in community colleges.[48]

While there is clearly a decline in the percentage of American undergraduates attending avowedly "liberal arts" colleges, it would be mistake to assume that importance of liberal education in American life has declined. A liberal education has long been considered as the "elite" educational track. And the intellectual pull of its paradigm remains exceptionally strong throughout higher education.[49] For example, even within the most highly selective large universities, the liberal arts colleges form the historic core of the institution and typically attract the largest share of undergraduates.[50]

4.2 First Exposure: the Liberal Education Tradition in American Secondary Schools

The concepts that underlie the American liberal education first begin to be institutionalized at the high school level. The paradigm is illustrated perhaps most clearly in the network of private "prep schools" that occupy the highest academic level of American secondary education. These prep schools arose, particularly in New England in the nineteenth century, because it was assumed that public education would focus on basic skills and prepare young people for trades, with no intention that it lead to university study. In contrast, the prep schools offered a broad-ranging exposure to arts and sciences that could prepare students for any educational path they might choose in college. Until after World War II, this was the main route into top-rank colleges and universities, a fact that reinforced the sense of liberal arts as the elite educational track.

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[48] Science and Engineering Indicators – 2000, Chapter. 4., p. 4-6.

[49] See, for a defense of liberal education against more "practical" educational trends, The Chronicle of Higher Education, January 2004.

Both the public school system and higher education were transformed during the post-WW II period. Colleges grew rapidly and opened their admissions to a wider range of students and classes. Financial aid was used as a way to attract the best students irrespective of income-level, and ensure diversity in the student body. At the high school level, the result was that most public high schools adopted a curriculum much like the traditional prep school approach, and became focused more on college preparation than on technical training. The liberal educational approach has thus become ubiquitous throughout the secondary school system. It is worth noting that this American tradition differs markedly from the tracking system that is the norm in Europe, in which students at the high school level focus on particular areas of study, and are expected to continue that focus at the university level.

In most American high schools today, the curriculum freely mixes those people drawn to science and technology with those that are not. Naturally, there is some self-selection in advanced courses, whether in math and science or arts and humanities, but the general assumption is that all students, regardless of their plans for later education, should get more or less the same liberal education and social experience. Naturally, too, there is some type-casting of those oriented toward science and technology as "techies," and their educational counseling and choices will reflect this.

The following chart gives some sense of the choices facing a "techie" young person on graduation from high school. Perhaps the most important point it makes is that choice is a dominant reality. At this point, technically oriented people are first faced with the choice of whether to go into a traditional liberal arts curriculum and college institution, or into a technical university. While this is a pivotal choice, it is not necessarily seen as limiting; nor is one route seen as so fundamentally different from the other, given the wide range of curricular choices either type of university affords. In

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[50] Among the "Ivy League" schools, the undergraduate liberal colleges typically account for more than half of the enrollment.

fact, many students apply to a portfolio of schools that lead in both directions, and their choice of which to accept may turn on factors other than the technical orientation of the university (such as financial aid or extracurricular opportunities). Indeed, it is at this point when American young people, whether technically oriented or not, begin acting as "paying consumers" with choices to be made in the educational marketplace.

Table 4 – 1: Portrait of a "Techie" Teenager[51]

The Education	The Assumptions
• Standard "Academic" Curriculum (no tracking)	• Non-specialization at high school level
• Portfolio of College Applications and Offers	• A Competitive Market for College "Consumption"
• Liberal Arts (and sciences) vs. Engineering	• College Education is Expensive and may be Financially Assisted

4.3 University Options for Technically Oriented People

For the technically oriented young person entering the U.S. university system, there are two basic options that can lead to a career in science or technology. One is to enroll in a liberal arts curriculum (either at a liberal arts college or within a large multi-purpose university). No matter what the student's field of study, the liberal arts option is generally recognized as a broad education and not a professional degree; further graduate study to this end is assumed. The other option is to enroll in an engineering program. Clearly a more focused than liberal arts, an undergraduate program in engineering is generally recognized as a first-level professional degree.

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[51] NISTEP Seminar, n. 40

4.3.1The Liberal Arts Track

In 1996, about 1,000,000 of the 14,000,000 students in higher education were enrolled in liberal arts colleges. This is about 7% of the total – a total, it must be noted, which includes both graduate and undergraduate programs[52]. A much higher percentage – approximately 50% -- enrolled in large, multipurpose universities.[53] In both types of institutions, technically oriented people can pursue a liberal arts track to the study of science and technology. Unfortunately, it is not known what percentage of prospective science and technology professional actually study in the liberal arts track. Some indication may come from the data presented below in Table 4-1 on bachelor's degree in science and engineering. Extrapolating from these data, the upper bound of possible liberal arts-track S&T students would include those in math and natural science (engineering and social science being excluded). This upper bound is about two-thirds of the total. However, since many of the natural science and math students are in fact studying outside of liberal arts, an estimate of about one-half the S&T students inside liberal arts programs seems reasonable.

Table 4-2: Bachelor's Degrees in S&E, 1996[54]

Total	Nat. Science	Engineering	Math/comput	Soc Sci.
384,674	98,322	63,114	37,621	185,617

The choice of liberal arts by no means indicates a lack of enthusiasm for a science and technology career. It does, however, recognize that a true technical specialization will be postponed until graduate school. The liberal arts track does indicate an enthusiasm for the idea of pursuing a technical specialty within the larger intellectual context. And for many students, the choice of liberal arts is made to benefit from the

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[52] S&E Indicators – 2000, p. 4-7

[53] Ibid

[54] Ibid, p. 4-9

more diverse social mix the liberal arts college typically attract, in comparison to engineering schools.

The general characteristics of the curriculum that would face a technically-oriented student in the American four-year liberal arts option is capsulized below in the following table.[55]

Table 4-3: The 4-Year Liberal Arts Option

The Program	Inferences
• Liberal Arts Combine Sciences and Humanities • 2 Years of General Education, Exploring Diverse Fields • Distributional Requirements and Major(s), Year 3 • Favorable Route to Science Graduate Programs • Half of Students May Receive Financial Aid	• Breadth of Educational Focus • Extensive Choice • Diverse Social Mix

The program has more or less a two-step structure: in the first two years a wide range of subjects (both humanities and sciences) will be mandated through "distributional" requirements; in the second two years, a major field of study will be pursued. In spite of such requirements, extensive ability to explore various fields is still the hallmark of the liberal arts experience. Nowadays, almost one half of students pursue "double" majors, which may combine their diverse interests. It is worth noting as well that there is a deliberate attempt in most such colleges (indeed, across all of American higher education) to create a diverse social mix for the college experience. Thus, students are recruited based on talents and characteristics that are not necessarily academic. And the attempt to draw from across the economic spectrum results in aggressive financial aid programs for about half the students in highly selective colleges, with the remainder paying extremely high tuition.

It has already been mentioned that liberal arts graduates in science typically find graduate study a career prerequisite. What is also clear is that the liberal arts option is a very favorable route into graduate programs in technical fields. Table 4-4 below indicates the origins of Ph.D. recipients according to the type of program from which they have come. While it is clear that most PhD's receive their undergraduate eduction in major research universities, the percentage from liberal arts colleges (15%) is more than double the percentage of all students in liberal arts colleges. For PhD's in chemistry, the liberal arts origin (23%) is much higher.

Table 4-4: Undergraduate Origin of Ph.D. Degrees in S&E[56]

	All PhD's	Chemistry PhD's
Research University B.S.	56%	23%
Liberal Arts College B.S.	15%	23%

There are several factors that account for the desirability of liberal arts students as Ph.D candidates. Perhaps foremost among them is the fact that liberal arts colleges are often highly selective, and thus produce many of the country's best students. Second, many liberal arts students major in science. Lastly, it is also widely believe that the breadth and rigor of inquiry implied by the liberal arts curriculum will prepare people well for a life of scientific creativity.

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[55] Ibid

[56] Ibid, p. 4-10.

4.3.2 The Engineering Track

Although the liberal arts route described above does not necessarily preclude the choice of engineering as a career in the U.S,[57] enrolling in an engineering school is by far the most common path for those who plan engineering as a career. That said, the numbers of people making such a choice has been in a long-term decline. Between 1983, which was the peak year for engineering enrollments, and 1999, bachelor's level engineering enrollments declined by about 20%.[58] Although overall higher education enrollments began to decline during the late 1990s, the decline in engineering outpaced the overall trend. Meanwhile, the percentage of "underrepresented groups" (i.e. racial, ethnic, gender and national minorities) tended to increase within the engineering school population, thus attesting to the increased diversity in engineering fields.[59]

Because engineering schools have a clear professional focus, they do not usually exhibit the wide-open intellectual atmosphere of a liberal arts school. Nevertheless, they too are infused to an important degree with the American tradition of a liberal education. It is worth noting in support of this point that the engineering school accreditation standards require at least one-eighth of degree credits to be gained from liberal arts and humanities.

The chart below, sketching the major elements of a typical traditional engineering B.S. program, illustrates this point. As can be seen, engineering education in the U.S. virtually uniformly includes significant study of humanities and social sciences, often mandated by the engineering schools at levels that exceed accreditation minima. The tendency toward multiple concentrations that is typical of the liberal arts is shown, though to a less formal extent, by the frequent requirement for areas of

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[57] Indeed, some liberal arts colleges contain engineering programs. And some percentage of liberal arts graduates go on to engineering graduate school. Although the exact numbers here are not known, the percentages are likely to be quite small – though they are also likely to be higher than in most other countries.

[58] S&E Indictors 2002, p. 2-12.

concentration beyond the engineering major field. Lastly, engineering undergraduate education is increasingly seen as desirable preparation for other professions that require graduate school, such a business, law or medicine. This is a particularly valuable background for those students interested in focusing the connection of such professions to technology.

Table 4-5: Traditional Four-Year Engineering B.S. Program[60]

- Based on a Substantial Core of Math and Sciences
- Includes Significant Humanities and Social Sciences
- Usually Incorporates a Major Field and Exposure to One or Two Other Fields
- Incorporates Preparation for Graduate Study in Engineering or the Professions, Such as Business, Law or Medicine

4.3.3 Innovative Engineering Programs

Although the above description implies that there is a standard pattern to engineering education in the U.S., it is also true that there is a great deal of flexibility, both for institutions and students – and a consequent huge latitude in the careers engineers can create. Table 4-6 below sketches some of the major characteristics of three engineering undergraduate programs that are recognized as particularly innovative: those at the Massachusetts Institute of Technology (MIT), the Worcester Polytechnic Institute (WPI) and Washington University (WashU).[61]

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[59] Ibid, p. 2-5.

[60] NISTEP Seminar, n. 40.

[61] While these three programs are certainly noteworthy by any standard, they have been chosen in part due to the authors' personal experience in them. There are certainly other innovative engineering programs in the U.S., although none the authors are equally familiar with.

A brief examination of the features of these programs illustrates the breadth, flexibility, decentralization, diversity and personal choice that are such strong characteristics of the American liberal education tradition.[62] In the MIT case, for example, students have the right to take course in any department of the university, no matter where they have originally been enrolled ("university-wide open enrollment"). And they can literally "make your own degree" by putting together any individualized pattern of student that faculty supervisors will approve. The many joint programs at MIT, which link technology and other fields (management, society, etc.) are a part of this synthetic and flexible approach.

Perhaps the most singular feature of the WPI program is a proliferation of courses, each lasting one quarter of the academic year. Students thus gain the widest possible exposure, not only to engineering but also to other fields. The ability to take a course and receive a "no-record" rather than a failing grade encourages this experimentation. In addition, the curriculum guarantees that engineering will be related to practical life problems (both societal and technical) by requiring projects, both in the major field, and in a cross-disciplinary area ("interactive").

Washington University's engineering program were among the first, and the strongest, to link engineering with societal concerns. They still place special emphasis of dual degrees and non-engineering requirements. This long-term WashU focus has required a major effort on the part of faculty to become acquainted with and advise students in appropriate directions.

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[62] As discussed in section 4.1 above

Table 4-6: Innovative Engineering Programs[63]

MIT	**WPI**	**Wash U**
University-wide Open Enrollment	4 Terms, Course Proliferation	Intensive Engineering Advising
Joint Programs	Major Qualifier Project	Engineering and Society
Make your own degree	Interactive Qualifier Project	Non-engineering requirements
Technology and …	"No-Record" Grading	Dual Degrees – BS/BA, BS/MBA

4.4 The Liberal Education Tradition and Career Flexibility

Since the essence of an undergraduate liberal education is to create broadly educated people who are lacking in specialization, it almost goes without saying that such people face a kind of open-ended, flexible set of career choices. As has been mentioned previously, the profesionally serious technically oriented person from the liberal educational tradition will almost certainly choose graduate school. Whatever the choice, by the time of receiving an undergraduate degree, most students are habituated to the need for making such choices. The following "flexibility indicators" show some of the choices that are implied by the liberal educational tradition, and which tend to impart further flexibility into career choices.

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[63] NISTEP Speech, ibid n. 40.

Table 4-7: Flexibility Indicators[64]

- Most University Students do not "Declare" a Major for 1 or 2 Years
- Majors are Often Changed
- Many BS Students Transfer from Community Colleges after 2 Years
- Many MS and PhD Students Change Fields After the BS
- Many BA/BS Students go into Law, Business or Medicine

The characteristics of the faculty in engineering schools presented in Table 4-8 below also illustrate the assumptions of mobility, flexibility , independence and personal choice that pervade the U.S. liberal educational tradition. Almost uniformly, the faculty in engineering schools mixes engineers and non-engineers. While certainly engineers are in the majority, there is always a significant component trained in the sciences, humanities, business and law. The faculty has virtually full responsibility for course design – both what courses will be taught and their content. Approval of new courses is exceptionally easy (usually requiring only a faculty vote and no external approval).[65]

Career mobility and flexibility within the science and engineering generally has been discussed in the previous two chapters. Suffice it to briefly reiterate here a few points about faculty employment, made in the table. First, many faculty are only given nine-month appointments. This creates both the necessity and latitude for them to develop other sources of income. Independent research funding thus becomes one of

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[64] NISTEP Speech, n. 40.

[65] The fact that accreditation of programs is generally only at the undergraduate level makes this all the moreso for graduate engineering courses.

the principal ways faculty support themselves and advance in their careers. Consulting assignments are widely encouraged for similar reasons. Both of these activities create the kinds of exposure and contacts that encourage faculty to move among institutions and sectors.

Table 4-8: The Engineering Faculty[66]

- Engineers and Non-Engineers (e.g., sciences, humanities, business)
- Entirely Responsible for Course Design
- Nine-month Appointments
- Independent Research Funding
- Consulting
- Move Among Institutions and Sectors

Once one moves outside of academic life, the trend to career flexibility in S&E professionals is undoubtedly even more pronounced. Table 4-9 below shows employment patterns for S&E degree holders, focusing only on those who are employed in non-S&E positions. This is approximately one-half of all scientists and engineers.[67] Examining such people at "all levels" of educational attainment, the table indicates that they are arrayed in about equal parts (i.e. in thirds) across the categories: close relation to degree, some relation, and no relation. As the level of educational attainment goes up, the tendency to work outside of one's field decreases. Nevertheless, more than 50% of the holders of PhD's in the survey are working outside

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[66] NISTEP Presentation, n. 40.

[67] The NSF estimates that there approximately 10 million employed scientists and engineers.

of the field in which they received their degree. This indicates a remarkable level of career flexibility.

Table 4-9: S&E Degree Holders Employed in Non-S&E Positions in 1999

	Number of S&Es in non-S&E Jobs	***% Close relation to Degree***	***% Some relation***	***% No***
All Levels	4.976,900	33.2	34.1	32.7
Bachelor's	4,092,800	29.9	34.7	35.5
Master's	724,800	48.7	31.2	20.1
PhD	155,200	46.0	35.6	18.5

Source: (NSF Science and Engineering Indicators 2002)

4.5 The Liberal Education Tradition and National S&T Needs

The U.S. tradition of a liberal education bears little or no explicit relationship to national science and technology policy. Nor can it be seen as a policy for economic growth. On the contrary, the development of both its idea-base and the institutions that carry it forward took place over a long history, and was based as much or more on educational ideals as on practical considerations. Certainly, it would be hard to find a participant in this tradition – faculty or student – who would characterize their activities as instruments of national policy. Indeed, some (particularly engineers) might hesitate admit that their education is indeed based on a liberal tradition, given how flexible, amorphous and deeply embedded in the fabric of U.S. society this tradition is.

That said, there are still important conclusions to be drawn about how the liberal education tradition in the U.S. contributes to the satisfaction of human resource needs in priority areas of science and technology. These conclusions, which follow below, particularly come to the fore when one contrasts the educational system in the U.S. with counterparts in Europe and Japan.

- The U.S. liberal education system rests heavily on individual choice – of paths of study, of particular courses, of institutions and of career paths – for the students and faculty involved in the enterprise. As little is prescribed, students become habituated to making choices that combine their personal interests with the fields that are most dynamic.

- The universities in the U.S. higher educational system clearly perceive themselves to be part of a "market" for students and research funds. They are habituated to striving for excellence and responsiveness to the demands of students and funding sources. This phenomenon is particularly intense in leading edge areas of science and technology.

- The U.S. liberal education tradition resists tracking of students, allowing them to pursue individual interests to an almost extreme extent, even through the end of the undergraduate years. The contrast with European models is strongest: while American students are unlikely to achieve the depth in a chosen field as soon as their European counterparts, they tend to study a wider range of fields and have much greater career options spread before them.

- The U.S. liberal educational system demands specialization at a point which is quite late, when judged against other national norms. By American standards, engineers tend to specialize rather early – often at the beginning of the undergraduate years. For those in the liberal arts/sciences tradition, many of whose major undergraduate fields differ from their graduate school choices, the decision-point is typically postponed into the early twenties. And it is far from uncommon for professionals to change focus in later years. The contrast with Europe – where almost irrevocable choices begin in high school – is most striking.

- The American belief is that the breadth and openness of inquiry gained from a liberal education will prove uniquely useful throughout one's life. It is believed particularly to promote creativity and leadership. Many Americans would further assert that the qualities gained from a liberal education are most value in times of rapid scientific change.

- The method through which the U.S. recruits talent to its priority S&T programs (see discussion below of nanotechnology and bioinformatics) is reminiscent in some respects of the operational aspects of the liberal education tradition. In both cases, opportunities are offered without of the supply of respondents that will be elicited or what their characteristics will be. In both case, the hope is that such ad hoc matches will prove fruitful.

5. HUMAN RESOURCES IN NANOTECHNOLOGY--A CASE STUDY

5.1 Introduction

This section, and the next, provide two brief case studies of how the United States meets the needs for scientists and engineers to work in rapidly emerging new fields, especially in fields that are highly interdisciplinary. The two cases examined are nanotechnology, in this section, and bioinformatics, in the next section.

The concepts underlying nanotechnology have been under consideration for more than four decades, ever since the famous Cal Tech physicist, Richard Feynman, gave his 1959 talk entitled, "There is Plenty of Room at the Bottom."[68] In this talk, Feynman asked his listeners to imagine devices and machines that he thought were theoretically possible that would use only tens to a few thousand atoms to accomplish useful tasks such as information storage, human surgery, and controlled emission of light. He acknowledged that such devices could not be made at that time, and he encouraged his listeners to work toward realizing his vision. His talk was prescient in many ways, including the fact that he understood that the ability to visualize and manipulate matter at the atomic scale was key to achieving his vision.

In the last decade, nanotechnology has moved from the realm of visionary extrapolation to serious research on, and development of, practical applications, many along the lines that Feynman foresaw. In the United States, this realization of nanotechnology reached national recognition with the passage in fall 2003 of comprehensive national legislation to encourage research and development of nanoscience and nanotechnology, the "21st Century Nanotechnology Research and Development Act.[69]

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[68] Available on the web at www.zyvex.com/nanotech/feynman.html

[69] Public Law 108-153

5.2 A Working Definition of Nanotechnology

"Nanotechnology" is a relatively ill-defined field, with no agreed-upon official or unofficial definition in the United States. In a recent program announcement, the National Science Foundation defined nanotechnology as "...the creation and utilization of functional materials, devices, and systems with novel properties and functions that are achieved through the control of matter, atom-by-atom, molecule-by-molecule, or at the macromolecular level.[70]

The official US Government National Nanotechnology Initiative (NNI) offers a more elaborate definition and delineation of nanotechnology:

> *While many definitions for nanotechnology exist, the NNI calls it "nanotechnology" only if it involves all of the following (see nano.gov/html/facts/whatIsNano.html):*
>
> > *1. Research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1 - 100 nanometer range.*
> >
> > *2. Creating and using structures, devices and systems that have novel properties and functions because of their small and/or intermediate size.*
> >
> > *3. Ability to control or manipulate on the atomic scale.*

Others have a much more expansive definition of the domain of nanotechnology. Some include within nanotechnology the realm of microelectronics and the closely-related MEMS (MicroElectronic Mechanical Systems). Still others argue that chemistry, biology, or both involve manipulation of matter at the molecular and atomic levels and that these fields, as well, should be included in nanotechnology. The incentive for some to broaden the scope of what is defined as nanotechnology is clear--nanotechnology is currently perceived as a "hot" field, and association with this field should put an activity in a stronger position to be eligible for, and to receive, new funding support.

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[70] See: Nanoscale Science and Engineering Education (NSEE) Program Solicitation, www.nsf.gov/pubs/2003/nsf03044/nsf03044.htm.

An illustration of the tendency to use an extended definition of nanotechnology is evident in the new College of Nanotechnology at the University of Albany in New York.[71] Even though the College is identified with nanotechnology, a review of its programs and facilities on its web site quickly shows that the research, education and training offered in this organization relates almost exclusively to microelectronic device design and fabrication; in fact, two new semiconductor chip fabs are the central capabilities of this college.

In this report, we focus on the more narrow definitions of nanotechnology used by the NSF.

Regardless of the specific definition and scope of nanotechnology that one uses, all experts agree that it is a field to which many different disciplines can contribute. Relevant fields include, but are not limited to, physics, chemistry, biology, materials science and engineering, electrical and mechanical engineering, systems analysis, computer and computational sciences, and control systems. There is a place in the field of nanotechnology for individuals with educational preparation ranging from technical high school through advanced post-doctoral training. In addition, specialized non-technical preparation is needed for lawyers, marketers, managers, communications specialists, and policy analysts to work in the field.

It is unlikely that nanotechnology will become a single, well-defined discipline. Most observers adhere to the notion that it is possible to enter nanotechnology from many different fields, and that familiarity with two or more relevant fields is especially important to success in this arena.

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[71] .See: www.albanynanotech.org/index.cfm

5.3 Policies and Programs to Develop Human Resources for Nanotechnology in the US

5.3.1 Federal

The first thing that should be said is that the United States has no explicit and substantial national program to support the education and training of specialists in nanotechnology. The recently passed federal nanotechnology legislation, the 21st Century Nanotechnology Research and Development Act, (hereinafter, the "Nano Act") is focused largely on support of research, facilities, and shared infrastructure development. It speaks explicitly to education only at Section 2 b 9, which gives as one of several purposes of the Act:

> *"...[to provide] effective education and training for researchers and professionals skilled in the interdisciplinary perspectives necessary for nanotechnology so that a true interdisciplinary research culture for nanoscale science, engineering, and technology can emerge...."*

However, the Act authorizes no program to help achieve this purpose. Instead, as is often the case in the United States, the Act implicitly depends on the support of research in universities to provide the funding to support graduate education through research assistantships to students who contribute to the research done under the Act's grant programs.

It is important to note the emphasis that the Nano Act places on "interdisciplinary perspectives" and on "a true interdisciplinary research culture" in the education and training of researchers and professionals in nanotechnology. Clearly, at this point in time U.S. policymakers do not foresee the emergence of a separate discipline of nanotechnology.

The National Science Foundation, which has been a leading federal agency in promoting a more aggressive nanoscience and technology program in the United States, operates a modest "Nanoscale Science and Engineering Education" program through its Education Directorate. The program is described by NSF as follows:

> *This solicitation represents a comprehensive effort on the part of the National Science Foundation (NSF) to enhance nanoscale science and engineering education. Its goals are to form strong partnerships between researchers in science and engineering and those in science education; to develop effective strategies and interventions for integrating nanoscale science and engineering that will inform other emerging areas of science and engineering, into formal education in grades 7-16; and to increase public awareness of advances in nanoscale research and technology and their impact on society. Among the activities that will be supported are doctoral programs in science education, the development of instructional materials and courses for adoption and implementation in classrooms, grades 7-16, and research on the cognitive and implementation aspects of the educational interventions. The goals are carried out through partnerships involving institutions with the requisite expertise in nanoscale science and engineering and in education.* [72]

To carry out these objectives, NSF has allocated a budget of approximately $12 million for FY04, distributed among programs in four areas intended to accomplish the goals stated above. As of this writing (March 2004), awards under this program have not yet been announced so it is not possible to know what kind of projects will be supported.

5.3.2 University Programs in Nanotechnology

A few U.S. universities have recently established programs identified as focusing on nanoscience and nanotechnology, somewhat countering the concept that skills related to nanotechnology can best be learned through immersion on one or two of the constituent fields. The web site (nano.gov/html/edu/eduunder.html) of the U.S. Nanotechnology Initiative lists the following degree programs at U.S. institutions:

- In conjunction with the University of Pennsylvania, an Associate Degree in Nanotechnology is now offered at community colleges in Pennsylvania.
- Dakota County Technical College (Rosemount, Minn.) in conjunction with the University of Minnesota, Associate in Applied Science Degree in Nanoscience Technology

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[72] www.nsf.gov/pubs/2003/nsf03044/nsf03044.htm

- Rice University offers a Professional Master of Science in Nanoscale Physics
- University of Albany, School of Nanosciences and Nanoengineering , offers a Ph.D. and M.S.
- University of Washington, Ph.D. in Nanotechnology

As noted above, however, at least one of these programs--the one at the University of Albany, appears to qualify as a nanotechnology program only under an expansive definition of nanotechnology.

Many other U.S. universities offer a few specialized courses in nanoscience or nanotechnology intended for students majoring in constituent fields. Such courses may be established in order to support specialized research in nanotechnology subjects, by preparing students to participate in the research. An interesting example of this kind of program is at Stanford University.[73] Stanford has indentied a group of about 20 graduate courses in a variety of fields related to nanotechnology that students can take as part of their regular academic program or to earn a graduate certificate in the field.

Finally, it should be noted that many academic institutions, nonprofit organizations, localities and companies interested in nanotechnology or in science and engineering education more generally have set up educational and internship opportunities for students and even for ordinary citizens in nanotechnology. For example, the Lawrence Berkeley Laboratory, a Department of Energy Laboratory managed by the University of California, has created a nanotechnology program called "Nano High" that "…brings students face to face with cutting edge research and gifted scientists, in the hopes of seducing them to the bright side of the nanoforce."[74] Some 375 students and teachers have registered for Nano High, an indication of widespread

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[73] (http://scpd.stanford.edu/SCPD/courses/contentView/nanotechnology

[74] Jackie Burrell, "Science of the Small Inspires Big Dreams at Berkeley's Nano High,"Contra Costa Times, posted to the web by Small Times at www.smalltimes.com/document_display.cfm?document_id=7241, January 16, 2004.)

interest. To some extent these kinds of programs are intended to interest participants in further education, training and employment in nanotechnology, but in many cases they are seen as being good ways to get participants interested in science and engineering more generally because nanotechnology is such a "hot" field right now.

5.4 The "Politics" of Nanotechnology

It would be remiss to leave the field of nanotechnology without noting that the field has a number of political dimensions.

First, many political and opinion leaders are convinced that nanotechnology is the "next big thing" in industrial technology; that it will replace biotechnology, the Internet and semiconductors as the foundation for a new generation of business development, jobs and wealth creation. In light of this belief, nanotechnology is the focus of a great deal of attention in the popular press, attention that is far in excess of actual practical applications and consequences to date. And, political leaders, who currently face a major challenge from the problems for jobs and growth created by outsourcing and the enormous U.S. unfavorable balance of trade, point to the promise of nanotechnology as one of the keys to ensuring that America remains at the forefront of new industry and can compete there from a strong position in nano-related industries. The high hopes that are widely held for the future of nanotechnology go a long way toward explaining why a Congress and an Administration that is generally quite hostile to industrial policy nevertheless adopted the 2003 Nano Act, which is a strong statement of commitment to this particular sector's future—and is thus a clear declaration of an industrial policy for nanotechnology.

Second, nanotechnology has been adopted as the symbol of a broader concern that the U.S. is not investing sufficiently in R&D in engineering and the physical sciences generally. The explosive growth of public funding for the life sciences and biomedicine has not been accompanied by similar growth in funds for engineering and the physical sciences. Because nanotechnology is “hot” and because it draws on so many different fields in engineering, physics, chemistry and others, it has been adopted by the proponents of “rebalancing” the national R&D portfolio as the best illustration of why it is important to increase support for these fields.

Third, there are continuing concerns that nanotechnology may pose new, undetected, and grave risks to human health and the natural environment. This concern, which has been amplified by popular novels based on disaster scenarios involving nanotechnology “out of control,” led to the inclusion in the Nano Act of funds to support studies of the social and economic impact of nanotechnology. So far, no organized opposition to nanotechnology has emerged of the sort that has arisen to oppose genetically modified organisms and foodstuffs, but such an eventuality can not be ignored for the future.

5.5 Observations on the Nanotechnology Case

The case of human resources for nanotechnology illustrates many of the points made in earlier chapters of this report. The United States is able to prepare people to move into new fields very quickly, in part because of the flexibility inherent in the system of human resources preparation. We have not adopted a comprehensive national policy on nanotechnology human resources, yet a wide variety of efforts are underway to prepare people for this new field at a variety of levels.

The United States depends heavily on research funding for nanotechnology to be the vehicle through which resources are directed to encourage students to enter this field, rather than on the creation of special federal programs to fund studies in specific fields like nanotech. In keeping with a more general characteristic of the U.S. policymaking system, major investments have been made available at the federal level for nanotechnology only in response to a perceived challenge from abroad—the promise of new opportunities was less persuasive than the threat of being overtaken by competitors.

The adoption of the 21st Century Nanotechnology Research and Development Act in 2003 is somewhat unusual, in that it created by law a mechanism to coordinate the research programs of diverse federal agencies in this field. Usually, such coordination is carried out through the less formal system of "presidential initiatives." It is not entirely clear why this departure occurred—perhaps strong external leadership had something to do with it. And, it remains to be seen whether, over time, the Nano Act actually makes a difference to the level and nature of federal funding for nanotechnology or to the outcomes of that funding.

6.0 HUMAN RESOURCES FOR BIOINFORMATICS--A CASE STUDY

6.1 Introduction

Bioinformatics is much newer conceptually than nanotechnology, but it is much further along as both a field of study and a field of professional practice. Bioinformatics emerged around 1990 as a response to real needs created by the explosion of data obtained in the course of sequencing the human and other genomes. Owing to the pace of data generation, as well as to the development of new methodologies dependent on computation and statistical analysis for sequencing large numbers of genes in combination, an immediate need arose for ways to manage and analyze very large data sets that included substantial biological content.

In 2004, bioinformatics is already a mature field of inquiry and practice. A recent compilation lists more than 70 U.S. colleges and universities that each have one or more educational programs in bioinformatics.[75] Founded in 1997, the International Society for Computational Biology, a leading professional society in the field and publisher of the journal, Bioinformatics, reported that its membership had grown to more than 1300 from 42 countries by 2002.[76]

6.2 Bioinformatics Defined

The Biotechnology Industry Organization, the leading trade association in the biotechnology industry, describes bioinformatics in the following way:

> *Bioinformatics technology uses computational tools provided by the information technology revolution, such as statistical software, graphics simulation, algorithms and database management, for consistently organizing, accessing, processing and integrating data from different sources. Bioinformatics consists, in general, of two branches. The first concerns data gathering, storing, accessing and visualization; the second branch focuses*

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[75] www.bioplanet.com/bioinformatics_courses.htm

[76] www.iscb.org/history.shtml

> *more on data integration, analysis and modeling and is often referred to as computational biology.* [77]

Bioinformatics is not by itself recognized as a scientific or engineering discipline or as an industry, and, thus, it is not represented as a category of employment in official statistics and analyses, such as those maintained by the Bureau of Labor Statistics in the U.S. Department of Labor. Like nanotechnology, bioinformatics draws on more than one discipline. At its core, however, are two fields: computer science and molecular biology. Owing to the recent formation of the field of bioinformatics and the evolving nature of the problems it addresses, very little data is available on employment of persons trained in, or doing, bioinformatics. Also, since nearly every modern biologist makes some use of computational methods, it is not always clear whether a particular biologist or biotechnologist should be considered as practicing bioinformatics.

Approximately five years ago, Paula Stephan and Grant Black analyzed the factors affecting supply and demand for professionals trained in bioinformatics.[78] The data collected by Stephan and Black, most of which were for 1999, indicated a growing gap in the number of persons prepared to work at advanced levels in bioinformatics relative to the apparent demand as reflected in job advertisements in Science magazine, one of the foremost scientific journals. The authors attributed this gap to several factors, including the small amount of federal funds for research in bioinformatics (at that time); the large cognitive leaps required of biologists who might learn computation as well as of computer professionals who might learn biology; the substantially higher salaries paid to computer scientists than to biologists, which would discourage the former from

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[77] Source: Biotechnology Industry Organization, www.bio.org/er/biotechtools.asp

[78] .See: Stephan, Paula E. and Grant Black, "Bioinformatics: Emerging Opportunities and Emerging Gaps," in Capitalizing on New Needs and New Opportunities: Government - Industry Partnerships in Biotechnology and Information Technologies, Board on Science, Technology, and Economic Policy, National Research Council, 2001, pp. 244-260. Available on the web at: http://books.nap.edu/books/0309082579/html/244.html#pagetop. Also available from the Board on a CD Rom compilation, "Board on Science, Technology and Economic Policy--The First Ten Years."

studying the latter; and the fact that biology students, as a group, have substantially weaker average preparation in and aptitude for mathematics than do computer and mathematics students, which calls into question whether most biologists are prepared to embark on a career in bioinformatics.

6.3 Policies and Programs to Develop Human Resources for Bioinformatics in the U.S.

The U.S. federal government has a few modest programs intended specifically to prepare persons for careers in bioinformatics. At the same time, massive federal investment in biomedical research, including genomics and proteomics, has paid for the education and training of students in this important new set of skills. And, such investments are growing. For example, the plan for the new National Institute of Biomedical Imaging and Bioengineering (NIBIB) within the National Institutes of Health incorporates specific mention of bioinformatics as one of its focal areas and calls for establishment of 14 new centers across the country to be funded by NIBIB in bioinformatics and the closely related field of computational biology.[79]

Recognizing the importance of attracting undergraduates into careers in bioinformatics and related fields, the NIBIB has teamed with the National Science Foundation to support summer study programs for undergraduates at a number of universities. According to an NSF press release, the two agencies have committed $6 million over four years to support nine such institutes at "...California State, Clemson, Iowa State, Pennsylvania State and Virginia Commonwealth Universities; Massachusetts and New Jersey Institutes of Technology; and the Universities of

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[79] See www.nibib.nih.gov/about/NIBIBCJFY2005.pdf

Minnesota and Pittsburgh. The institutes will include classes on such subjects as biology and physiology and research in computer modeling and gene function."[80]

At the other end of the higher education spectrum, NSF has a program of support for "Postdoctoral Research Fellowships in Biological Informatics." The budget for this program is just over $1 million annually, which supports 15 postdoctoral fellows and five starter grants. NSF describes its program thusly:

> *The Directorate for Biological Sciences (BIO) offers Postdoctoral Research Fellowships in Biological Informatics to recent recipients of the doctoral degree for research and training in developing and using computational, statistical, and other tools in the collection, organization, dissemination, and use of information to solve problems in biology. The research and training plan of each fellowship is expected to address important scientific questions in contemporary biology and include a strong linkage between computer, information, and computational science and biology and develop and/or apply state-of-the-art informatics tools or approaches to the stated problem. Fellows who accept a tenure-track position following the fellowship may apply for research starter grants.* [81]

6.4 Bioinformatics and Temporary Contract Scientific Employees

One of the most interesting new developments in the employment of high-level scientists and engineers is the growth of temporary employment of such persons. In such arrangements, scientists serve as contractors to companies for limited periods of time, ranging from days to months. They may do under an agreement with a firm that specializes in providing temporary employees, or they may do is as free agents. According to a recent article, [82] this practice is growing rapidly in the biotechnology industry, and computer specialists in this industry are "leading the way." Gura says that in 2002, biotech companies employed 94% of their computer specialists on a contract basis. This is not necessarily the same as hiring bioinformatics specialists on a

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[80] See www.nsf.gov/od/lpa/news/02/tip021022a.htm

[81] See: www.nsf.gov/pubs/2004/nsf04539/nsf04539.html

[82] Gura, Trisha, "Joining a Trend, Scientists Increasingly Say 'Call My Agent,'" Science, January 16, 2004, pp. 303-305

contract basis, since many of those computer specialists may have been systems administrators and business applications experts rather than specialists in bioinformatics. Nonetheless, this is an astonishingly high proportion of computer specialists within such firms.

6.5 Observations on the Bioinformatics Case

Bioinformatics has experienced explosive growth over the past decade, drawing many computer specialists, mathematicians and statisticians into the life sciences and biotechnology, and causing many biologists to reinforce their training in mathematics and computational methods. Unlike nanotechnology, which has emerged as a new field based on new science looking for new applications, bioinformatics emerged as a response to a recognized critical need for help in managing data and doing analyses in the life sciences. Incentives to enter bioinformatics have been strong, as have the barriers to entry by individuals from both sides of a wide intellectual gulf.

Government has participated to some degree in enhancing the supply of bioinformatics graduates, but industrial demand has far exceeded academically-based supply. Government has funded a few very modest training and educational efforts but bioinformatics has had difficulty attracting government research support sufficient to provide all the new graduates needed in the industry. Fortunately, the long American tradition of job switching and field switching has helped to fulfill industry's needs.

7. CONCLUSIONS

This report has addressed the issue of how the U.S. meets its human resource needs in science and technology, particularly in "priority" areas at the forefront of new development. In spite of this focus, it needs to be stated that the concept of "priority" areas in science and technology is not a recognizable element of U.S. science and technology policy, which has long eschewed the planning that this term implies.[83] Nevertheless, new programmatic initiatives are always being put forward, and certainly they represent new national priorities that make demands and create opportunities for the nation's human resources.

If there is a single concept that pervades the analysis herein, it is probably "mobility." By this we refer to the ability of the U.S. to "mobilize" (i.e. develop and utilize) new sources of human capital, as well to "move" human resources in new directions as new national needs emerge. All of the chapters address these themes. In Chapter 2, for example, the mobility of human resources (across fields and institutions) is the main focus. Chapter 3 looks in detail at the movement of foreign-born technical professionals into the U.S. Chapter 4's focus, the U.S. liberal education tradition, analyzes the educational mindset that underlies the willingness of Americans to embrace career mobility. The two case studies – nanotechnology and bioinformatics – illustrate how human resources are mobilized by public policy in fields at the forefront of science and technology.

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[83] The identification of priorities in, in contrast, very much an aspect of Japanese Plans for Science and Technology.

The main conclusions from each of these chapters follow:

Chapter 1 – A System of "Opportunity-Tropism"

- While the U.S. has neither a clear system nor a plan, it clearly has a vibrant "market" for science and technology human resources. The context for this market is set not only by the preferences and practices of institutions, but also by public policies and a social tradition that expects technical professionals to exercise a high degree of individual choice. Borrowing from biology, we have coined the word "opportunity-tropism" to describe this phenomenon. The fundamental point it suggests by is that actors in the U.S. system are strongly motivated by the search for new opportunities and the rewards they present, and that this "opportunity-tropism" is the basic mechanism through which national needs are met.

Chapter 2 – Mobility of Human Resources in the US

- To understand the mobility of scientists and engineers in the United States, it is important to appreciate two general national characteristics: the generally high degree of mobility, which has historical and cultural origins; and general reliance on market mechanisms and individual choice to make career choices and set salaries for professionals.

- In the science and technology labor market, demand for scientists and engineers comes primarily from industry, academia, and government. The supply of scientist and engineers is determined by the numbers new scientists and engineers coming out of academia, and by the number of foreign scientists coming to work in the United States. Each is subject to multiple influences.

- Most fields of science and technology show fairly steady increases over the last three decades, but there are also some sharp increases and decreases that reflect changes in the job market. Engineering degrees, more closely tied to the industrial job market, show even more variation.

- Over the last 20 years, the composition of the science and engineering workforce has changed considerably as more female and minority scientists and engineers have entered the workforce. This trend reflects broad social changes in the U.S.

- Changes in government R&D priorities affect both the supply and the demand for scientists and engineers. Many public initiatives are designed with a substantial amount of university funding, where it supports graduate students, and thus trains people with relevant skills.

- Two trends are evident in data on mobility: First, people tend to move away from their degree field over time. Second, the higher the degree level, the more likely people are to be working in a job related to their degree.

- Several trends and factors are increasing mobility: industrial positions are less secure; companies and government are relying on outsourcing; and pensions are portable.

Chapter 3 – Mobility to the US from Abroad

- The United States benefits enormously from foreign-born scientists and engineers. In 1999, 27 percent of doctorate-holders in science and engineering were foreign born, and almost one-fifth (19.9 percent) of those with master's degrees.

- Foreign-born individuals typically take one of three routes into the U.S. science and engineering community: they come to the United States as children of immigrant parents; they stay after completing undergraduate or graduate education in science and engineering; or they come later, either as immigrants or under temporary visas (including H-1B).

- Recently, foreign-born individuals have become increasingly important as high-tech entrepreneurs. It is estimated that in the late 1990s more than one-third of the engineers and scientists in Silicon Valley's technology workforce were foreign-born, mostly of Asian descent.

- Two main trends are now affecting supply: post 9/11 procedures and restrictions regarding the admission of foreign nationals into the United States; and the fact that foreign-born scientists and engineers working in the United States are returning to their native countries. In the first area, changes in visa policies have created particular concern in the university community. In the second area, the rubric has changed from "Brain Drain" to "Brain Circulation." Nevertheless, it is also true that historically, the United States has altered its immigration policies in response to changing needs and political pressures.

- "Traditional" factors may increase the U.S. demand for scientists and engineers and for foreign-born scientists and engineers in Particular – i.e. continued job growth at a rate higher than the general economy. "Offshoring' and overseas outsourcing will also present new influences.

- While the U.S. remains very dependent on foreign-born researchers, there is little evidence that the number or quality of these researchers will decline any time soon.

If problems do arise, universities are more likely to experience them than companies.

Chapter 4 – The Liberal Education Tradition

- The American concept of a "liberal education" consists of a broad set of assumptions about the nature and purpose of education, coupled with a reasonably coherent and widely accepted set of design principles for educational institutions. Its curriculum is often capsulized in the rubric, "arts and sciences."

- The liberal educational tradition is certainly the oldest, and probably still the strongest, in American intellectual life. While there is a decline in the percentage of American undergraduates attending avowedly "liberal arts" colleges, it would be mistake to assume that importance of liberal education in American life has declined.

- The liberal educational approach has become ubiquitous throughout the secondary school system. This American tradition differs markedly from the tracking system that is the norm in Europe.

- For the technically oriented young person entering the U.S. university system, there are two options that can lead to a career in science or technology: liberal arts (either at a liberal arts college or within a large multi-purpose university), and engineering. The former is not normally considered a professional degree, and thus assumes graduate school; the latter represents a first professional qualification.

- In the first two years of liberal arts there is a mandated wide range of subjects, and in the second two years, a major field. Nowadays, almost one half of students pursue "double"majors. In liberal arts and across all of American higher education there is a strong attempt to create a diverse social and economic mix for the college experience.

- The numbers of U.S. students choosing engineering has been in a long-term decline. Even "traditional" engineering programs include significant study of humanities and social sciences. The tendency toward multiple concentrations that is typical of the liberal arts is also shown. And engineering undergraduate education is increasingly seen as desirable preparation for other professions.

- An examination of "innovative" engineering programs shows them to be pervaded with the breadth, flexibility, decentralization, diversity and personal choice that are so strong in the American liberal education tradition.

- A high degree of career mobility is implicit in the U.S. liberal education model. Liberal arts graduates are over-represented in science Ph.D. programs. Even among the most educationally committed to science and technology (i.e. Ph.D. holders), 50% work outside the field of their degree.

- The U.S. tradition of a liberal education bears little or no explicit relationship to national science and technology policy. Nor can it be seen as a policy for economic growth. The American belief is that the breadth and openness of inquiry gained from a liberal education will prove uniquely useful throughout one's life. It is believed particularly to promote creativity and leadership. Many Americans would further assert that the qualities gained from a liberal education are most value in times of rapid scientific change.

Chapter 5 – Nanotechnology Case

- Nanotechnology has moved from visionary extrapolation to comprehensive national legislation encouraging R&D in 2003.

- The definition of nanotechnology is still ill-codified and expansive, especially for those who wish to cast themselves with the net of this "hot" field. In this report, we employ the more narrow definition used by the NSF.

- Irrespective of definition, nantoechnology is a field that it is possible to enter from many directions; indeed, familiarity with more than one field is important for success.

- In spite of national legislation, there is no explicit US program to support the training of specialists in nanotechnology. Instead, as is often the case in the United States, the Act implicitly depends on the support of research in universities to provide the funding to support graduate education through research assistantships to students who contribute to the research done under the Act's grant programs.

- The emphasis in Federal nanotechnology programs is on a truly interdisciplinary research culture.

- A few US universities have established nanotechnology programs, and well as internship and outreach programs for the general populace.

- There are a number of important political dimensions to nanotechnology: enthusiasm for it as "the next big thing;" as a symbol of the need for more US investment in physical sciences and engineering; and continuing concerns over the risks nanotechnology may pose.

Chapter 6 – Bioinformatics Case

- Bioinformatics is much newer conceptually than nanotechnology, but it is much further along as both a field of study and a field of professional practice.

- Bioinformatics is not by itself recognized as a scientific or engineering discipline or as an industry, and, thus, it is not represented as a category of employment in official statistics. Thus, like nanotechnology, it draws on more than one discipline.

- There appears to be a growing gap between the demand for persons prepared to work in bioinformatics and the current supply.

- The U.S. federal government has a few modest programs intended specifically to prepare persons for careers in bioinformatics. At the same time, massive federal investment in biomedical research, including genomics and proteomics, has paid for the education and training of students in this important new set of skills. And, such investments are growing.

- One of the most interesting new developments in the employment of high-level scientists and engineers is the growth of temporary employment of such persons. Short-term contractual employment appears to be especially high in bioinformatics.

- Industrial demand for bioinformatics outstrips government and academic training efforts. The long American tradition of job switching and field switching has helped to fill industry's needs.