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Knowledge as Power

Robert L. Paarlberg

Science, Military Dominance, and U.S. Security

Can the United States maintain its global lead in science, the new key to its recently unparalleled military dominance? U.S. scientific prowess has become the deep foundation of U.S. military hegemony. U.S. weapons systems currently dominate the conventional battlefield because they incorporate powerful technologies available only from scientifically dominant U.S. weapons laboratories. Yet under conditions of globalization, scientific and technical (S&T) knowledge is now spreading more quickly and more widely, suggesting that hegemony in this area might be difficult for any one country to maintain. Is the scientific hegemony that lies beneath U.S. weapons dominance strong and durable, or only weak and temporary?

Military primacy today comes from weapons quality, not quantity. Each U.S. military service has dominating weapons not found in the arsenals of other states. The U.S. Air Force will soon have five different kinds of stealth aircraft in its arsenal, while no other state has even one. U.S. airborne targeting capabilities, built around global positioning system (GPS) satellites, joint surveillance and target radars, and unmanned aerial vehicles are dominating and unique.¹ On land, the U.S. Army has 9,000 M1 Abrams tanks, each with a fire-control system so accurate it can find and destroy a distant enemy tank usually with a single shot. At sea, the U.S. Navy now deploys Seawolf nuclear submarines, the fastest, quietest, and most heavily armed undersea vessels ever built, plus nine supercarrier battle groups, each carrying scores of aircraft capable of delivering repeated precision strikes hundreds of miles inland. No other navy has even one supercarrier group.²

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1. The United States controls 90 percent of all the world's military satellites. Eight days before Operation Iraqi Freedom in 2003, Maj. Gen. Franklin J. Blaisdell, U.S. Air Force director of space operations and integration, stated, "We are so dominant in space that I pity a country that would come up against us." Quoted in Andy Oppenheimer, "Arms Race in Space," *Foreign Policy*, No. 138 (September/October 2003), pp. 81–82, at p. 81.

2. For a comprehensive examination of U.S. weapons dominance, particularly in the air, in space,

Such weapons are costly to build, and the large relative size of the U.S. economy (22 percent of world gross domestic product [GDP]) plus the even larger U.S. share of global military spending (43 percent of the world total in 2002, at market exchange rates) have been key to the development and deployment of these forces. Yet economic dominance and spending dominance would not suffice without knowledge dominance. It is a strong and rapidly growing S&T capacity that has allowed the United States to move far ahead of would-be competitors by deploying new weapons systems with unmatched science-intensive capabilities.

It was in the middle of the twentieth century that the global arms race more fundamentally became a science race. Prior to World War II, military research and development (R&D) spending absorbed on average less than 1 percent of total major power military expenditures. By the 1980s, the R&D share of major power military spending had increased to 11–13 percent.³ It was precisely during this period, as science became a more important part of military might, that the United States emerged as the clear global leader in science. During World War II, the military might of the United States had come more from its industrial capacity (America could build more) than from its scientific capacity (Europe, especially Germany and the United Kingdom, could still invent more). As that war came to an end, however, a fortuitous migration of European scientists to the United States plus wartime research investments such as the Manhattan Project gave the United States the scientific as well as the industrial lead.

During the Cold War, the U.S. lead grew stronger. Scientists from the Soviet Union briefly challenged the United States in space, but then decisively lost the race to the moon. The United States responded to the Soviets' successful launching in 1957 of the world's first earth-orbiting satellite, *Sputnik I*, with much larger investments in its own science education and weapons R&D programs. By the later stages of the Cold War, U.S. weapons had attained a decisive quality advantage over Soviet weapons. This first became fully apparent to U.S. intelligence in 1976, when a Soviet pilot flew his mach-3 MiG-25 Foxbat jet interceptor to Japan in search of asylum. Upon inspection the Foxbat was found to be virtually devoid of any next-generation technologies; it was little

and at sea, see Barry R. Posen, "Command of the Commons: The Military Foundation of U.S. Hegemony," *International Security*, Vol. 28, No. 1 (Summer 2003), pp. 5–46.

3. These data from the Stockholm International Peace Research Institute (SIPRI) and Mary Acland-Hood are cited in Vally Koubi, "Military Technology Races," *International Organization*, Vol. 53, No. 3 (Summer 1999), pp. 537–565, at p. 537.

more than a “rocket with a window.” Following the defeat of U.S. forces in Vietnam, some popular critics questioned the military advantage of high-technology (“gold plated”) weapons systems, and suggested that the United States might be better off investing in quantity rather than quality.⁴ But the U.S. decision, post-Vietnam, to move away from a large conscript army and toward a smaller and better-trained all-volunteer force became a reason to increase rather than decrease science investments in weapons quality. During President Ronald Reagan’s administration, U.S. military R&D expenditures doubled, leaving Soviet weapons scientists even further behind and contributing in some measure to the final demoralization of the Soviet leadership.⁵

The U.S. weapons quality advantage was in full view for the first time during the 1991 Persian Gulf War, when stealth aircraft, lasers, infrared night vision, and electronics for precision strikes gave U.S. forces a decisive edge.⁶ Iraqi forces using Soviet equipment were easily broken and expelled from Kuwait at a total cost of 148 U.S. battle deaths. In the 1999 Kosovo conflict, the United States conducted (this time with no battle deaths) an air campaign so dominating that the Serb air force did not even attempt to fly. By the time of the Afghanistan war in 2001, the United States was using GPS satellite-guided bombs capable of striking with devastating precision in any weather, as well as in the dark. From a safe altitude, the U.S. Air Force now could destroy virtually any target on the surface of the earth, if that target had fixed and known geographic coordinates.

In the second Persian Gulf War launched against Iraq in March 2003, the U.S. qualitative edge was even more prominent. U.S. forces were able to go all the way to Baghdad using only half the number of troops deployed in 1991 and only one-seventh as many (but far more precise) air-launched munitions, and without a thirty-eight-day bombing campaign (as in the first Gulf War). Only 105 U.S. battle deaths were suffered during the assault itself; there were fewer unintended civilian casualties (one civilian died for every thirty-five munitions dropped), plus far less damage to Iraqi buildings, bridges, and roads.⁷ U.S.

4. James Fallows, *National Defense* (New York: Random House, 1981).

5. Koubi, “Military Technology Races.” President Ronald Reagan’s 1983 Strategic Defense Initiative to develop and deploy a space-based shield against Soviet intercontinental missiles promised far more than U.S. laboratories could deliver at the time, yet it left a demoralizing impression on leaders in Moscow.

6. Delores M. Etter, “Defense Science and Technology,” in Albert H. Teich, Stephen D. Nelson, and Stephen J. Lita, eds., *AAAS Science and Technology Policy Yearbook* (Washington, D.C.: American Association for the Advancement of Science, 2002), pp. 167–181.

7. Williamson Murray and Robert H. Scales Jr., *The Iraq War: A Military History* (Cambridge, Mass.: Harvard University Press, 2003), p. 179.

strike aircraft flying up to 1,000 sorties a day were able, even through a blinding sandstorm, to destroy the tanks and infantry vehicles of the Republican Guard.⁸ Pervasive GPS capabilities, new sensor systems, near real-time “sensor to shooter” intelligence, and computer-networked communications allowed U.S. forces to leverage the four key dimensions of the modern battlespace—knowledge, speed, precision, and lethality—and to prevail quickly at minimal cost.⁹

The key to this revolution in military affairs (RMA) has been the application of modern science and engineering—particularly in fields such as physics, chemistry, and information technology (IT)—to weapons design and use. It is the international dominance of the United States in these fields of science and technology that has made possible U.S. military dominance on the conventional battlefield.¹⁰ It thus becomes important to judge the magnitude and durability of U.S. scientific hegemony. In the sections that follow, I first measure the U.S. lead in S&T relative to the capabilities of potential rival states by using a variety of science output and resource input indicators. By every indicator, the current lead of the United States is formidable. Then I judge the durability of the U.S. lead by examining two possible weaknesses within its foundation. The first is the greater speed with which scientific knowledge can diffuse (perhaps away from the United States) in the modern age of globalization. The second is the poor science preparation still provided by so many U.S. public schools in grades K–12.

Upon examination, these two factors need not present a significant threat to the U.S. global lead in science and technology, assuming the United States can remain a large net importer of scientific talent and knowledge from abroad. Preserving this vital net inflow of scientific assets has been made more difficult, however, by the homeland security imperatives arising from the terrorist attacks of September 11, 2001. It should be the policy of the United States to devise a homeland security strategy that does not impair the nation’s access to foreign science talent. One part of this strategy should be to contain the fur-

8. *Ibid.*, p. 172.

9. On the deficit side, several quick-response “decapitation” strikes against regime leaders failed to produce results. A classified assessment of the war by the U.S. Joint Forces Command cites several other performance deficits as well, including weak battlefield damage assessment capabilities and “fratricide” losses to friendly forces. Thom Shanker, “Pentagon Criticizes High Rate of Allied Deaths by Allied Fire,” *New York Times*, October 3, 2003, p. A14.

10. U.S. conventional military preponderance depends on more than just its lead in science and technology, to be sure. Also necessary for this dominance are the nation’s vast economic resources, its skilled military personnel, and its unmatched international military basing structure. For a more complete review of the magnitude and limits of U.S. conventional military dominance, see Posen, “Command of the Commons,” p. 21.

ther growth of terrorist threats by avoiding conventional military campaigns that create determined new political adversaries abroad. Victories that bring resentment will breed resistance, most easily expressed in the form of asymmetric threats against soft targets, including homeland targets. Another part of this strategy should be a more effective mobilization of the nation's massive S&T capacity when responding to the asymmetric threats that do arise. The United States is uniquely capable of innovating new "smart" technologies to protect soft homeland targets against unconventional threats. The current Fortress America approach risks undercutting the nation's lead in science by keeping too many talented foreigners out.

How Large Is the U.S. Lead in Science and Technology?

The U.S. lead in science and technology can be measured in terms of either final scientific output or R&D input. Scientific and technical output is most often measured by counting numbers of scientific papers published, numbers of papers cited in other published papers, numbers of registered patents, or numbers of prizes won. By all such measures, the United States holds a commanding global lead.

The Institute for Scientific Information (ISI) has maintained since 1981 a database of scientific citations from roughly 9,000 indexed journals published worldwide from all scientific fields, excluding mathematics, social sciences, and the humanities. From 1992 to 2002, scientists working in the United States led other nations by a large margin in both numbers of papers published and numbers of citations. Table 1 reveals that scientists working in the United States have been publishing roughly four times as many papers as scientists in Japan, the second-ranking country, and papers published by U.S. scientists have received roughly five times as many citations as papers from the second-ranking U.K. scientists. This wide U.S. lead in scientific papers and citations has been diminishing over time. Over the period 1981–94, while worldwide scientific paper output increased 3.7 percent per year, U.S. output increased only 2.7 percent per year. Scientific paper growth rates above 10 percent per year were registered by China, Singapore, South Korea, and Taiwan, yet these were higher growth rates from a much smaller base.¹¹

The U.S. scientific lead also can be measured in numbers of patented inven-

11. Robert M. May, "The Scientific Wealth of Nations," *Science*, Vol. 275, No. 7 (February 1997), p. 793.

Table 1. Top Ten Countries, Published Papers by Scientists, and Citations to Papers, January 1992–June 2002

Rank by Papers/ Citations	Country	Papers	Citations
1/1	United States	2,618,154	30,765,049
2/4	Japan	672,308	4,591,831
3/3	Germany	619,323	5,186,228
4/2	England	570,667	5,628,105
5/5	France	459,963	3,777,753
6/6	Canada	346,126	3,259,935
7/7	Italy	288,763	2,245,050
8/17	Russia	255,548	665,442
9/10	Australia	198,006	1,523,844
10/20	China	193,006	494,157

SOURCE: *ISI Essential Science Indicators*, <http://www.in-cites.com/countries/2002allfields.html>.

tions. During the mid-1980s, the large U.S. share of patents awarded in the United States began to decline, reinforcing worries about a supposedly diminished U.S. competitiveness vis-à-vis Japan and other rising economies in Asia. In 1970 American inventors had accounted for 66 percent of U.S. patents, but by 1989 that share had fallen to just 52 percent. Even Joseph Nye, who was otherwise confident in his 1990 book *Bound to Lead* of the continued strength of the United States, viewed this patent trend as a “cause for concern.”¹² Nye need not have been concerned. Patenting by U.S. inventors revived in 1990 and began growing more rapidly than patenting by foreign inventors once again. By 1999 the U.S. share of new patents was back up to 54 percent.¹³ U.S. inventors have also continued to lead in patenting within foreign countries, registering more patents than local competitors in Brazil, Canada, France, Germany, Italy, Japan, Russia, and numerous other countries.¹⁴

Prize winnings are another output indicator of relative science strength, albeit a lagging indicator because science prizes are usually awarded years or even decades following the moment of scientific achievement. A count of win-

12. Joseph S. Nye Jr., *Bound to Lead: The Changing Nature of American Power* (New York: Basic Books, 1990), p. 212.

13. National Science Foundation, *Science and Engineering Indicators, 2002* (Arlington, Va.: National Science Foundation, 2002), <http://www.nsf.gov/sbe/srs/seind02/c6/c6s4.htm#c6s411>.

14. Patent counts have numerous limitations as a measure of science strength because the significance of different inventions varies widely. Counts of patent citations can help get around this problem, and here as well the United States dominates. A more difficult problem is differing national approaches to intellectual property. In many countries inventions are not patented at all, either because intellectual property laws are weak or because industrial trade secrets enjoy blanket protection.

ners of all internationally recognized science prizes worth more than \$200,000, including Nobel Prizes and the Fields Medal in mathematics, reveals that German scientists won most of the awards early in the twentieth century, with American scientists entering the winning ranks in large numbers only in the 1930s. In the decades around World War II, proportionately fewer German and French scientists won, and American scientists began to establish a commanding lead, winning roughly half of all prizes given. This is a lead that has continued into the twenty-first century. Of the seven 2003 Nobel Prize laureates in physics, chemistry, physiology, and medicine, five were living and working in the United States.¹⁵

A more derivative indicator of the U.S. lead in S&T is the country's share of world production of technology-intensive manufactured goods, known as "high-technology manufactures." Throughout the 1980s the U.S. share of global high-technology production remained at a strong 33 percent. It then declined to 30 percent from 1988 to 1995, while Japan's share grew from 20 percent in 1980 to 26 percent in 1991. Concerns spread that Japan might be emerging as a technological challenger at least in commercial manufacturing, but more careful thinkers argued that the U.S. lead was still strong.¹⁶ Popular concerns were laid to rest when the U.S. share of global high-technology production subsequently revived to reach an unprecedented 36 percent by 1998, while the Japanese share fell back down to its 1980 level of just 20 percent.¹⁷

In addition to papers, citations, patents, prizes, and high-technology production, it is also possible to count numbers of highly productive scientists. The ISI has used its citation database to generate a list of the world's 1,222 most "highly cited scientists," working at 429 different institutions in twenty-seven different countries around the world. Two-thirds of these scientists (815) worked at institutions in the United States. The next four countries in rank order are the United Kingdom (with 100 of these top scientists), Germany with 62, Canada with 42, and Japan with 34. Russia has 2, India 2, and Taiwan 1; the People's Republic of China has none.¹⁸

These ISI database results also indicate that highly cited scientists tend to

15. Scientists from the United Kingdom consistently won approximately 10 percent of all awards in the twentieth century. Complete Nobel Prize records are available from the Nobel e-Museum, <http://www.nobel.se/index.html>.

16. See Henry R. Nau, *The Myth of America's Decline: Leading the World Economy into the 1990s* (New York: Oxford University Press, 1990). See also Paul Krugman, "The Myth of Asia's Miracle," *Foreign Affairs*, Vol. 73, No. 6 (November/December 1994), pp. 62–78.

17. National Science Foundation, *Science and Engineering Indicators*, 2002.

18. Michael Batty, "The Geography of Scientific Citation," *Environment and Planning A*, Vol. 35 (2003), pp. 761–765.

work in tight geographic clusters. In the area of Boston, for example, all of the institutions that house ISI's highly cited scientists lie within a two-mile radius of the Massachusetts Institute of Technology. Such geographic clusters of scientists can grow into highly productive "innovation hubs" if they feature the right mix of both public- and private-sector laboratories, several competing first-class universities, close contacts with nonprofit foundations, and access to venture capital.¹⁹ A recent global inventory of such innovation hubs in the area of information technology found that a preponderant number were indeed located within the United States. In 2000, *Wired* magazine consulted local sources in government, industry, and the media to find the geographic locations that matter most for innovation in the new digital age. Each location was rated on a scale of one to four in four areas: ability of area universities and research facilities to train skilled workers or develop new technologies; the presence of established companies and multinational corporations to provide expertise and economic stability; the population's entrepreneurial drive to start new ventures; and the availability of venture capital.²⁰ A total of forty-six locations around the world were identified in this manner as "technology hubs," and thirteen of these forty-six hubs were in the United States. Of the seventeen hubs that had the highest aggregate scores, eight were in the United States.²¹ The closest competitor was the United Kingdom, with four hubs total, and only two in the top seventeen. The closest security rival of the United States with multiple hubs on this list was China, with three hubs total, but none of China's hubs were in the top seventeen, or even in the top thirty.²²

U.S. R&D INVESTMENT

Perhaps the best way to measure the U.S. lead in science and technology is to consider inputs of R&D investment. The total U.S. R&D portfolio (private as well as public investments) exceeds \$250 billion a year. These investments have a recent history of steady expansion; in constant dollar terms, total U.S. R&D grew from \$100 billion in 1976 to \$265 billion in 2000.²³ These R&D in-

19. Steven W. Popper and Caroline S. Wagner, *New Foundations for Growth: The U.S. Innovation System Today and Tomorrow*, MR-1338.0-OSTP (Santa Monica, Calif.: Science and Technology Policy Institute, RAND, January 2002).

20. Batty, "The Geography of Scientific Citation."

21. These eight U.S. hubs were Albuquerque, Austin, Boston, New York City, Raleigh-Durham-Chapel Hill, San Francisco, Seattle, and Silicon Valley.

22. United Nations Development Programme, *Human Development Report, 2001* (New York: Oxford University Press, 2001), p. 45.

23. Elisa Eiseman, Kei Koizumi, and Donna Fossum, *Federal Investment in R&D*, MR-1639.0-OSTP (Santa Monica, Calif.: Science and Technology Policy Institute, RAND, September 2002), p. 15.

vestments are routinely credited with boosting U.S. economic growth and commercial competitiveness internationally,²⁴ yet they are also at the foundation of U.S. military supremacy.

U.S. investments in R&D far outstrip those of other wealthy states. Total gross domestic expenditures on R&D in the United States exceed those of Japan, the second-largest R&D-investing country, by 158 percent.²⁵ The United States invests 40 percent more in R&D than the original fifteen European Union (EU) states combined. This is a reflection of a greater U.S. effort, not just larger economic size. Total R&D investments in the EU in 2000 equaled 1.9 percent of GDP, compared with 2.69 percent in the United States. In 2002, the European Commission reported that the U.S. lead over the EU in R&D spending had widened for the seventh year in a row. In June 2003, EU Commissioner Chris Patten warned his fellow Europeans of what he called a “brutally simple statistic”: the United States with just 4 percent of the world’s population accounted for 50 percent of the world’s R&D spending.²⁶ EU officials have repeatedly described these figures as worrying for the future economic performance of Europe compared with the United States; it is also worrying for Europe’s future capacity to rival the United States in highly capable military technologies.

To judge the military value of these R&D investments more carefully, it is necessary first to separate the less vital private component from the more vital public component. The private share of the total U.S. R&D portfolio has increased significantly, from 50 percent in the mid-1980s to more than 66 percent of the total in 2003.²⁷ During an interlude in the 1990s, this continued privatization of U.S. R&D, which reflected in part a real dollar shrinkage of public federal R&D, caused some defense advocates to worry. In constant dollar terms (fiscal year 2002 dollars), total public-sector federal R&D budget authority (defense plus nondefense) had earlier increased from \$60 billion in 1976 to nearly \$90 billion during the Reagan administration, but then fell back to just \$80 billion in the mid-1990s. This concern was only temporary. The federal R&D investment decline was reversed for nondefense programs in the late 1990s in

24. Charles I. Jones, “Sources of U.S. Economic Growth in a World of Ideas,” Stanford University Economics Working Paper No. 97-015 (Stanford, Calif.: Stanford University, July 8, 1998), http://papers.ssrn.com/sol3/papers.cfm?abstract_id=72188.

25. Eiseman, Koizumi, and Fossum, *Federal Investment in R&D*.

26. Claire Sanders, “European R&D Draining to U.S.,” *Times Higher Education Supplement* (London), June 27, 2003.

27. Eric Bloch, “Securing U.S. Research Strength,” *Issues in Science and Technology*, Vol. 19, No. 4 (Summer 2003), pp. 20–22.

response to lobbying efforts from the U.S. scientific community. For defense programs, the decline was decisively reversed after the September 11 attacks. Thus by FY 2003, total federal R&D outlays were back up to \$112 billion, roughly 20 percent in real dollars above the earlier Reagan-era peak.

Federal R&D investments in nondefense programs recovered partly due to the political strength of a new domestic science lobby. As Allan Bromley, former assistant to the president for science and technology, explains, "Scientists have become much more politically savvy, developing effective advocacy groups that drive federal policies and budgets through grassroots lobbying, media initiatives, and Capitol Hill events."²⁸ When total federal R&D spending went into a decline in the mid-1990s, this domestic science lobby pushed successfully to revive at least the nondefense component of that spending.

The Clinton administration had initially been neglectful of federal R&D investments. In his first term, Bill Clinton failed to meet even once with the President's Council of Advisors on Science and Technology. He also undercut the executive branch access of scientists by replacing the Federal Coordinating Council for Science, Engineering, and Technology with a new National Science and Technology Council that he chaired but failed to use.²⁹ Beginning in 1995, the domestic science community responded to this neglect with a successful Congress-based lobbying effort. In June 1996, the American Association for the Advancement of Science circulated in Congress a budget analysis that projected a further 25–30 percent constant-dollar decrease in federal science and technology support between FY 1995 and FY 2000, prompting five Republican senators led by Phil Gramm of Texas to submit legislation in January 1997 calling for a doubling of the nondefense federal science and technology budget over the next decade. In the post–Cold War political environment of the 1990s, the scientific community used national economic competitiveness as its justification for advocating more nondefense federal R&D money. As a result of these lobbying efforts, the president's FY 1999 budget request contained significant new increases for nondefense federal R&D. In addition, between FY 1996 and FY 2000, federal nondefense R&D budget authority was increased 24 percent in nominal terms.

The post–Cold War decline in federal military R&D spending took longer to reverse. In constant dollar terms, U.S. military R&D fell 16 percent between

28. D. Allan Bromley and Michael S. Lubell, "Science's Growing Political Strength," *Issues in Science and Technology*, Vol. 19, No. 4 (Summer 2003), pp. 13–15, at p. 13.

29. *Ibid.*

1991 and 1996.³⁰ While federal nondefense R&D began increasing after 1996, spending for military R&D remained essentially flat. By 1998, defense S&T advocates in the U.S. Senate led by Senators Joseph Lieberman, Jeff Bingaman, and Rick Santorum were sounding the alarm and calling for annual 2 percent increases in military R&D, above the rate of inflation. In 1999, writing in *Joint Force Quarterly*, Lieberman asked, "With a 30 percent decline in military research, and another decrease slated for the next fiscal year . . . where will our technical superiority come from?"³¹

Such alarms failed at first to trigger any noticeable presidential or congressional response, and by FY 2001, Department of Defense R&D spending was down to just 43 percent of total federal R&D spending, well below the FY 1986 peak level of 63 percent.³² Support for military R&D spending was only restored following the arrival of a new Republican administration in Washington in January 2001, and then most decisively following the September 11 terror attacks. Total defense spending increased dramatically; and as a subcategory, military R&D investments increased as well. By 2002, according to calculations prepared by the Stockholm International Peace Research Institute, U.S. military R&D spending had recovered enough in constant dollar terms to surpass even the 1991 late Cold War-era level, as shown in Table 2. This recovery of U.S. federal defense R&D outlays continued into 2003, when total Department of Defense outlays for research, development, testing, and evaluation reached \$56 billion.³³ The United States, by 2003, was spending roughly as much on just the weapons development component of its military budget as any other single state was spending on its entire military budget.

Most U.S. defense R&D investments are in the development, testing, and evaluation of specific weapons systems, but the Department of Defense also engages in more basic S&T research, to provide the more fundamental science and technology knowledge needed to meet future military requirements. Current priorities for S&T spending include further investments in IT so as to ad-

30. SIPRI Military Expenditure and Arms Production Project, June 2002, http://projects.sipri.se/milex/aprod/nationaldata/equip_exp_mil_r&d.pdf.

31. Joseph I. Lieberman, "Techno-Warfare: Military R&D," *Joint Forces Quarterly*, No. 22 (Summer 1999), pp. 13–17, at p. 14.

32. "FY 2001 Department of Defense Share of Federal R&D Funding Falls to Lowest Level in 22 Years," Data Brief NSF 01-319 (Arlington, Va.: Division of Science Resources Studies, National Science Foundation, February 26, 2001). The Department of Defense R&D budget accounts for roughly 94 percent of total national defense R&D budget authority. R&D funding for the Department of Energy's atomic energy defense activities accounts for the remaining share.

33. Current information on U.S. defense R&D spending policy is available at the American Institute of Physics *Bulletin of Science Policy News*, <http://www.aip.org/enews/fyi/>.

Table 2. Expenditure on Military R&D in the United States and Western Europe, 1991–2002 (U.S.\$ billions, at constant 2000 prices)

	1991	1995	1996	1997	1998	1999	2000	2001	2002
United States	49.7	42.1	41.6	42.5	42.0	42.7	42.6	44.5	50.6
United Kingdom	4.4	3.6	3.7	3.9	3.4	3.7	3.7	—	—
France	6.5	4.5	4.3	3.4	3.2	3.1	3.1	3.5	—
Germany	2.0	1.6	1.7	1.7	1.5	1.4	1.3	1.2	—
Total European Union	14.9	11.1	10.9	10.5	9.8	9.8	9.7	—	—

SOURCE: SIPRI Military Expenditure and Arms Production Project, June 2003, http://projects.sipri.se/milex/aprod/nationaldata/equip_exp_mil_r&d.pdf.

vance the RMA; missile defense; and new weapons and capabilities based on nanotechnology, biological sensors, and robotics. This S&T budget in the Department of Defense supports roughly 35 percent of all federal research in computer sciences and 40 percent of all federal engineering research. Following the September 11 attacks, this important subcategory of defense R&D spending increased as well, reaching \$10 billion in FY 2002, back up in real dollar terms to the early 1990s' level.³⁴

THE POSITION OF POTENTIAL RIVALS

As U.S. investments in defense R&D were recovering from their initial post–Cold War slump, other governments allowed such investments to continue sliding. Table 2 reveals that Europe was falling further behind the United States in military R&D investment even prior to September 11. The ratio of U.S. to total EU spending on military R&D was slightly more than three to one when the Cold War ended in 1991, and by 2000 had increased to more than four to one. Among all the wealthy nations of the Organization for Economic Cooperation and Development (OECD) between 1990 and 1998, the defense share of budgetary R&D appropriations declined from 37 percent to 30 percent, but the ratio in the United States declined briefly and then recovered to 55 percent.³⁵ The closest competitor to the United States in terms of allocating R&D budget shares to the military has been the United Kingdom (35 percent), followed by the Russian Federation (30 percent), but these countries have much smaller R&D budgets overall. The United States still puts 0.4 percent of

34. Eiseman, Koizumi, and Fossum, *Federal Investment in R&D*, p. 69.

35. Organization for Economic Cooperation and Development, "R&D Defence Spending Falls," *OECD Observer*, April 28, 2000.

its GDP into military R&D, more than twice the proportion allotted by the United Kingdom or France. Japan is a heavy R&D spender, but it allocates only a trivial 0.03 percent of its GDP to defense R&D.

The military R&D efforts of today's Russian Federation are only a fraction of the determined (yet still inadequate) efforts made by the Soviet Union during the Cold War. The Soviet Union at one point was devoting as much as 2–3 percent of its gross national product to military R&D, a larger share than most industrial countries now invest in total R&D.³⁶ When the Soviet system collapsed, state spending on military R&D was sharply reduced, and Russia's once-privileged defense scientists were suddenly obliged to accept low salaries and to work in deteriorating research facilities with outdated equipment. Nuclear physicists protested with hunger strikes or took menial jobs in other fields. In 1996 the director of the second largest nuclear research center in Russia took his own life because he could no longer endure a situation in which his employees had not been paid for five months and, in his words, were "close to starvation."³⁷ Science in Russia will recover only slowly from this collapse. Total R&D expenditures in Russia are now smaller than those in Canada, and only about 4 percent the level of total R&D spending in the United States.³⁸

The Chinese economy has now enjoyed twenty-six consecutive years of strong growth based in part on the acquisition of new technologies. Today China's leaders clearly aspire to close the military technology gap with the United States, yet their science capacities remain far behind those of the United States. The list of deficits is long. In microelectronics China's most advanced facilities have been six to eight years behind the state of the art and continue to be critically dependent on imports. China has only limited supercomputer capabilities and its PCs are composed primarily of imported parts. In telecommunications China depends on foreign firms for advanced transmission technologies. China's nuclear power industry is rudimentary, and its aviation industry is based mostly on antiquated Soviet technology. In space China's launch capability is impressive for a developing country, but its satellite capa-

36. Roger Cliff, *The Military Potential of China's Commercial Technology*, MR-1292-AF (Santa Monica, Calif.: RAND, 2001), p. 63.

37. Quoted in Theodore P. Gerber, "From Crisis to Transition: The State of Russian Science Based on Focus Groups with Nuclear Physicists (U)," UCRL-JC-146574 (Livermore, Calif.: Lawrence Livermore National Laboratory, U.S. Department of Energy, 2001), http://cgsr.llnl.gov/future2002/ponars_version3_12-10-01.html.

38. Comparisons are made converting foreign currencies to U.S. dollars with OECD purchasing power parity exchange rates. Eiseman, Koizumi, and Fossum, *Federal Investment in R&D*, p. 117.

bilities remain limited.³⁹ According to a 2001 assessment, in military technology China is destined to remain significantly behind well into the future:

China's overall military technology in 2020 will still be significantly inferior to that of the United States, for several reasons. First, . . . China's average level of commercial technology will still lag behind advanced world practice. Second, because development cycles for weapons are long, military systems are often designed around technologies that are a decade or more old by the time the weapons become operational (In the United States, 13 to 15 years typically elapse between the initiation of a major weapon development program and the initial operational capability of the first production units). Thus, the military systems that the United States and China field in 2020 will largely reflect the technologies available to those countries in 2010 or earlier. Finally, the process of translating civilian technological capabilities to military technology is nontrivial. Even though military systems build on technologies that are fundamentally civilian, they still involve technologies that are specifically military and thus must be independently developed. Furthermore, even if all the component technologies of a weapon system are available, the process of integrating them into a smoothly functional whole is challenging. This has been demonstrated, for example, by the difficulties Japan's defense industries have experienced in developing F-2 indigenous fighter aircraft.⁴⁰

China's stock of scientific capital is growing rapidly, but it still remains limited by advanced country standards. Despite China's size, total numbers of scientists and engineers currently being trained in China are substantially fewer than in the United States. The United States awards roughly eight times as many doctoral degrees in the natural sciences and in engineering as China. Despite several decades of strong economic growth, China's total R&D spending remains less than 25 percent of the U.S. R&D total (in purchasing power dollars) and only 50 percent of the Japanese total. Much of China's scientific progress results not from indigenous R&D but from technology transfers associated with foreign investments by private firms. Indigenous innovation remains difficult in China because of various institutional constraints including continued state controls over information flows, weak factor markets, and inadequate protections for intellectual property. Roger Cliff concluded in 2001 that China's resources for technological progress were roughly comparable to those

39. Cliff, *The Military Potential of China's Commercial Technology*, pp. x-xi. In 2003 China used a modified version of the Russian Soyuz technology to put its first manned satellite into orbit, four decades after this had been done by the Soviet Union and the United States.

40. *Ibid.*, p. 62.

of South Korea or Taiwan in the 1970s, implying that by 2020 China's civilian economy might be able to attain the average technological level of South Korea or Taiwan today.⁴¹ This will not be enough to catch the United States, which will hardly be standing still, given its continued four to one advantage over China in new R&D investments.

China's post-Maoist leaders appreciated the contribution of science to military preparedness, as Deng Xiaoping put technology and the military third and fourth—after agriculture and industry—on his list of the “four modernizations” that China should pursue in the 1980s. High technology was then elevated to even higher priority after 1986, when China launched the so-called National High-Technology Research and Development Program (the 863 Program, so-named because it was initiated in March 1986) to speed the development of military and dual-use technologies in areas such as IT, lasers, biotechnology, and space. In 1987 the father of China's strategic missile program, Qian Xuesen, told his colleagues that China must ready itself for what he called a century of sustained “intellectual warfare.”⁴² The urgency of this new effort was reinforced when China witnessed the dominance of U.S. high-technology weapons in the 1991 Gulf War. At that point, Chinese military theoreticians began to endorse an even wider range of military high technologies, including information warfare, space weapons, directed energy, nano-weapons, unmanned combat planes, and more. The People's Liberation Army (PLA), which traditionally had counted on quantity to trump quality, began to talk of switching to a quality-based RMA.⁴³ In September 2003 China's military chief, Jiang Zemin, officially announced that the nation would reduce the size of its current forces so as to redeploy its limited resources to “quicken the pace of constructing our military's information technology.”⁴⁴

Such efforts notwithstanding, China will not be able to switch quickly from a high-quantity force to a high-quality force. The Soviet Union failed to catch up in a qualitative arms race with the United States in the 1970s and 1980s even though it devoted 2 to 3 percent of its entire gross national product to military R&D. For China, a comparable level of military R&D spending today

41. *Ibid.*, p. xv.

42. Evan A. Feigenbaum, *China's Techno-Warriors: National Security and Strategic Competition from the Nuclear to the Information Age* (Stanford, Calif.: Stanford University Press, 2003).

43. Richard D. Fisher Jr., “Military Sales to China: Going to Pieces,” *China Brief*, Vol. 2, No. 23 (November 21, 2002), Jamestown Foundation.

44. Quoted in Joseph Kahn, “China Plans to Cut 200,000 Troops over 2 Years,” *New York Times*, September 2, 2003, p. A9.

would require an unlikely doubling of total military budget outlays.⁴⁵ Rather than trying to match the United States B-2 bomber for B-2 bomber, China will more likely focus in the short run on possible “niche” or “asymmetric” responses to the overwhelming U.S. superiority in science-based weapons. Virus attacks on U.S. computer networks or laser attacks on U.S. satellites might be an example.⁴⁶

How Secure Is the U.S. Lead in Science and Technology?

Two hypothetical threats to the current U.S. lead in S&T must be considered. The first is the more rapid pace at which scientific innovations now spread across borders in the age of globalization. Will this more rapid diffusion of scientific knowledge give a catch-up advantage to laggards and make it difficult for the United States to hold its current lead? The second is the continuing underperformance of U.S. public schools in teaching science and mathematics in grades K–12. Will poor science education at home undercut the U.S. lead abroad? A front page *New York Times* article in May 2004 asserted that the United States had “already started to lose its worldwide dominance in critical areas of science and innovation.” Some of this loss may be real, but much is imagined.⁴⁷

45. Cliff, *The Military Potential of China's Commercial Technology*, p. 63. Estimating China's total spending on military R&D is difficult, even for Chinese officials, because much of the official defense budget excludes R&D outlays. The nominally private defense industries run by civilian ministries under the State Council, or operated now by corporation groups, maintain production lines for PLA military orders and have their own R&D institutes that develop military products from weapons to satellites. Most investment in military R&D in China comes not from the defense budget but from the civilian investment budget. Xiaonong Cheng, “Written Testimony for U.S.-China Commission Public Hearing on China's Budget Issues,” December 7, 2001, <http://www.uscc.gov/textonly/transcriptstx/tesxia.htm>.

46. James R. Lilley and David L. Shambaugh, eds., *China's Military Faces the Future* (Armonk, N.Y.: M.E. Sharpe, 1999). A PLA Art Press publication in 1999 entitled *Warfare beyond the Rules* argued that China should not fall into the trap of trying to match or defeat U.S. forces on the RMA battlefield. Instead China should consider a number of radically asymmetric actions (called “nonmilitary war” actions or “nonwar military” actions) including cyberattacks, terrorism, drug smuggling, environmental disruption, and the use of weapons (including chemical and biological weapons) not recently permitted under the international laws or rules of war. See Ming Zhang, “China: War without Rules,” *Bulletin of Atomic Scientists*, Vol. 55, No. 6 (November/December 1999), pp. 16–18.

47. This article cited a dip in numbers of papers published by U.S. physicists, and a drop in the U.S. share of its own industrial patents, back down to 52 percent (i.e., the 1990 level). William Broad, “U.S. Is Losing Its Dominance in the Sciences,” *New York Times*, May 3, 2004, p. A1.

THE MORE RAPID DIFFUSION OF TECHNICAL KNOWLEDGE

In the age of globalization, with scientific knowledge diffusing more rapidly across borders, will leading scientific states find it more difficult to maintain their advantage? The wider availability of low-cost telecommunications has indeed led to a “demise of distance” as regards information flows.⁴⁸ One empirical study of science and technology information flows within the United States between 1975 and 1999 discovered the average geographic distance between scientific collaborators and the average distance between inventors and those citing their inventions had increased by roughly two-thirds.⁴⁹ Yet “digital divides” between advantaged and disadvantaged societies can impede this spread of scientific and technical information, and such divides cannot easily be bridged through new investments in hardware alone.⁵⁰ Uptake and effective use at the receiving end depends heavily on levels of social or institutional development, and on the scientific and technological literacy of the receiving society.⁵¹ One empirical study found that societies with a science production rate of fewer than 150 scientific papers per 1 million inhabitants per year are markedly less able to absorb flows of scientific or technical knowledge. The study expected this threshold to rise with the steadily increasing knowledge requirements of today’s catching-up process.⁵² For societies at the bottom of the science capabilities ladder, more knowledge is now available from abroad through globalization, but the quantity needed to catch up is even greater, and too little of what is currently available is taken up or put to effective use.

Among countries that are scientifically capable, the international sharing of knowledge does have large effects, and far more sharing among such capable countries is clearly taking place. Between 1981 and 1995, the internationally coauthored share of all published scientific and technical articles, as tabulated by the National Science Foundation, increased from 17 percent to 29 percent. Scientists in the United States participated heavily in these international col-

48. James Gleick, *What Just Happened: A Chronicle from the Information Frontier* (New York: Pantheon, 2002).

49. Daniel Johnson, Nalyn Siripong, and Amy Brown, “The Demise of Distance? The Declining Role of Physical Distance in Knowledge Transmission,” Working Paper 2002-06 (Wellesley, Mass.: Department of Economics, Wellesley College, September 2002).

50. Pippa Norris, *Digital Divide: Civic Engagement, Information Poverty, and the Internet Worldwide* (New York: Cambridge University Press, 2001).

51. Mark Warschauer, *Technology and Social Inclusion: Rethinking the Digital Divide* (Cambridge, Mass.: MIT Press, 2003).

52. Americo Tristao Bernardes and Eduardo da Motta e Albuquerque, “Cross-over, Thresholds, and Interactions between Science and Technology: Lessons for Less-Developed Countries,” *Research Policy*, Vol. 32, No. 5 (May 2003), pp. 865–885.

laborations, publishing more internationally coauthored articles than scientists in any other country.⁵³ The leading scientific societies now tend to be global, not national. For example, more than one-fifth of all the members of the American Physical Society live abroad, and 60 percent of institutional subscriptions to the journal of this society are purchased by foreign universities and laboratories. Yet this increased internationalization of science need not imply a net leakage of scientific knowledge out of the United States, for several reasons.

First, a great deal of American science remains autonomous despite increased international linkages. U.S. scientists do publish more internationally coauthored articles than scientists in other countries, but this is only because the total number of articles published by U.S. scientists is so large. The internationally coauthored *share* of U.S. published articles is relatively low by international standards, lower than in Canada, China, the United Kingdom, or any of the continental European countries.⁵⁴ The bulk of all collaborations in American science still remain contained within the country (the greatest demise of distance has been among collaborators within the United States, rather than across international borders). Second, a leading reason for the growth of international collaboration in science has been an increased number of “big science” projects that require the sharing of expensive large-scale equipment, and a preponderance of this equipment is located in the United States. This means that most of the foreign collaborators of American scientists are coming to the United States, rather than the other way around, and it means that the essential nodes of innovation remain geographically located within the United States. Also, many of these talented foreign scientists never go home. Nearly 30 percent of all Ph.D.’s currently engaged in R&D in the United States were born abroad.⁵⁵ This brain drain works strongly to the relative scientific advantage of the United States.

Hypothetically, the United States might risk a net loss of scientific advantage if foreign scientists or students were to come on temporary visas, work briefly in U.S. laboratories and universities, and then return home. Many of those who come, however, are in fact looking to stay. One 1998 study found that 47 per-

53. Caroline S. Wagner, Allison Yezril, and Scott Hassell, *International Cooperation in Research and Development* (Santa Monica, Calif.: Science and Technology Policy Institute, RAND, 2001).

54. Only India, Japan, and Russia are less internationalized, by this measure, than the United States. *Ibid.*

55. National Science Foundation, *International Mobility of Scientists and Engineers to the United States—Brain Drain or Brain Circulation?* NSF 98-316 (Arlington, Va.: Directorate for Social, Behavioral, and Economic Sciences, National Science Foundation, revised November 10, 1998).

cent of foreign students on temporary student visas who earned doctorates in the United States in 1990 and 1991 stayed on and were still working in the United States in 1995, and the students most likely to stay were those from nonallied countries. Nearly 90 percent of science Ph.D.'s from South Korea went home, and roughly half of the Canadians went home, but 79 percent of Indian Ph.D.'s were still working in the United States when this 1998 study was done, and 88 percent of Chinese Ph.D.'s had stayed on.⁵⁶ U.S. law has made it easier for Chinese students to remain in the United States following the Tiananmen Square crisis of 1989, and thousands of China's brightest young scientists have taken advantage. More than 500,000 students from developing countries, communist countries, and former communist countries are currently studying outside of their home countries—many in the United States—and the National Intelligence Council estimates that roughly two-thirds of these students will never go home.⁵⁷ The comforting picture that emerges for the United States is one of "brain circulation" among allied states, combined with a strong net brain drain away from rival or potentially powerful neutral states.

Science knowledge also moves internationally when multinational business firms transfer technology through commercial sales or foreign direct investments, yet this is hardly an uncontrolled process. The U.S. State Department's Directorate of Defense Trade Controls, in the Bureau of Political Military Affairs, is empowered under the 1976 Arms Export Control Act to control through the issuance of licenses the export of specifically identified military items and technologies, including "technical data." Under the International Traffic in Arms Regulations (ITAR), the Department of State controls all items on a specific munitions list, and enforcers do not require proof that technical data changed hands; simply talking to a foreign engineer can trigger a violation charge.⁵⁸ Commercial products and technologies with a potential military dual-use are similarly controlled under the 2001 Export Administration Act, administered by the Department of Commerce.⁵⁹ There is of course no way to

56. Ibid. Numbers of science and engineering doctoral graduates from China and India who say they intend to stay began to decline after 1996, according to the National Science Foundation. Broad, "U.S. Is Losing Its Dominance in the Sciences."

57. National Intelligence Council, *Growing Global Migration and Its Implications for the United States*, NIE 2001-02D (Washington, D.C.: National Intelligence Council, March 2001), p. 23.

58. Bruce Berkowitz, *The New Face of War: How War Will Be Fought in the 21st Century* (New York: Free Press, 2003), p. 195.

59. Communications satellite technologies were recently removed from Department of Commerce control and placed under more restrictive State Department ITAR control, when it was learned that U.S. companies had been providing sensitive information to China. Eugene B. Skolnikoff, "Re-

keep knowledge of sensitive new technologies locked up forever. Yet when potentially hostile foreign states do occasionally gain access to finished dual-use technologies, the security loss is often contained because the weaponization of these technologies still requires a strong local R&D capability, one that most lagging technology importers—such as China—still do not have.⁶⁰

In the modern age of more collaborative science, even U.S. weapons laboratories have to some extent become globally networked. Roughly 70–75 percent of the research needed to make progress in weapons-related work is still unclassified, and it is often best developed in part through international collaboration. In 1998 America's Los Alamos, Lawrence Livermore, and Sandia Laboratories received 6,398 foreign visitors, including 1,824 visitors from sensitive countries, and the U.S. employees of these labs traveled frequently to scientific conferences and laboratories abroad.⁶¹ Is there a danger in such collaborations that U.S. military R&D discoveries will diffuse internationally? Security precautions notwithstanding, knowledge of U.S. advancements in military R&D will almost surely spread internationally through such linkages, but copying and imitation through espionage will not be enough to bring laggard states all the way up to a full RMA capability.

Copying was at one time a viable option for those trying to catch up with technology leaders. When Britain developed its new super battleship HMS *Dreadnought* in 1906, it took only three years for Germany to build its own Nassau-class copy. A scientifically lagging Soviet Union was able (together with the United States) to borrow and build on German rocketry innovations after World War II, and the initial U.S. lead in atomic weapons that emerged from that same war proved fleeting as well. The first U.S. fission weapon detonation in 1945 was followed by a Soviet detonation only four years later, and the first U.S. fusion weapon detonation in 1952 was followed by a Soviet detonation just ten months later.

Currently, the risk that U.S. rivals will be able to copy and match lead-

search Universities and National Security: Can Traditional Values Survive?" in Teich, Nelson, and Lita, *AAAS Science and Technology Policy Yearbook*, pp. 65–73.

60. Roger Cliff explains: "No matter how advanced the technological level of China's civilian industries or how sophisticated the civilian equipment and components available for import, all Chinese weapon systems ultimately have to incorporate purely military technologies, and these have to be developed indigenously." Cliff, *The Military Potential of China's Commercial Technology*, p. 9.

61. Irving A. Lerch, "Terrorism, Globalization, and Fear: Science in the 21st Century," paper presented at the "International Conference on Science, Technology and Innovation: Emerging International Policy Issues," John F. Kennedy School of Government, Harvard University, September 23–24, 2002.

ing-edge military technology innovations is greatly reduced. First, the very few states that might be able to copy and match U.S. IT-based military innovations are not rivals. In the IT sector, one indicator of absorption capacity is density of internet use, and among the twenty-nine states in the world in 2000 with more than twenty internet hosts per 1,000 people (the United States had nine times that number), all but four were democracies within the OECD, formally or informally aligned with the United States.⁶² The only four states above this threshold level of IT density outside the OECD were Hong Kong, Israel, Singapore, and the United Arab Emirates. Or consider those states that have demonstrated some scientific prowess by patenting inventions in the United States. About 70 percent of these foreign origin patents were granted to inventors from just four countries—France, Germany, Japan, and the United Kingdom, all formal U.S. allies. The two most rapidly growing foreign patent applicant countries are Taiwan and South Korea, two more allied states. Taiwan and South Korea surpassed Canada in 1998 to become the fifth and sixth most-active sources of foreign inventors patenting in the United States.⁶³

Dominant military innovations will also be more difficult for rival states to copy because they are no longer stand-alone pieces of hardware. The RMA depends on entire systems of both hardware and software—sensors, satellites, program codes, and command systems, not just weapons platforms. Moreover, only teams of technically skilled, highly trained, and continuously practiced personnel can operate these networked RMA weapons systems. The superb U.S. all-volunteer military force, built specifically to provide such operating personnel, is a unique human and institutional asset that less capable foreign rivals can neither copy nor steal.

Potential rivals such as China cannot hope to develop an RMA capability through simple transfer, whether by purchase or theft. Through espionage China may have been able to gain information on the W-88 warhead used on U.S. Trident missiles, and China was nearly successful in purchasing from Israel the Phalcon system (which contained modern phased-array technology) before the U.S. government halted this sale in 2000.⁶⁴ Yet even with access to such imported or stolen technology, the Chinese military system will not be able to advance to an RMA capability, given the notorious weakness of the PLA in areas such as command, control, communications, and intelligence.

62. United Nations Development Programme, *Human Development Report, 2001*, p. 60, Table A2.4.

63. National Science Foundation, *Science and Engineering Indicators, 2002*.

64. Fisher, "Military Sales to China."

WEAK K-12 SCIENCE TRAINING?

Another hypothetical threat to U.S. scientific dominance is the continuing underperformance of the primary and secondary (K-12) education system in the United States. America's universities are world leaders in science, but many primary and secondary public schools in the United States have long underperformed in science, technology, engineering, and mathematics (the so-called STEM fields). In 1983 the National Commission on Excellence in Education found the United States lagging behind most other industrialized nations and concluded that the nation's security was consequently at risk: "If an unfriendly foreign power had attempted to impose on America the mediocre educational performance that exists today, we might well have viewed it as an act of war. As it stands, we have allowed this to happen to ourselves. We have even squandered the gains in student achievement made in the wake of the Sputnik challenge. Moreover, we have dismantled essential support systems which helped make those gains possible. We have, in effect, been committing an act of unthinking, unilateral educational disarmament."⁶⁵

U.S. political leaders struggled to respond to this 1983 warning. All states established new content standards in mathematics, and most did so in science as well. Finally in 1990, the president and the state governors adopted the following national goal, "By the year 2000, United States students will be the first in the world in mathematics and science achievement."⁶⁶ Yet this goal was not met. In September 2000, a new National Commission on Mathematics and Science Teaching for the 21st Century, chaired by former Senator John Glenn, reviewed the Third International Mathematics and Science Study and discovered that the performance of U.S. students at the 12th-grade level, relative to peers in other countries, was "disappointingly unchanged." Out of twenty-one countries compared in this study, the United States came in nineteenth. Among twenty nations assessed specifically in advanced math and physics, none scored significantly lower than the United States in advanced math, and only one scored lower in physics. Results from the latest National Assessment of Educational Progress in 2000 were equally dismal, with fewer than one-third of all U.S. students in grades 4, 8, and 12 performing at or above the "proficient" achievement level in math and science, and with more than one-third below

65. National Commission on Excellence on Education, *Nation at Risk* (Washington, D.C.: U.S. Government Printing Office, April 1983), p. 5.

66. Cited in Lynn Arthur Steen, "Math Education at Risk," *Issues in Science and Technology*, Vol. 19, No. 4 (Summer 2003), pp. 79-81, at p. 80.

even the “basic level.”⁶⁷ Since 1975 the United States has fallen from third place to seventeenth place in the proportion of its 18–24 year olds earning science and engineering degrees.

U.S. science has found a way to overcome this domestic educational handicap by importing trained science talent from abroad. In this sense, globalization can be counted as a support for U.S. science hegemony, not a threat to that hegemony. U.S. universities make up for K–12 educational deficits in science and math by attracting well-trained STEM students from abroad, and then by persuading the best of these foreign students to stay. In all the natural sciences and engineering, 35 percent of U.S. Ph.D.’s are now awarded to foreign students. In the physical sciences and engineering specifically, roughly 50 percent of U.S. Ph.D.’s now go to foreign students.⁶⁸ In addition to universities, high-technology U.S. manufacturing firms have also come to rely heavily on foreign-born graduates for a substantial portion of their growing workforce.⁶⁹ Between 1990 and 2000, the foreign-born share of science and engineering doctorates in the U.S. workforce increased from 24 percent to 28 percent. When it comes to science, the United States remains the preeminent land of immigrants. In 1999 all four of the U.S. Nobel Prize winners in physics, chemistry, physiology/medicine, and economics were born outside of the United States.

Roughly one-third of the foreign scientists now working in the United States arrived already fully trained.⁷⁰ When the United States allows graduates from India’s elite institutes of technology to enter with temporary visas, the nation gains access at no charge to a human capital resource that costs the government of India roughly \$15,000–\$20,000 per student to train. By implication, when Congress in 1998 eased the annual quota on H-1B visas, thus facilitating movement into the country for roughly 100,000 of these well-trained Indian professionals, the training cost savings for the United States equaled \$2 billion per year.⁷¹ As long as the United States can continue to attract this trained for-

67. *Before It’s Too Late: A Report to the Nation from the National Commission on Mathematics and Science Teaching for the 21st Century*, <http://www.ed.gov/inits/Math/glenn/report.pdf>.

68. Irving A. Lerch, “Terrorism, Globalization, and Fear: Science in the 21st Century.” See also Duncan T. Moore, “Establishing Federal Priorities in Science and Technology,” in Teich, Nelson, and Lita, *AAAS Science and Technology Policy Yearbook*, pp. 273–283.

69. John A. Armstrong, “The Foreign Student Dilemma,” *Issues in Science and Technology*, Vol. 19, No. 4 (Summer 2003), pp. 22–23.

70. National Science Foundation, *International Mobility of Scientists and Engineers to the United States—Brain Drain or Brain Circulation?*

71. United Nations Development Programme, *Human Development Report, 2001*. According to an estimate by the American Immigration Lawyers’ Association, there are some 900,000 H-1B employees in the United States today, 35 percent to 45 percent of them from India. Cited in Saritha

eign talent, the weakness of its own K–12 science preparation system will not have to undermine U.S. science hegemony overall.

New Risks Post–September 11: Asymmetric Attack?

The September 2001 terrorist attacks and their aftermath highlight several new risks in this regard. The attacks are a vivid reminder that science-based dominance on the conventional battlefield does not protect against unconventional attacks on soft nonbattlefield targets, using fuel-laden hijacked airliners, weaponized anthrax spores, dirty bombs, or worse. As U.S. conventional weapons supremacy grows, those who resent and resist U.S. power may be driven to employ increasingly asymmetric attack responses against ever-softer targets, including homeland targets. There is no way to completely eliminate this asymmetric challenge, but there are ways to contain it.

First, this threat can be addressed through science itself. In 2002 the National Science Foundation initiated a series of new grants designed specifically to counter asymmetric terror threats by supporting breakthroughs in areas such as cybersecurity and the detection and decontamination of biological or chemical warfare agents. The new U.S. Department of Homeland Security is investing more than \$1 billion a year in R&D. Such efforts can and should be expanded, as is noted below.

Policy judgment and restraint are the second key to containing asymmetric threats. Science-based dominance has made the use of conventional force much easier for U.S. officials to contemplate, which brings a danger of more frequent and more careless use of force in circumstances where the conventional military results may be positive, but the political results negative.⁷² If a conventional military “victory” creates new and determined political enemies, one unintended consequence can be an increase in asymmetric threats, either to deployed U.S. forces (as in Iraq), or U.S. citizens and commercial assets abroad, or even to the homeland. More frequent and more aggressive U.S. military actions might also speed the proliferation of nuclear weapons capabilities among states hoping to deter U.S. conventional might. To contain the growth of asymmetric threats, it thus becomes essential to make sound judg-

Rai, “Cap on U.S. Work Visas Puts Companies in India in a Bind,” *New York Times*, October 1, 2003, p. W1.

72. Seyom Brown, *The Illusion of Control: Force and Foreign Policy in the 21st Century* (Washington, D.C.: Brookings, 2003).

ments about the most likely political reactions of conventionally defeated or threatened adversaries. Williamson Murray and Robert Scates argue that the United States needs to make larger investments in political and cultural knowledge, not just scientific knowledge, if it is to wage conventional wars with success.⁷³ Knowing when an exercise of U.S. conventional military dominance will be resented and resisted becomes essential to minimizing a proliferation of asymmetric threats. This calls for more political science, not just more rocket science.

That said, the threat of asymmetric responses would not be any less if the United States were to decide to invest less in science. Thomas Homer-Dixon has argued that scientifically sophisticated systems and societies somehow present softer and more inviting targets to terrorist groups.⁷⁴ This argument is belied, so far, by the actual target choices made by the terrorists themselves: low-technology targets in low-technology societies (embassies or hotels in Africa), or middle-technology targets in low-technology societies (commercial aircraft operating in Africa and U.S. naval ships at anchor in Arabian ports), or at most middle-technology targets in high-technology societies (commercial and government buildings in the United States or commuter trains in Spain). High-technology targets in high-technology societies are apparently not that inviting, even to relatively sophisticated middle-technology terrorist groups such as al-Qa'ida. Even in the face of asymmetric threats, more science usually means more security.

New Risks Post-September 11: Reduced Access to Foreign Scientists

More science will be good for security, but an overzealous pursuit of homeland security now risks a weakening of U.S. science. An excessive tightening of U.S. visa policies post-September 11 is reducing the vital flow of foreign scientists into the United States. Between FY 2001 and FY 2003, successful U.S. visa applications in all categories fell from 10 million down to 6.5 million. The number of temporary worker visas issued specifically for jobs in science and technol-

73. Murray and Scates, *The War in Iraq*, p. 241.

74. According to Homer-Dixon, "Violent groups will soon recognize the rewards from attacking non-redundant, high-value nodes in our increasingly complex technological and economic networks. These attacks will be intended to precipitate cascades of failures or the collapse of whole technological and social systems." See "Synchronous Failure: The Real Danger of the 21st Century," remarks by Thomas Homer-Dixon to the Elliot School of International Affairs, George Washington University, Washington, D.C., March 24, 2004, <http://www.gwu.edu/~newsctr/newscenter/1212/homerdixon.html>.

ogy in the United States dropped more sharply, falling by 55 percent in 2002 alone.⁷⁵ The weaker post–September 11 U.S. economy can be blamed for some of this decline, but not all. Tightened visa procedures are making entry into the United States by foreign scientists significantly more difficult.

Some tightening of U.S. visa and immigration policies was appropriate after September 11, as the Immigration and Naturalization Service (INS) had gone too far in allowing suspect foreign nationals to abuse their visa status. The Palestinian immigrant who drove a truck of explosives into the World Trade Center's underground parking garage in 1993 had come to the United States legally on a student visa in 1989, but then overstayed and was two years "out of status" by the time of the attack. Congress in 1996 passed an Illegal Immigration and Immigrant Responsibility Act designed to police such visa abusers, but the university-based National Association of Foreign Student Advisors prevented effective implementation.⁷⁶ If a stronger student visa monitoring system had been in place in 2001, the September 11 hijackers would have found it more difficult to elude detection. Instead the hijackers remained famously unnoticed by the INS even months after the attack. Exactly six months after the attack, a belated notification was delivered to a flight school in Venice, Florida, granting visa renewal requests for two of the hijackers who died in the attacks.⁷⁷ Following this embarrassment, INS was moved into the new Department of Homeland Security and renamed U.S. Citizenship and Immigration Services in 2003.⁷⁸

Having previously erred on the side of being too lax, U.S. visa authorities are now erring on the side of being too strict. Traditionally, foreign nationals accepted to study science at American universities could expect to receive visas at U.S. embassies by providing only a passport, a university letter of endorse-

75. James Glanz, "Study Warns of Lack of Scientists as Visa Applications Drop," *New York Times*, November 20, 2003, p. A24.

76. Nicholas Confessore, "Borderline Insanity," *Washington Monthly*, May 2002, <http://www.washingtonmonthly.com/features/2001/0205.confessore.html>.

77. See Mark Potter and Rich Phillips, "Six Months after Sept. 11, Hijackers' Visa Approval Letters Received," <http://www.cnn.com/2002/US/03/12/inv.flight.school.visas/>.

78. An urge to tighten this relaxed approach had arisen even prior to September 11, following the 1998 nuclear tests conducted by India and Pakistan and also with the sensational allegations in 1999 (which later proved mostly wrong) that a Taiwanese-born scientist acting out of disloyalty had perpetrated a security breach at Los Alamos National Laboratory. In the aftermath of this Los Alamos panic, the State Department began working more aggressively to screen immigrant visa applications from scientists in particular, using an expanded list of twenty different sensitive disciplines and an equally long list of sensitive countries, including China, Pakistan, Russia, and even South Africa.

ment, and records showing they could afford to live in the United States. Following the September 11 attacks, U.S. consular officers have become subject to criminal penalties if they grant a visa to someone who subsequently commits a terrorist act in the United States, so as a consequence larger numbers of visa requests are either denied or delayed. Foreign scientists were among the first to be squeezed out by such new policies.⁷⁹ In 2002 compared with the year before, the United States gave 8,000 fewer visas to visiting scholars, researchers, teachers, and speakers. Some individuals caught in this squeeze were prominent foreign scholars invited to speak at scientific meetings or teach at American universities. In December 2002 the three presidents of the U.S. National Academies of Sciences, Engineering, and Medicine issued a statement warning that ongoing research collaborations had already been hampered, outstanding foreign scientists had already been prevented from entering the country, and important international conferences were already being canceled or disrupted because of visa delays.⁸⁰ In 2003 a new rule required most visa applicants to undergo in-person interviews with U.S. consular officials overseas, causing still more delays.⁸¹

Valuable science students are being kept out of the United States by these new procedures. According to a spring 2003 report by the American Institute of Physics, numbers of international students entering graduate physics programs dropped by roughly 15 percent after September 11, and a survey of physics department chairs revealed that at the beginning of the 2002 academic year, about 20 percent of international students admitted into graduate physics programs had been unable to start specifically because of visa problems.⁸² All three of the top students (from an applicant pool of 224) accepted by the Biostatistics Department at Johns Hopkins University in 2003 could not start because of visa problems.⁸³ In one case, several hundred outstanding young

79. Dana Wilkie, "Foreign Scientists Steer Away from States," *Scientist*, March 24, 2003.

80. As an example, when the World Space Congress was held in Houston, Texas, in 2002, more than 100 overseas delegates—including an eminent Russian astrophysicist—could not get visas in time and missed the meeting. See "Current Visa Restrictions Interfere with U.S. Science and Engineering Contributions to Important National Needs," statement from Bruce Alberts, president, National Academy of Sciences; William A. Wulf, president, National Academy of Engineering; and Harvey Fineberg, president, National Institute of Medicine, December 13, 2002, <http://www4.nationalacademies.org/news.nsf/isbn/s12132002?OpenDocument>.

81. Marjorie Valbrun, "U.S. Passport Rules Could Hit Allies," *Wall Street Journal*, June 20, 2003, p. 2.

82. John A. Armstrong, "The Foreign Student Dilemma," *Issues in Science and Technology*, Vol. 19, No. 4 (Summer 2003), pp. 22–23.

83. Joseph Joffe, "Locking Out the Brainpower?" *Washington Post*, November 23, 2003, p. B7.

Pakistani students who had been carefully selected by their government as potential future university leaders, and who had been accepted for graduate training in the United States, experienced a 90 percent visa denial rate in the United States post-September 11. These denials are now discouraging new applicants. At 90 percent of American colleges and universities in 2004, applications from international students had fallen, with applications from Chinese and Indian students dropping by 76 percent and 58 percent respectively. Meanwhile in Australia, France, and the United Kingdom enrollments are rising rapidly.⁸⁴

Many visa applicants also experience a kind of virtual denial, due to longer processing delays post-September 11. In the months following the attacks, the number of names on the State Department's antiterrorist lookout list doubled, and consulates were required to run more visa applicant names through Washington's cumbersome interagency clearance system. Thus by the fall of 2002, the State Department had a backlog of 25,000 visa applications that had not been processed.⁸⁵ For science and technology students, the average wait to receive a visa increased to sixty-seven days, and in some cases delays extended up to a full year.⁸⁶ Publicly funded science research in the United States has already been disrupted by these new security measures. At the Fermi National Accelerator Laboratory, a government facility in Illinois that employs 500 scientists from eighteen different countries, those scientists who make routine visits home to see family experience visa troubles that can block their timely return to work. At the National Institutes of Health, where nearly half of the 5,500 staff members with advanced degrees are foreign nationals, employees are being informally warned about the perils of visiting home.⁸⁷

Tighter surveillance and security procedures have also begun to discourage talented foreign scientists from coming to the United States. New federal procedures imposed in May 2002 require universities to monitor the activities of their international students more closely. For international students from countries that the U.S. government considers to be sponsors of terrorism, the National Security Entry and Exit Registration System began to require special procedures such as fingerprinting, photos, and trips to check in at district

84. Robert M. Gates, "International Relations 101," *New York Times*, March 31, 2004, p. A23.

85. Bernard Wysocki Jr., "Foreign Scientists Are Being Stranded by War on Terror," *Wall Street Journal*, January 20, 2003, p. 1.

86. Diana Jean Schemo, "Decline Seen in Science Applications from Overseas," *New York Times*, February 26, 2004, p. A16.

87. Wysocki, "Foreign Scientists are Being Stranded by War on Terror."

offices.⁸⁸ In May 2003 the Homeland Security Department announced as well a requirement for “biometric” screening at U.S. borders (using photos and fingerprints) for an estimated 23 million foreign nationals entering the country every year, many of them science students or researchers. This new “Fortress America” approach to homeland security puts important social and cultural values at risk. It is also demonstrably bad for the competitive health of U.S. science, and hence for U.S. military primacy in the long run. The homeland may be slightly more secure in the short run because of these new procedures, but the long-term health of U.S. science is being impaired. David Heyman, director of the Homeland Security Program at the Center for Strategic and International Studies, warned in April 2004 that “to win the war on terror, we [the United States] may lose our scientific preeminence.”⁸⁹

Conclusion: Smart Weapons, and Policies, against Asymmetric Threats

Military primacy today rests on scientific primacy, and the scientific primacy of the United States rests on a remarkably durable foundation. Rather than threatening U.S. primacy in science, globalization has strengthened it. Yet science-based military primacy on the battlefield is clearly not a guarantee of security. Determined adversaries can innovate increasingly asymmetric tactics against an endless list of soft targets, and the more domination and resentment they feel under U.S. conventional military hegemony, the more incentive they will have to move toward these unconventional responses. Conventional victories that make new enemies may encourage a dangerous shift toward asymmetry, and if the United States then responds by indiscriminately denying foreigners access to the homeland, U.S. primacy in science could itself be critically weakened.

The war against international terror should be fought with science, rather than at the expense of science. The homeland security strategy of the United States should include much larger science investments in disciplines such as chemistry, physics, biotechnology, nanotechnology, and information technology, where promising new counterterror applications are sure to be found. Smart societies can develop not only smart new weapons for conventional use abroad, but also smart new capabilities for threat detection and soft target pro-

88. Wilkie, “Foreign Scientists Steer Away from States.”

89. Quoted in Eugene Russo, “U.S. Security Bad for Science?” *Scientist*, April 26, 2004, p. 1.

tection at home. For example, nanofabrication may hold the key to a timely detection system for some terror bombing threats. Silicon polymer nanowires 2,000 times thinner than a human hair can cheaply detect traces of TNT and picric acid in both water and air, and might someday be developed and deployed into “smart” cargo containers, to protect against terrorist bombs. New information technologies using powerhouse terascale computing capabilities may soon be able to help in tracking and anticipating the behavior of terror networks.⁹⁰ New systems capable of detecting dangerous amounts of radiation are increasingly affordable and unobtrusive, and the Department of Homeland Security has proposed development of a fully networked national sensor system to monitor the air continuously for pathogens, dangerous chemicals, and other public hazards. One line of defense already in place in thirty cities is a Lawrence Livermore National Laboratory–designed system for monitoring the air for biological attack.

Federal investments are already moving the United States down this smart science-based response path. In the Bush administration’s FY 2005 budget, roughly \$7 billion was proposed to develop high-technology defenses against terror attacks, including \$3.5 billion specifically for research and development. For example, the Department of Energy will receive \$232 million for research on the detection of nuclear weapons production. Penrose Albright, assistant secretary for science and technology at the Department of Homeland Security, defends this approach by arguing that “science is the big advantage the West has over these people who would throw us back to the Stone Age.”⁹¹

Science can indeed bring big security gains in asymmetric as well as in conventional military affairs. Yet protection of national security requires that all military advantages be used with judgment and care. Security requires smart policies as well as smart weapons. When conventional military victories are made easy by smart weapons, an extra measure of caution is needed to avoid the careless creation of dangerous new asymmetric adversaries.

90. Rita R. Colwell, director, National Science Foundation, remarks to Council of Scientific Society Presidents, Washington, D.C., November 19, 2001.

91. Quoted in Ralph Vartabedian, “U.S. Funnels Billions to Science to Defend against Terrorism,” *Los Angeles Times*, March 7, 2004, <http://www.latimes.com/news/nationworld/nation/la-na-homeland7mar07,0,2406782.story?coll=la-headlines-nation>.