TECHNICAL
REPORT

The Global Technology Revolution 2020, In-Depth Analyses

Bio/Nano/Materials/Information Trends, Drivers, Barriers, and Social Implications

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with

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Preface

Various technologies—including biotechnology, nanotechnology (broadly defined), materials technology, and information technology—have the potential for significant and dominant global impacts by 2020. This report is based on a set of foresights (not predictions or forecasts)[1] into global technology trends in the abovementioned areas and their implications for the world in the year 2020. These foresights were complemented by analysis of data on current and projected S&T capabilities, drivers, and barriers in countries across the globe.

This work was sponsored by the National Intelligence Council (NIC) to inform its publication of *Mapping the Global Future: Report of the National Intelligence Council's 2020 Project Based on Consultations with Nongovernmental Experts Around the World*, December 2004. In addition, funding was provided by the Intelligence Technology Innovation Center (ITIC) and the Department of Energy. It is a follow-on report to RAND MR-1307-NIC, *The Global Technology Revolution* (2001), which was sponsored by the NIC to inform its 2000 document, *Global Trends 2015*. *Global Trends 2015* and the 1996 NIC document *Global Trends 2010* identified key factors that appeared poised to shape the world by 2015 and 2010, respectively.

This report should be of interest to policymakers, intelligence community analysts, technology developers, the public at large, and regional experts interested in potential global technology trends and their broader social effects.

This project was conducted jointly in the Intelligence Policy Center and the Acquisition and Technology Policy Center of the RAND National Security Research Division (NSRD). For further information regarding this report, contact its authors or the Intelligence Policy Center Director, John Parachini. NSRD conducts research and analysis for the Office of the Secretary of Defense, the Joint Staff, the Unified Combatant Commands, the Department of the Navy, the Marine Corps, the defense agencies, and the Defense Intelligence Community, allied foreign governments, and foundations. NSRD is a division of RAND, a non-profit corporation chartered in the public interest to conduct policy analysis (see www.rand.org/NSRD/).

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[1] A foresight activity examines trends and indicators of possible future developments without predicting or describing a single state or timeline and is thus distinct from a forecast or scenario development activity (Salo and Cuhls, 2003; Martin and Irvine, 1989; Larson, 1999; Coates, 1985).

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Foreword

The National Intelligence Council (NIC) sponsored this study by The RAND Corporation to inform the NIC's 2020 project[2] and help provide US policymakers with a view of how world developments could evolve, identifying opportunities and potentially negative developments that might warrant policy action. From June 2004 through August 2005, RAND undertook the challenging task of identifying technologies and applications that have the potential for significant and dominant global impacts by 2020.

As RAND found in its prior study for the NIC, *The Global Technology Revolution* (2001), technology will continue to accelerate and integrate developments from multiple scientific disciplines in a "convergence" that will have profound effects on society. RAND's new study, however, has delved further into social impacts and concluded that:

- Regional and country-specific differences in social need and S&T capabilities are resulting in differences in how technology is revolutionizing human affairs around the world,
- Regional differences in public opinion and issues may strongly influence technology implementation,
- Maintaining S&T capacity requires consideration and action across a large number of social capabilities and stability dimensions,
- Capacity building is an essential component of development, and
- Public policy issues relating to some technology applications will engender strong public debate.

The implications of these findings are important to US policymakers. For example, while the United States remains a leader in S&T capability and innovation, it is not the sole leader and thus will not always dominate every technical area. Also, many technologies will evolve globally in ways that differ from their evolution in the United States, so we cannot merely apply a US view as a cookie cutter to understanding how technology will change the world. In addition, US understanding of potential technological threats from foreign powers requires a broad understanding not just of S&T skills and capabilities but also the institutional, human, and physical capacity to exploit technological opportunities. Finally, innovative combinations of new and existing technologies can help to meet region-specific needs despite their lack of use in the US sector.

[2] See www.cia.gov/nic/NIC_2020_project.html for further information on the NIC 2020 Project and its final report, *Mapping the Global Future*.

I commend this report to you as a resource for understanding how S&T and social issues interact and depend not only on technological advances but also on the broader capabilities of countries that seek development and economic rewards through S&T exploitation. As important as S&T is today to the United States and the world, it will become even more important in the future.

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Summary

We live in an era of increasing use of diverse technologies in all aspects of life, from ingestible radio transmitters and fluorescent quantum dots for medical diagnosis and treatment, to multifunctional cell phones that take digital photographs and receive and transmit electronic mail. In a previous study,[3] we concluded that the world is undergoing a global technology revolution that is integrating developments in biotechnology, nanotechnology, materials technology, and information technology at an accelerating pace. Based on several parallel analyses of the state of globally important technology trends and how they are being constructed into specific applications (reviewed in Appendices A through F), we conclude in this report that the technology of 2020 will continue to integrate developments from multiple scientific disciplines in a "convergence" that will have profound effects on society. Examples of some of the integrated technology applications (TAs) that may be feasible by 2020 include:

- Personalized medicine and therapies
- Genetic modification of insects to control pests and disease vectors
- Computational (or "in-silico") drug discovery and testing
- Targeted drug delivery through molecular recognition
- Biomimetic and function-restoring implants
- Rapid bioassays using bionanotechnologies
- Embedded sensors and computational devices in commercial goods
- Nanostructured materials with enhanced properties
- Small and efficient portable power systems
- Mass-producible organic electronics, including solar cells
- Smart fabrics and textiles
- Pervasive undetectable cameras and sophisticated sensor networks
- Large, searchable databases containing detailed personal and medical data
- Radio frequency identification (RFID) tracking of commercial products and individuals
- Widespread bundled information and communications technologies, including wireless Internet connectivity
- Quantum-based cryptographic systems for secure information transfer.

Technology Applications and Their Impact on Society

To evaluate the potential impact of TAs on society, we defined (see Table 2.2 in Chapter Two) a rough net assessment index composed of the sum of the number of societal sectors[4] that the TA could affect and measures of technical feasibility, implementation

[3] Philip S. Antón, Richard Silberglitt, and James Schneider, *The Global Technology Revolution: Bio/Nano/Materials Trends and Their Synergies with Information Technology by 2015*, Santa Monica, Calif.: RAND Corporation, MR-1307-NIC, 2001.

[4] Including water, food, land, population, governance, social structure, energy, health, economic development, education, defense/conflict, and environment/pollution.

feasibility, and global diffusion. While this rough net assessment index does not measure the magnitude of impact on specific sectors, it does highlight feasible TAs with multi-sectoral impact and global reach. Of the 56 TAs that emerged in our review and analysis of the technical foresights described in the appendices, the following "top 16," based on this net assessment index, formed a representative group that allowed evaluation of worldwide variation in technology implementation and its relevance to significant societal problems and issues.[5]

1. Cheap solar energy
2. Rural wireless communications
3. Communication devices for ubiquitous information access anywhere, anytime
4. Genetically modified (GM) crops
5. Rapid bioassays
6. Filters and catalysts for water purification and decontamination;
7. Targeted drug delivery
8. Cheap autonomous housing
9. Green manufacturing
10. Ubiquitous RFID tagging of commercial products and individuals
11. Hybrid vehicles
12. Pervasive sensors
13. Tissue engineering
14. Improved diagnostic and surgical methods
15. Wearable computers
16. Quantum cryptography

The TAs we identified vary significantly in assessed technical feasibility and implementation feasibility by 2020. Table S.1 shows the range of this variation on a matrix of 2020 technical feasibility versus 2020 implementation feasibility for all 56 TAs. Technical feasibility is defined as the likelihood that the application is available for commercialization by 2020, which is based principally on the technical foresight papers in Appendices A through F. Implementation feasibility is the net of all nontechnical barriers and enablers, such as market demand, cost, infrastructure, policies, and regulations.[6] We based its assessment upon rough qualitative estimates of the size of the market for the application in 2020 and whether it raises significant public policy issues. In parentheses are the number of sectors that the technology can influence, and the designation *G* (for *global)* or *M* (for *moderated*) indicates our estimate (based on both the technical foresights and our discussions with regional experts at the RAND Corporation) of whether the application will be diffused globally in 2020 or will be moderated in its diffusion (i.e., restricted by market, business sector, country, or region).

[5] Including promoting rural economic development, promoting economic growth and international commerce, improving public health, improving individual health, reducing resource use and improving environmental conditions, strengthening the military and warfighters of the future, strengthening homeland security and public safety, and influencing governance and social structure.

[6] See additional discussions on the effects of markets and public policy issues on technology development in Anderson et al. (2000) and Hundley et al. (2003).

Table S.1
Technical and Implementation Feasibility of Illustrative 2020 Technology Applications

Technical Feasibility	Implementation Feasibility: Niche market only (– –)	May satisfy a need for a medium or large market, but raises significant public policy issues (–)	Satisfies a strong need for a medium market and raises no significant public policy issues (+)	Satisfies a strong need for a large market and raises no significant public policy issues (+ +)
Highly Feasible (+ +)	• CBRN Sensors on ERT (2,G)	• Genetic Screening (2,G) • GM Crops (8,M) • Pervasive Sensors (4,G)	• Targeted Drug Delivery (5,M) • Ubiquitous Information Access (6,M) • Ubiquitous RFID Tagging (4,G)	• Hybrid Vehicles (2,G) • Internet [for purposes of comparison] (7,G) • Rapid Bioassays (4,G) • Rural Wireless Comms (7,G)
Feasible (+)	• GM Animals for R&D (2,M) • Unconventional Transport (5,M)	• Implants for Tracking and ID (3,M) • Xenotransplantation (1,M)	• Cheap Solar Energy (10,M) • Drug Development from Screening (2,M) • Filters and Catalysts (7,M) • Green Manufacturing (6,M) • Monitoring and Control for Disease Management (2,M) • Smart Systems (1,M) • Tissue Engineering (4,M)	• Improved Diagnostic and Surgical Methods (2,G) • Quantum Cryptography (2,G)
Uncertain (U)	• Commercial UAVs (6,M) • High-Tech Terrorism (3,M) • Military Nanotechnologies (2,G) • Military Robotics (2,G)	• Biometrics as sole ID (3,M) • CBRN Sensor Network in Cities (4,M) • Gene Therapy (2,G) • GM Insects (5,M) • Hospital Robotics (2,M) • Secure Video Monitoring (3,M) • Therapies based on Stem Cell R&D (5,M)	• Enhanced Medical Recovery (3,M) • Immunotherapy (2,M) • Improved Treatments from Data Analysis (2,M) • Smart Textiles (4,M) • Wearable Computers (5,M)	• Electronic Transactions (2,G) • Hands-free Computer Interface (2,G) • *In-silico* drug R&D (2,G) • Resistant Textiles (2,G) • Secure Data Transfer (2,M)
Unlikely (–)	• Memory-Enhancing Drugs (3,M) • Robotic Scientist (1,M) • Super Soldiers (2,M)	• Chip Implants for Brain (4,M)	• Drugs Tailored to Genetics (2,M)	• Cheap Autonomous Housing (6,G) • Print-to-Order-Books (2,G)
Highly Unlikely (– –)	• Proxy-bot (3,M) • Quantum Computers (3,M)	• Genetic Selection of Offspring (2,M)	• Artificial Muscles and Tissue (2,M)	• Hydrogen Vehicles (2,G)

NOTE: For each technology, the parenthetical information indicates the number out of 12 societal sectors (water, food, land, population, governance, social structure, energy, health, economic development, education, defense and conflict, and environment and pollution) that can be impacted by the technology, and if the diffusion will be *global* (G) or *moderated* (M). For example, Hybrid vehicles affect two sectors and will have global diffusion.

Regional and International Effects

We consulted experts within and outside RAND for their assessment of the impact of TAs in different regions of the world. The important problems and issues and relevant TAs in each region of the world are briefly discussed in Chapter Three. Motivated by the extent of regional variation, as well as significant differences between countries within regions, we identified 29 representative countries that allowed analysis of international variations in TAs and implementation across the globe. These countries were selected to reflect diversity in physical size, natural conditions, and location (e.g., large versus small, tropical versus temperate, land-locked versus island); population size and demographics (e.g., high birth rate versus low birth rate, rapidly aging versus youthful); level of economic development and types of economy (e.g., developed versus developing, market capitalist versus controlled economy); types of government (e.g., competitive liberal democracies versus authoritarian regimes); and science and technology (S&T) capacity levels (e.g., scientifically advanced versus scientifically lagging). While these criteria are not independent of each other, together they represent the principal geographical, social, economic, political, and scientific characteristics of international variation.

Within each region of the world, we identified several candidate countries. We then reviewed this initial country list to eliminate highly similar countries within a region. Countries across regions were then compared with each other to remove those that might be represented by others.

Capacity to acquire a TA does not necessarily equal capacity to implement, because the latter requires a threshold level of physical, human, and institutional capacity; financial resources; and the social, political, and sometimes even cultural environment necessary to maintain and sustain widespread use of the TA. Accordingly, we analyzed the drivers for and barriers to technology implementation in each of the 29 representative countries.

Figure S.1 shows the specific top 16 TAs that these selected countries have the capacity to acquire, as well as the drivers for, and barriers to, technology implementation that are present in each country.

Countries in blue boxes (and identified by dots in the country line icon) are economically and scientifically advanced and have the capacity to acquire 14 to 16 TAs. Countries in green boxes (with triangles in country line icons) have the capacity to acquire 10 to 12 TAs. Countries in yellow boxes (with diamonds in country line icons) have the capacity to acquire six to nine TAs. And countries in red boxes (with squares in country line icons) have the capacity to acquire one to five technology applications.

Through the 29 representative countries, Figure S.1 illustrates regional variations in capacity to acquire TAs. The most economically advanced and scientifically developed countries (shown in blue with a circle icon) represent North America, Western Europe, Australia, and the developed economies of East Asia (e.g., Japan and South Korea). Most of the rest of Asia and Eastern Europe are represented by the next level of capacity to acquire TAs (shown in green with a triangle icon). Latin America, parts of Southeast Asia, Turkey, and South Africa represent a lower level of capacity to acquire TAs (shown in yellow with a diamond icon). Finally, the countries with the least capacity to acquire TAs—most of Africa and the Middle East, as well as the Caribbean and Pacific Island countries—are represented by the countries shown in red with a square icon. Although our 29 selected countries have exceptions—for example, Georgia and Nepal (“red” countries in a “green” region) and Israel (“blue” country in a “red” region)—Figure S.1 provides a useful overall representation of regional variations across the globe of the capacity to acquire TAs.

Our assignments of drivers and barriers—based on the same data used to determine country capacity to acquire technologies, plus applied expert judgment on political, economic, and social conditions in these selected countries—indicate that countries most capable of acquiring TAs (the economically and scientifically advanced countries in the blue group) have the highest number of drivers and simultaneously the lowest number of barriers. By comparison, all selected countries in the green, yellow, and red groups have fewer drivers for, and face many more barriers to, technology implementation.

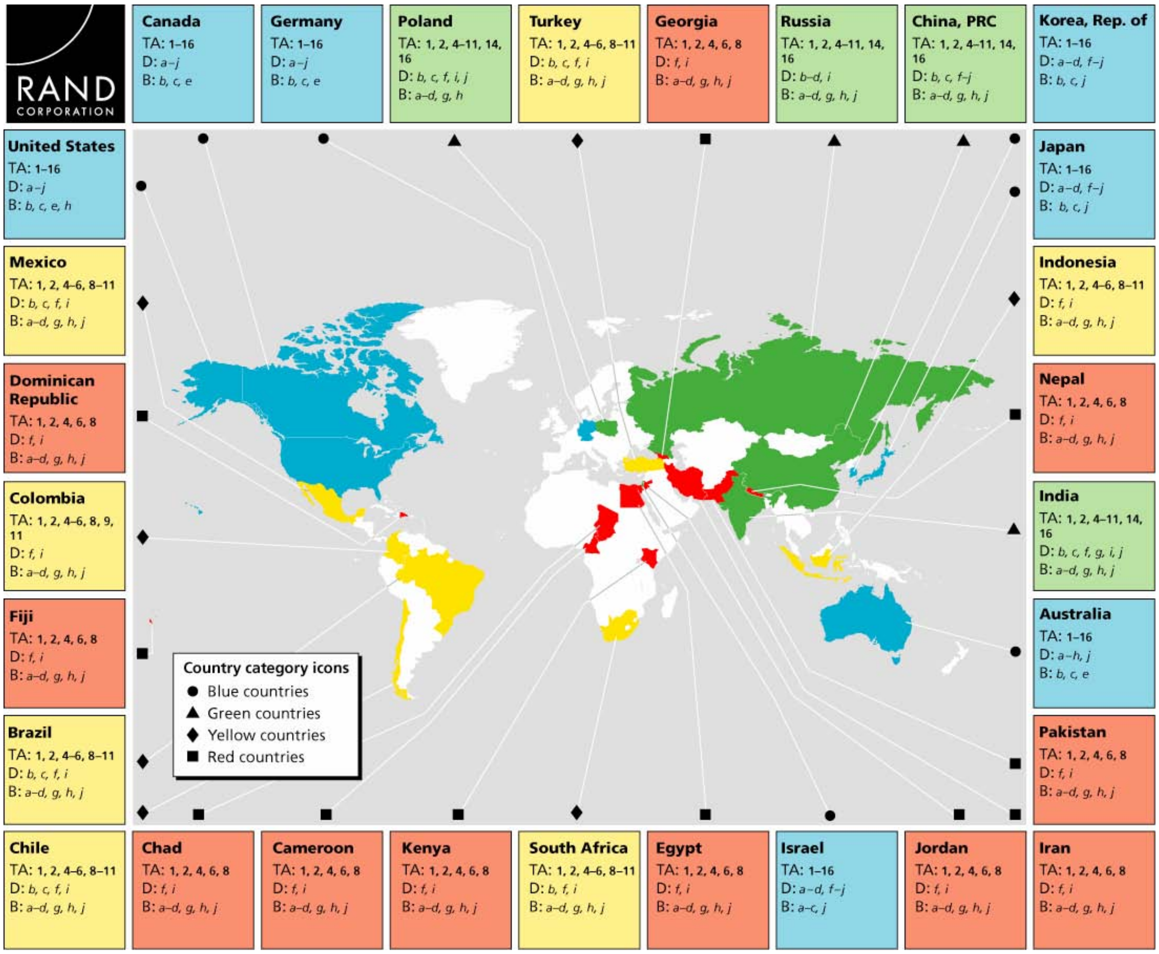
We used these data to analyze each country’s capacity to implement TAs, taking into account: (1) capacity to acquire, defined as the percentage of “top 16” TAs listed for that country in Figure S.1, (2) the percentage of the ten drivers for implementation applicable to that country, and (3) the percentage of the ten barriers to implementation applicable to that country.[7]

Figure S.2 shows the position of each of the 29 representative countries on a plot for which the y-axis is the product of factors (1) and (2),[8] and the x-axis is factor (3). Both axes are shown as percentages, with the y-axis starting at zero (i.e., no capacity to acquire TAs or drivers) and ending at 100 (i.e., capacity to acquire all 16 TAs and all 10 drivers are applicable), and the x-axis starting at 100 (i.e., all 10 barriers are applicable) and ending at zero (i.e., no barriers are applicable). Countries are represented in Figure S.2 by the colors and icons established for them in Figure S.1. We note that Figure S.2 provides a first-order assessment of the capacity to implement TAs, in that we applied equal weighting to all TAs, drivers, and barriers, although we recognize that specific TAs, drivers, and barriers might be more significant in particular countries.

[7] A detailed analysis of where on each driver-barrier continuum particular countries fall was beyond the scope of this study. However, we did identify which drivers and barriers are present in specific countries, so that the percentage of drivers and the percentage of barriers that apply are the appropriate quantitative metrics for a country at this level of analysis.

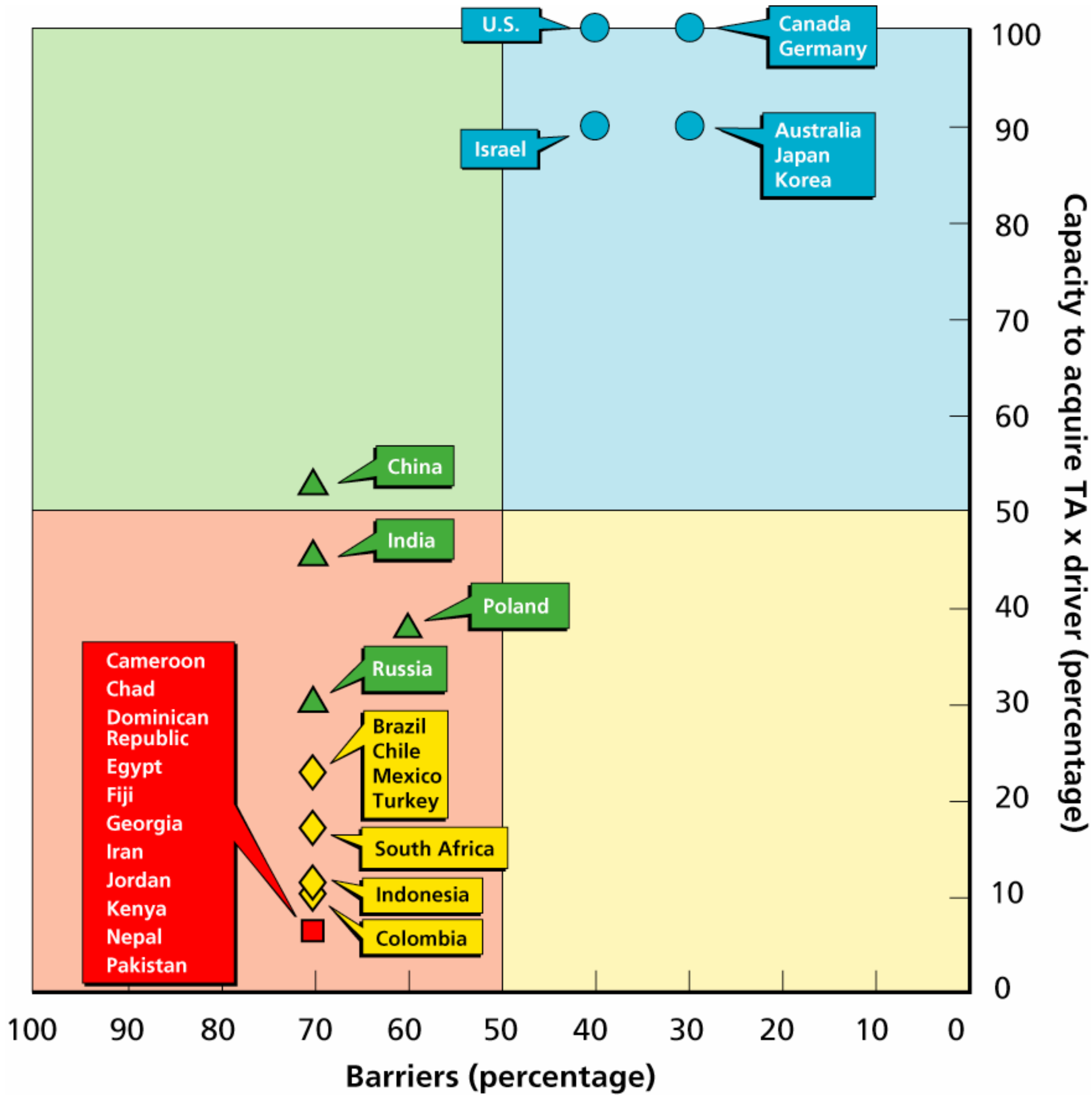
[8] That is, the capacity to acquire scaled by the percentage of drivers. Multiplying capacity to acquire by the percentage of drivers is consistent with the view that the absence of drivers reduces the probability that the TAs a country can acquire will be implemented.

Figure S.1
Selected Countries' Capacity to *Acquire* the Top 16 Technology Applications



NOTE: Countries were selected as representative of groups of similar nations in a single geographical area. Countries are color coded by their S&T capacity: scientifically advanced (blue), scientifically proficient (green), scientifically developing (yellow), and scientifically lagging (red). TA numbers are according to the list presented in text above. D signifies driver and B barrier, and *a* through *j* identify drivers and barriers according to the following: (*a*) cost/financing; (*b*) laws/policies; (*c*) social values, public opinions, politics; (*d*) infrastructure; (*e*) privacy concerns; (*f*) resource use and environmental health; (*g*) investment in research and development; (*h*) education and literacy; (*i*) population and demographics; (*j*) governance and stability.

Figure S.2
Selected Countries' Capacity to *Implement* the Top 16 Technology Applications



The upper right-hand quadrant of Figure S.2 (shaded in blue) represents countries for which implementation of TAs is strongly driven by a high level of S&T capacity and the presence of many drivers but few barriers. The upper left-hand quadrant (shaded in green) represents countries for which implementation of TAs is strongly driven by a high level of S&T capacity and the presence of many drivers but for which many barriers are simultaneously present. The lower right-hand quadrant (shaded in yellow) represents countries for which implementation of TAs is not supported by a high level of S&T capacity and for which the number of both drivers and barriers is small. The lower left-hand quadrant (shaded in red) represents countries for which implementation of TAs is not supported by a high level of S&T capacity and for which the number of barriers exceeds the number of drivers.

This approach is consistent with current research in international development that shows that multiple factors must be present to enable sustainable economic growth and development (e.g., infrastructure, good governance, healthy population, literacy, political stability, sound banking and financial structure, dynamic innovation system).[9]

Figure S.2 indicates that the blue countries of Figure S.1 are most capable of implementing the TAs that they have the capacity to acquire. By comparison, the red countries of Figure S.1 have the least capacity to implement TAs that they have the capacity to acquire. It is interesting to note that the green and yellow countries of Figure S.1, except for China, appear in the lower left-hand (red) quadrant in Figure S.2. Having a smaller "tool kit" of technology applications than the blue countries, and possessing fewer drivers and more barriers, means that these green and yellow countries encounter greater challenges in attempting to implement TAs beyond laboratory research, demonstrations, or limited diffusion. We also note that no country appears in the lower right-hand (yellow) quadrant. This reflects the fact that reducing most of the barriers listed above requires developing drivers as well as S&T capacity.

For the most economically and scientifically advanced countries, our assessment indicates a strong capacity to acquire and implement the full range of technology applications to address a diversity of problems and issues. For the less economically and scientifically advanced nations, however, we observed substantial disparities between their capacity to acquire and implement TAs. For example, China, India, Poland, Brazil, and Chile are growing economically and scientifically. Increasing S&T capacity and growth in their institutional, human, and physical capacities will help to narrow the gap in technology implementation between them and the scientifically advanced countries. However, for those countries that have less dynamic economies and less scientific growth, and also suffer from political and social instability, implementation of technology applications will be very difficult, even when they have the capacity to acquire the relevant technology applications.

There is a group of problems and issues for which all countries show promising capacity to implement relevant TAs. For these problem areas—promoting rural economic development, improving public health, and reducing resource use and improving environmental health—the scientifically proficient green countries, China and India, have moved squarely into the upper half of quadrant charts similar to Figure S.2, with Poland not far behind. Moreover, several of the scientifically developing yellow countries show increased capacity—most notably Brazil, Chile, Mexico, and Turkey—which move up to occupy the same position as the scientifically proficient green country—Russia. Also, South Africa rises above the position occupied in Figure S.2 by Brazil, Chile, Mexico, and Turkey.

Therefore, the global technology revolution can be a major factor in addressing global issues of rural economic development, public and environmental health, and resource use. However, the barriers discussed above must be addressed, and these are most challenging for the scientifically lagging (red) countries, which have the greatest needs.

The overall capacity to implement technology applications, as indicated by Figure S.2, illustrates the following widely recognized trends:

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[9] See Kaufman and Kray (2003).

- The technological preeminence of the scientifically advanced countries of North America, Western Europe, and Asia
- The emergence of China and India as rising technological powers, with the scientifically proficient countries of Eastern Europe, as represented by Poland, not far behind
- The wide variation in technological capability among the scientifically developing countries of Southeast Asia and Latin America
- The large scientific and technological gap between most of the countries of Africa, the Middle East, and Oceania and the rest of the world.[10]

The capacity to implement the TAs relevant to strengthening homeland security, public safety, and the military and warfighters of the future does not differ greatly from overall capacity for technology implementation. This observation implies that the global technology revolution is likely to support the emergence of China and India as military, as well as economic, powers.

For the remaining problem areas—promotion of economic growth and international commerce and influencing governance and social structure—all countries (except the most scientifically advanced) show less capacity to implement relevant TAs than their overall technology implementation capacity. This reflects the fact that TAs such as ubiquitous information access, pervasive sensors, tissue engineering, and wearable computers, which require a high level of infrastructure and institutional, physical, and human capacity, are unlikely to be widely adopted outside the most scientifically advanced countries. Thus, the greatest economic benefits stemming from such advanced technologies will likely be gained by these countries, although countries such as China and India may benefit via increased opportunities for manufacturing and services, respectively. As China and India improve their drivers, however, they will begin to reap the benefits seen by the scientifically advanced countries.

With respect to the influence of technology applications on governance and social structure, it appears that the combination of many barriers, few drivers, and capacity to acquire only a small number of the relevant TAs will moderate the impact of the global technology revolution in most of the developing world. However, individual TAs, such as cheap solar energy, rural wireless communications, and cheap autonomous housing, could have significant impact—for example, by simplifying household tasks and providing a gateway to the outside world, thus empowering women and changing their role in society—by providing opportunities for education and commerce in poor rural areas and by strengthening the hand of civil society groups and the general public in influencing government decisions and actions.

We note that our analysis provides an assessment of the average capacity of each country to implement the full range of TAs relevant to each problem and issue. This represents a floor on which individual countries will have the ability to focus their capacity development to create spikes in their capacity to acquire and implement TAs relevant to specific problems and issues of national priority. Countries with a greater

[10] Notable exceptions to these regional trends among our selected countries are Israel, Turkey, and South Africa.

level of S&T capacity (countries in the green group and those leading the yellow group) will have the best opportunity to use their developing institutional, human, and physical capacity to exceed their assessed capacity to implement technology applications in selected areas, both civilian and military.

Conclusions

We draw the following conclusions from the data and analysis presented in this report.

Accelerated Technology Development Will Continue

Based on our technical foresights (e.g., see Appendices A through F and related references), we see no indication that the accelerated pace of technology development is abating, and neither is the trend toward multidisciplinarity nor the increasingly integrated nature of technology applications. Indeed, most of the top 16 TAs involve at least three of the technology areas addressed in this study, and many involve all four. Underlying all of this is the continuing trend toward globally integrated publications media, Internet connectivity, and scientific conferences, as well as the development and cross-fertilization of ever more sensitive and selective instrumentation.

Capability and Need Differences Are Driving Global Technology Revolution Differences Around the World

Because of vast differences in countries' S&T capacity, as well as their institutional, human, and physical capacity required to develop drivers for, and overcome barriers to, implementing technology applications, the impact of the global technology revolution will show substantial regional and international variation. In addition, regional differences in needs will affect the market pull on technology applications.

The scientifically advanced countries of North America, Western Europe, and Asia (including Australia) are likely to gain the most, because they have the capacity to acquire and implement all of the top 16 TAs, as well as all those relevant to important problems and issues.

If they can address the multiple barriers to technology implementation (laws, policies, infrastructure, investment in research and development [R&D], education and literacy, and last but not least, governance and stability), emerging economies such as China and India in Asia and Brazil and Chile in Latin America will be able to use TAs to support continued economic growth and human development for their populations. China and India are emerging technological powers with the best opportunity to begin to approach the ability of the scientifically advanced countries to use technology applications to achieve national goals. Eastern Europe (represented in our analysis by Poland), as a region, appears to be poised next in line behind China and India. Russia's capacity to implement TAs appears to be deteriorating, and the most advanced of the scientifically developing countries (represented in our analysis by Brazil, Chile, Mexico, and Turkey) appear to be almost overtaking this former superpower.

The scientifically lagging developing countries, because of the severity of such problems as disease, lack of clean water and sanitation, environmental degradation, and the lack of resources to address these problems, have the most to gain from implementing the 2020 TAs. However, this implementation will require substantial building of institutional, physical, and human capacity, which will no doubt be assisted by the efforts and sponsorship of international aid agencies and rich countries. But a necessary and enabling requirement will be improved governance and country stability.

Public Policy Issues May Strongly Influence Technology Implementation

The nature of a technology application can determine the politics that surround it. Many of the most controversial TAs involve biotechnology—for example, GM crops, GM insects, genetic screening, gene therapy, and genetic selection of offspring. Other TAs spark heated debate because of their potential implications for personal privacy and freedom. These include pervasive sensors, certain uses of RFID implants for tracking and identification of people, chip implants for the brain, and biometrics as sole personal identification. Genetic screening is a biotechnology application that also raises privacy concerns. For example, would individuals with certain genetic characteristics and established links to certain types of disease and illness be denied health insurance or jobs, or face other forms of discrimination?

Maintaining Science and Technology Capacity Requires Consideration and Action

Because of the accelerating pace of technology development and the rapid improvement of capacity to acquire and implement TAs in emerging economies, maintaining country position in relative capacity to implement TAs will require continuing efforts to ensure that, for example, laws, public opinion, investment in R&D, and education and literacy are drivers for, and not barriers to, technology implementation. In addition, infrastructure needed for desired TAs must be built, supported, and maintained. This, of course, is not a blanket advocacy for all TAs. Some ethical, safety, and public concerns require careful analysis and consideration. Just because we can do something does not always mean that we should.

Capacity Building Is an Essential Component of Development

The implementation of TAs to address the problems and issues that developing countries face is not primarily about technology, or even S&T capacity. The greater challenge is the development of institutional, human, and physical capacity, including effective and honest governance. Development is the consequence of improvements in such areas as economic growth, social equity, health and the environment, public safety and security, and good governance and stability. Thus, those countries that have the best performance in these indicators of development have the strongest institutional, human, and physical capacity to implement technology applications. Comparison of data in Appendix H on S&T capacity with data in Appendix J on human development shows that the scientifically advanced countries also rank highest on the Human Development Index. This suggests that less-developed countries hoping to benefit from implementation of TAs will have to improve their performance in many of the development indicators shown in Appendix J in order to build the requisite institutional, human, and physical capacity.

Public Policy Issues Relating to Technology Applications Will Engender Strong Public Debate

Some important TAs raise significant public policy issues that engender strong and sometimes conflicting reactions and opinions within and between countries, regions, and various ethnic, religious, cultural, and other interest groups. When raised, public policy issues need to be resolved if the full benefits of a TA are to be realized. These issues need to be debated in an environment that seeks to resolve conflicts. Such public debates, in addition to being based on sound data, need to be inclusive and sensitive to the country's traditions, values, and cultures. In some cases, issues will remain and will moderate or even halt technology implementation—sometimes for good reasons (e.g., when safety concerns cannot be adequately addressed) and at other times simply because collective decisionmaking will decide what a particular society wants and does not want. Market forces will also moderate and vector the course of the global technology revolution, its technology applications, and their implementation. Predicting the net effect of these forces is literally predicting the future—wrought with all the difficulties of future predictions. However, these technology trends and applications have substantial momentum behind them and will be the focus of continued R&D, consideration, market forces, and debate. Many of these technologies will be applied in some guise or other, and the effects will be significant and astonishing, changing lives across the globe.

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Glossary

AIDS	acquired immune deficiency syndrome
Barrier	Obstacle to technology implementation
CARTA	capacity to acquire relevant technology applications
CBRN	chemical, biological, radiological, or nuclear
CMOS	complementary metal-oxide semiconductor
CPI	Corruption Perception Index
DNA	deoxyribonucleic acid
DRAM	dynamic random access memory
Driver	Facilitator of technology implementation
EU	European Union
FDA	Food and Drug Administration
FET	field-effect transistor
Foresight	Examination of trends, breakthroughs, and indicators of possible future developments based on sound research progress today, without predicting a single future state or timeline
GDP	gross domestic product
GM	genetically modified
GMO	genetically modified organism
GNP	gross national product
GPS	Global Positioning System
GTR2015	*The Global Technology Revolution: Bio/Nano/Materials Trends and Their Synergies with Information Technology by 2015*, RAND MR-1307-NIC (2001)
HDI	Human Development Index (United Nations)
HIV	human immunodeficiency virus
ID	Identification
IEEE	Institute of Electrical and Electronics Engineers
Implementation feasibility	Likelihood that a technology application will be implemented
in situ	Experiment performed in a natural or original environment

in vitro	Experiment performed outside of a living organism
in vivo	Experiment performed inside a living organism
IT	information technology
IVF	in vitro fertilization
MEMS	microelectromechanical systems
NATO	North Atlantic Treaty Organisation
NEMS	nanoelectromechanical systems
NIC	National Intelligence Council
PDA	personal digital assistant
PIRA	Provisional Irish Republican Army
R&D	research and development
RFID	radio frequency identification
RNA	ribonucleic acid
RTA	relevant technology application
SARS	severe acute respiratory syndrome
S&T	science and technology
TA	technology application
Technical feasibility	Likelihood that a technology application will be available for implementation
Technology	The practical use of a scientific advance
Technology application	Application of a technology to accomplish one or more specific functions
Technology implementation	Use of a technology application in society
TIL	tumor-infiltrating lymphocyte
UAV	unmanned aerial vehicle
UNDP	United Nations Development Programme
WHO	World Health Organization
Wildcard	Technology application unlikely to be widely available, but if unlikely breakthroughs happened, would have broad and substantial impacts

CHAPTER 1
INTRODUCTION

We live in an era of increasing use of diverse technologies in all aspects of life, from ingestible radio transmitters and fluorescent quantum dots for medical diagnosis and treatment,[11] to multifunctional cell phones that take digital photographs and receive and transmit electronic mail. In a previous RAND Corporation study, *The Global Technology Revolution: Bio/Nano/Materials Trends and Their Synergies with Information Technology by 2015* (hereafter referred to as GTR2015),[12] we investigated the pace and impacts of technology development, projected to 2015, and concluded that the world is undergoing a global technology revolution that is integrating developments in biotechnology, nanotechnology, materials technology, and information technology at an accelerating pace.[13] This report describes the results of a recent effort to update this foresight activity and extend its time horizon to 2020. It is important to note that these studies are *foresight activities*[14] that examined trends, breakthroughs, and indicators of possible future developments based on sound research progress today, *without predicting a single future state or timeline*. Foresights are useful in that they explore the possible to give a sense of what might happen without trying to make predictions that are impossible given uncertainties. While surprises may still happen, and can certainly have significant impact in the time period considered, our assessments are grounded in that we assess technical viability based on real research and development (R&D) progress (versus pure science and technology [S&T] conjecture) and consider modifying factors such as demand, drivers, and barriers to help balance out the possible from the unlikely.

The technology of 2020 will continue to integrate developments from multiple scientific disciplines in a "convergence" [15] that will have profound effects on society. Sometimes people believe that they understand the implications, and in some cases even the working principles, of certain technologies and what they mean for everyday life (e.g., hybrid vehicles, disease vaccines, cell phones, memory sticks). At other times, however, the implications seem obscure and are not grounded in everyday activities (e.g., genetic decoding for studies of genetic links to disease and for drug research, electronic and optical technologies used in film animation, magnetic resonance imaging diagnostic tests, microelectromechanical system [MEMS] accelerometers that control airbag deployments and measure tire pressures in automobiles). A description of this phenomenon attributed to science-fiction author Arthur C. Clarke is that "any sufficiently advanced technology is indistinguishable from magic."[16] Thus, rather than focusing on

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[11] Ballou et al. (2004); Gao et al. (2004). See, for example, http://www.smartpilldiagnostics.com.
[12] Antón, Silberglitt, and Schneider (2001).
[13] More precisely, the integrated technology developments to 2015 were seen as likely to result in accelerated expansion of the human lifespan, along with significant improvements in quality of human life and the possibility of eugenics and cloning, as well as products, components, and systems that are smaller, smarter, multifunctional, environmentally compatible, more survivable, and customizable.
[14] Salo and Cuhls (2003).
[15] Glenn and Gordon (undated a; undated b; 2004); U.S. National Science Foundation and U.S. Department of Commerce (2002).
[16] "Spectral Lines" (2004).

the technologies themselves, we will emphasize in this report the significant *applications* enabled by developing technology trends, as well as the drivers, barriers, and potential for *implementation* of these applications in 2020.

The application and implementation of the global technology revolution will not be homogeneous, but they will display important variation throughout the world as different regions, countries, groups, and individuals reinforce, weaken, and react in widely different ways to the drivers and barriers. For example, several Asian countries lead the United States and Europe in the implementation of advanced cell phone technology.[17] Sub-Saharan Africa has been slow to implement wide-scale vaccination programs to fight infectious diseases.[18] Asia appears poised for early adoption of genetically modified (GM) foods and other organisms, while strong sentiment and pending legislation aim to impede their use in Europe.[19] As part of this study, the authors consulted with several RAND regional experts on important regional problems and issues that might be addressed by technology, as well as the nature of the environment for adoption of emerging technologies by 2020 in different regions of the world. The discussion and tables in the following chapters of this report are based in part on the results of these consultations.

The Global Technology Revolution to 2020

GTR2015 discussed the effects of the accelerating pace of technology development on the engineering and health of living things, as well as the design and use of materials, devices, and manufacturing. Many of the effects discussed in the 2015 foresight remain important as we look toward 2020. Continuing developments in genomics and related areas of biochemistry and biotechnology have kept the issues of genetic profiling, cloning, and modification current in public policy debates.[20] Progress continues in targeted diagnostics and drug delivery, prosthetics, and tissue engineering,[21] with the prospect for significant improvement in quantity and quality of life by 2020, albeit with substantial remaining gaps between rich and poor populations and countries. The ability to design and fabricate increasingly smart, multifunctional, and environmentally compatible materials has already produced self-cleaning clothing,[22] self-healing construction components,[23] and smart, implantable drug delivery devices.[24] Developments in information and communications technology, robotics, and rapid prototyping continue to feed the global development of agile manufacturing capabilities.[25] Additional important technology trends and applications include:

[17] Ignatius (1999); Trujillo (2004).
[18] Timberg (2004); Butler (2004).
[19] Tomson (2004); King (2003); Cayford (2003); Stafford (2005).
[20] Lin (2004); Fairchild and Bayer (2004); Bright (2002); Roberts (2004); Perpich (2004); Dalton (2004); Cayford (2003); Pilcher (2004a).
[21] Cohen and Leor (2004); Lavik and Langer (2004); Jones (2004b); Gao et al. (2004); Allen and Cullis (2004); Patolsky et al. (2004); Rincon (2004).
[22] Peplow (2004a); Borchardt (2005); Daoud and Xin (2004).
[23] Vernet (2004).
[24] Allen and Cullis (2004); Sinha et al. (2004).
[25] Mukunda and Dixit (2002); Forsythe (1997); Merat et al. (1997); Sanchez and Nagi (2001); Kanellos (2004).

- Personalized medicine and therapies
- Genetic modification of insects to control pests and disease vectors
- Computational (or "in-silico") drug discovery and testing
- Targeted drug delivery through molecular recognition
- Biomimetic and function-restoring implants
- Rapid bioassays using bionanotechnologies
- Embedded sensors and computational devices in commercial goods
- Nanostructured materials with enhanced properties
- Small and efficient portable power systems
- Mass-producible organic electronics, including solar cells
- Smart fabrics and textiles
- Pervasive undetectable cameras and sophisticated sensor networks
- Large, searchable databases containing detailed personal and medical data
- Radio frequency identification (RFID) tracking of commercial products and individuals
- Widespread bundled information and communications technologies, including wireless Internet connectivity
- Quantum-based cryptographic systems for secure information transfer.

Most of the technologies listed above depend on developments in more than one of the technology areas being investigated. As noted above, it is in fact the convergence of these disciplines and technologies that is contributing to the accelerated pace of development. Table 1.1 illustrates the intimate relationships between developments in biotechnology, nanotechnology, materials technology, and information technology. These relationships have continued to grow and mature over the past decade, to the extent that integration and cross-functionality of advanced technologies has become the rule rather than the exception, especially as technologies are employed in applications that require different disciplines to solve multiple challenges in the system concepts. Examples of such cross-discipline integration include nanoparticle-based biosensors, bioassays, and tumor therapies;[26] electronic textiles with consumer and medical applications;[27] and continued miniaturization and increased functionality of RFID chips and distributed sensor networks.[28] We consider and analyze the impact of this continued cross-disciplinary integration on TAs in Chapter Two.

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[26] Lurie (2004); Nettikadan et al. (2004); O'Neal et al. (2004).
[27] Schreuder-Gibson and Lynn (2003).
[28] O'Harrow (2004a).

Will Moore's Law Continue Through 2020?

Continuation of the exponential increase with time in computer performance—Moore's Law—is not a physical law but rather an observed trend that can be characterized in terms of the rate of growth of computational speed, memory density, reduction in cost per computation, or other computer characteristics or performance specifications. As described in the International Technology Roadmap for Semiconductors,[29] the growth rate has been achieved by a continual progression to increasingly more-dense complementary metal-oxide semiconductor (CMOS) chip fabrication technologies. Recent advances and current research suggest that this progression will continue for at least another 10 to 15 years.[30] Current commercial fabrication methods are already at the nanoscale, with nominal feature size of 90 nanometers and gate width of 50 nanometers, and approaches to scale down to 10 nanometers feature size are under research.[31] In GTR2015, we noted that it was unlikely that alternatives to CMOS would be competitive by 2015. However, by 2020, the continued reduction of feature size is likely to require nonconventional and hybrid methods; several different approaches (e.g., based on nanotubes, nanowires, and molecular switches) have been suggested and are being pursued.[32] Thus, our foresight assessment for continuation of Moore's Law to 2020 is highly feasible, but we note that in the period just beyond 2020, most practitioners in this field anticipate that nonconventional fabrication methods, and perhaps components, will be beginning to be used, for example, in hybrid chip architectures.[33]

We also discussed in GTR2015 a few "wildcard" technologies—that is, those that appeared unlikely to be widely available in 2015, but if unlikely breakthroughs happened, would have broad and substantial impacts. One of these technologies, self-assembly of materials from the "bottom-up" using principles and forces of chemistry and biology, has matured greatly in the past few years, not merely as a stand-alone method but also as a powerful tool often used in combination with "top-down" methods such as lithography.[34] While self-assembly methods are not likely to be a panacea for all manufacturing, they are now a significant component in the "toolbox" of materials developers and are routinely developed and used in nanotechnology laboratories throughout the world. For example, a recent review article describes the use of self-assembly methods to fabricate a variety of functional nanostructures for integration into devices and systems.[35]

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[29] International Roadmap Committee (2004).
[30] Stevens (2004); IBM (2003).
[31] Ieong et al. (2004).
[32] Kanellos (2004).
[33] International Roadmap Committee (2003).
[34] Falconnet et al. (2004).
[35] Brinker (2004).

Approach

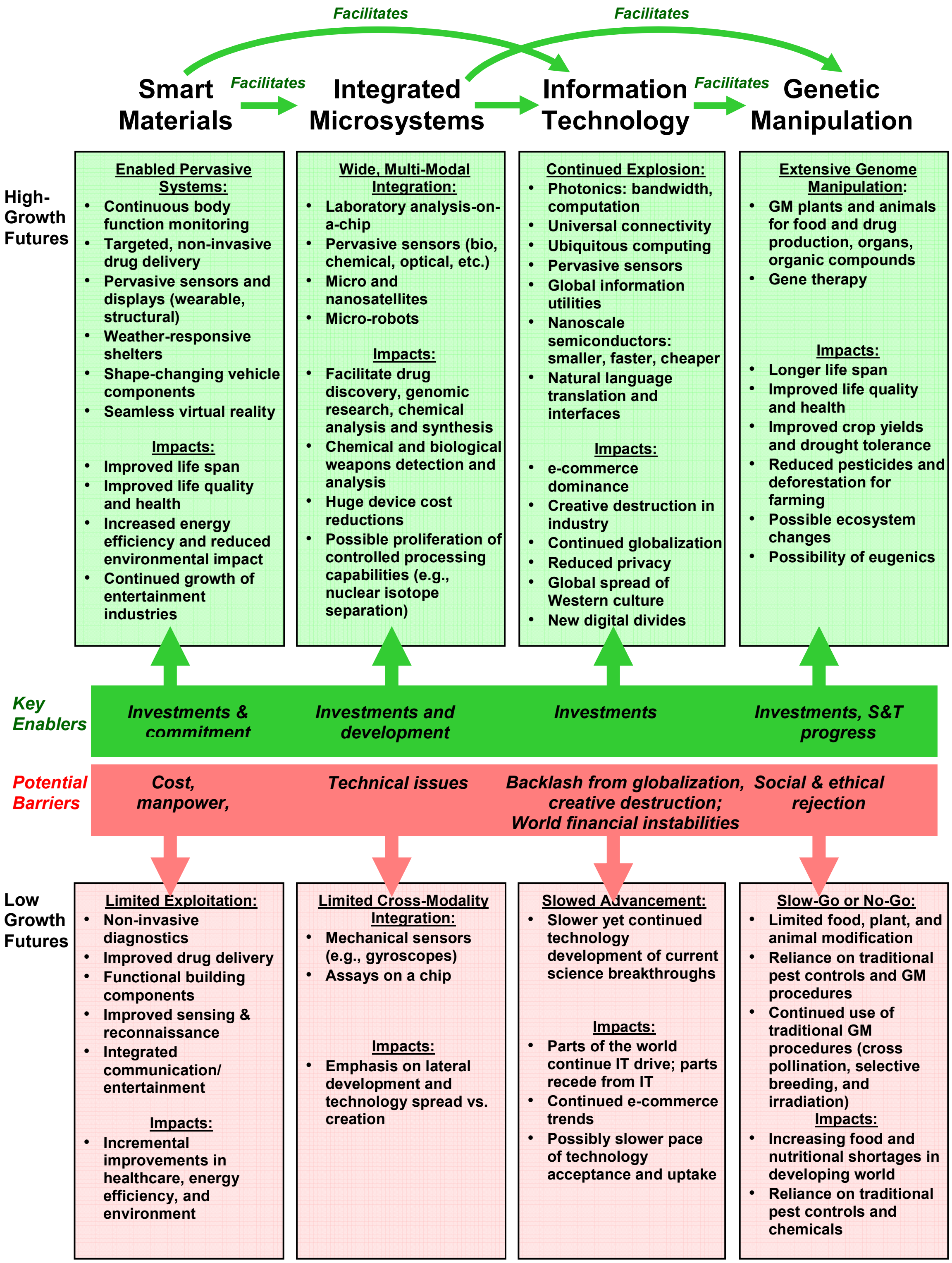
In updating GTR2015 to 2020, we wanted not only to examine the progress made with respect to prior trends (and to look for new trends) but also to use the description of potential *applications* to help convey to the nonscientist the potential kinds of effects and their implications that are likely from the trends we discuss. Thus, we wanted to spend more time discussing these *application concepts* and their implications for various regions of the world rather than narrow technological advances independent of how they might be applied. For example, we did not focus on genetic modification techniques but rather on how they are applied through such concepts as GM foods to improve nutritional content. Likewise, we did not focus on specific technical breakthroughs in wireless networking, such as protocols and bandwidth compression techniques, but rather on concepts such as rural wireless communication capabilities.

Technology Trend Foresight

First, we conducted several parallel analyses of the state of globally important technology trends and how they are being built into specific applications. In this analysis, we reviewed major S&T journals and magazines, assessing the viability of projected technology trends based on the degree to which real progress is being made in R&D laboratories, the degree of interest and investments in these trends, and our expert judgments of the overall likelihood of the applications having a significant impact on major global demand sectors and policy drivers.

Several RAND technology experts contributed to the updated technology foresights that formed the basis for the analysis of technology application and implementation described in this report. These individuals researched and wrote background papers analyzing the likely technology trends to 2020 in their areas of expertise. These papers, which can be found in the appendices, formed the primary basis for the applications discussed in Chapter Two. They describe a variety of technology areas with varying levels of maturity and prevalence in which important advances have been made since the publication of GTR2015, and which show promise for applications in 2020.

Table 1.1
Schematic Illustration of the Highly Interactive Nature of Technology Areas



International Implications

Next, we connected technology trends to regional problems and issues identified by regional experts (i.e., the “So what?” test). This analysis assessed which technology applications will be important in which regions of the world based on regional needs, investments, political and cultural drivers, natural resources, and other factors. Several RAND regional and country experts reviewed the TAs identified. They suggested, based on their knowledge and experience, which ones best addressed important regional or national problems and issues, and which ones were more or less likely to match the needs and characteristics of each region or country. Interviews with these regional experts formed the initial basis for the discussions.

Finally, we considered the effects of global variations in S&T capacity and the drivers and barriers that determine the environment in which technology developments are applied and implemented. For a representative group of TAs that our foresight analyses suggested could have broad societal impact by 2020, we then evaluated the relative potential for their implementation and its possible effects in important policy areas such as economic development, public and individual health, resource use and the environment, defense, public safety and homeland security, governance, and social structure. While such an evaluation for the 200-plus nation-states of the world was beyond our resources, we performed this analysis for 29 countries selected to represent the most important international variations in S&T capacity, as well as the drivers and barriers to implementation of these TAs. We based our analysis on a broad spectrum of available indices that measure the economic and human development, social and political environment, and scientific capacity of the selected countries, as well as on relevant reports and studies by national, regional, and international institutions. Also, while these assessments were based on current statistics on S&T capacity, drivers, and barriers, our analyses of regional and international effects were augmented by insights into the directions certain countries appear to be taking in improving or slipping in these dimensions, including the possibility for rapid change.

Structure of the Report

Chapter Two summarizes our findings on the technology trends, the kinds of applications they will empower, and a sense of the maturity and feasibility of these applications given the current state of scientific results in the laboratory and in the development labs of companies. Chapter Three discusses the possible impacts of these TAs in different parts of the world, taking into account differences in the capacity to acquire TAs and the drivers for and barriers to technology implementation. Chapter Four summarizes our conclusions concerning technology development, applications, and implementation, and their possible international ramifications. Appendices A through F provide details on specific technology trends. Appendix G provides additional detail on some of the TA concepts. Appendices H through K provide information and indicators related to S&T capacity, economic development, governance, quality of life, and other societal characteristics for the representative countries selected for analysis in this study.

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CHAPTER 2
TECHNOLOGY APPLICATIONS AND THEIR EFFECTS

Technology applications affect society through the functions that they accomplish (e.g., health, food, shelter, climate control, transportation, communication, computation). The accelerating pace of technology development is important because it has brought new functions to large numbers of people worldwide (e.g., communication and information searching via the Internet), has improved the speed and accuracy of existing functions (e.g., lab-on-a-chip bioassays, functional Magnetic Resonance Imaging (fMRI) for medical diagnostics), and is producing a variety of multifunctional applications (e.g., wearable computers).

In this chapter, we will describe applications of technology that may become feasible by 2020, explore the functions that these applications provide, and analyze their potential impact on society. We begin with brief summaries of the foresight papers prepared by RAND's technology experts (the full papers are presented in the appendices). We note that these papers and the TAs described below are representative of the trends we have analyzed. One can certainly envision other applications that combine the trends in different ways, but we believe that they reflect the breadth and depth of plausible technology futures to 2020.

As pointed out in GTR2015, the disciplinary categories (i.e., biotechnology, nanotechnology, materials technology, and information technology) are becoming increasingly blurred and almost artificial. Applications increasingly draw from more than one category to produce increasingly capable systems. Thus, many of the applications listed in the following summaries could have been listed in other summaries. For example, nanostructures and nanoscale coatings could be listed under nanotechnology rather than materials; bioassays and biosensors rely on nanoscale reactions and could be listed under nanotechnology; biometrics employ biological properties as well as information systems and thus could be listed in the biotechnology section.

Technology Trends and Applications

The following highlights some of the more significant technology trends and applications likely by 2020. While illustrative, they are not necessarily exhaustive. They do, however, convey a sense of many of the major trends in these areas.

Biotechnology Trends and Applications to 2020

Recent advances in our ability to manipulate and modify living systems have enabled dramatic improvements in health monitoring, disease control, and therapeutic and prosthetic options, and they have even given rise to the possibilities of designed organisms.[36] The reaction to these developments has varied widely throughout the world, with some countries and regions opting for slower development because of ethical issues and concerns about environmental risks,[37] while other countries and regions have

[36] Ferber (2004); Wang et al. (2004); Ritter (2002); Simpson (2003); Silver (1997).
[37] Roosevelt (2004); Anonymous (2004).

embarked on a faster development path.[38] However, the global flow of information, people, and resources that is characteristic of the early 21st century has weakened the power of states to impede technology development, as evidenced, for example, by the adoption of GM crops in Asia and the emergence of substantial private-sector support for research in areas such as stem cells and cloning.[39] Thus, we suggest that by 2020, the following applications of biotechnology will be technically feasible:

- Performance of many different bioassays on a sample at once, which will enable rapid analyte identification from very small amounts of material, for both medical diagnoses and forensic evaluations
- Personalized medicine, based on large databases of patient information and disease states, as well as the ability for rapid and parallel gene sequencing
- Development of GM insects, such as pests that produce sterile offspring or that do not carry or transmit disease vectors
- Widely available capability for GM staple food crops, with especially strong impact in the developing world
- Ability to design and test new drugs using computer simulations ("in silico"), as well as new capabilities to test for harmful side effects on model systems assembled on computer chips ("lab-on-a-chip")
- Targeted drug delivery to organs or tumors using molecular recognition
- Implants and prostheses that mimic biological functions, restore critical functions to existing organs or tissues, or even augment those functions.

Nanotechnology Trends and Applications to 2020

Nanotechnology, which for the purposes of this report is taken to mean R&D in nanometer scale science and related technologies,[40] is a burgeoning field worldwide. Most working definitions of nanoscience and nanotechnologies define the nanoscale in the size range of 1 to 100 nanometers.[41] The 21st Century Nanotechnology Research and Development Act of 2004 provides for approximately $1 billion annually in U.S. government nanotechnology funding through 2008,[42] and global funding for nanotechnology is currently several times larger, with every major economic power and many developing economies investing substantial resources.[43] This worldwide interest is based on the belief that the ability to understand and affect atomic and molecular interactions at the nanoscale is both a prerequisite and an enabler for a host of technological capabilities, from smart, multifunctional materials to designer drugs and new generations of information and communications systems. In fact, a number of products employing nanoscale technologies have already reached the market. For example, Nano-Tex, of Greensboro, North Carolina, has developed several textile

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[38] Wu (2005).

[39] Lysaght and Hazlehurst (2003). This trend could be weakened or reversed in specific technology areas by an event such as the release of an engineered pathogen of real or perceived danger to a large number of people.

[40] A nanometer is a billionth of a meter (10^{-9}), approximately 10 times the atomic size scale.

[41] National Nanotechnology Initiative (undated).

[42] Nanoscale Science, Engineering, and Technology Subcommittee (2004).

[43] Roco (2001).

treatments based on nanoscale fiber coatings that repel liquids, resist stains, and soften the feel of fabrics.[44] Wilson Sporting Goods has marketed tennis balls with a nanocomposite coating that retains inner pressure longer, and composite tennis rackets with improved strength and stiffness resulting from nanoscale particles that fill voids in the material.[45] Other existing products based on nanotechnologies include computer hard drives, electrospray-painted auto components, catalytic converters, sunscreens, and burn and wound dressings.[46]

Perhaps the earliest commercial use of nanoscale S&T has been in the semiconductor industry, which is currently using 90-nanometer lithography in fabrication of integrated circuits and is pursuing several different R&D efforts to use nanotechnologies to meet future goals for increased computational speed.[47] In fact, while we noted in GTR2015 that unconventional nanotechnology is not expected to compete with conventional silicon technology by 2015, it is anticipated that meeting the semiconductor industry road-map objectives beyond 2020 may require the employment of nonconventional processing approaches using nanotechnologies.[48] Therefore, nanotechnology will be required to extend Moore's Law to 2015 (using nanoscale silicon technology) and beyond 2020 (using unconventional nanotechnology concepts).

Beyond existing commercial products and the ever-decreasing size of semiconductor electronics, a host of new nanotechnologies are under development worldwide.[49] Some of these have promise for improving quality and quantity of life, as noted in the biotechnology section above. Others are being considered for environmental remediation.[50] The emergence of nanomaterials in the marketplace and in the environmental sector has recently spurred public awareness and scientific interest in research on their transport, fate, and potential toxicity. While nanoscale particulate emissions (e.g., from diesel engines) have been a regulated environmental emission for some time, the increasing use of nanoscale materials in new commercial products raises new regulatory issues.[51] Research that will underpin regulatory decisions and best practices in handling nanomaterials is being led in the United States by the National Institute for Occupational Safety and Health, and coordinated by a working group under the National Nanotechnology Coordination Office.

Taking into account the rapid advances, the strong U.S. and international research efforts, the commercial interest, and the importance of the societal impacts, our foresight suggests that the following applications of nanotechnologies will be feasible by 2020:

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[44] Nano-Tex's textile treatments can be found in brand-name clothes, including those made by Eddie Bauer, Gap, Levi Dockers, L.L. Bean, Nike, and Old Navy. For details, see http://www.nano-tex.com.
[45] Cronin (2004); Paull (2003).
[46] For more information, see the U.S. National Nanotechnology Initiative at http://www.nano.gov or *Small Times* magazine at http://www.smalltimes.com.
[47] Intel (2002); Kanellos (2004).
[48] International Roadmap Committee (2004).
[49] Cientifica (2003).
[50] National Science Foundation (2003).
[51] Royal Academy of Engineering (2004). For more information, see http://www.cdc.gov/niosh/topics/nanotech (as of December 2004).

- New families of miniaturized, highly sensitive and selective chemical and biological sensors
- Improvements in battery power management and capacity
- Individually worn sensors, especially for military and emergency personnel
- Computational devices embedded in commercial goods (already being done today and likely to become more widespread)
- Wearable personal medical monitoring devices with data recording and communications capability
- Functional nanostructures for controlled drug delivery and for improved performance of implants and prosthetic devices
- Capability for widespread human and environmental surveillance and monitoring.

The rapid emergence of nanotechnology also gives rise to "wildcard" nanotechnologies (i.e., technologies that we do not expect to be widely available by 2020 but, if they are, will likely have broad and substantial effects). These wildcard nanotechnologies include applications of carbon nanotubes or semiconducting and metallic nanowires as individual (designed) functional elements in electronic circuits,[52] and manufacturing using molecular or biological methods.[53]

Materials Trends and Applications to 2020

In GTR2015, we discussed the process of materials engineering, from concept and design through materials selection, fabrication, and processing to achieve the properties and, ultimately, the performance required for a product. This multidisciplinary field has grown over the past few decades through integration of physics, chemistry, metallurgy, ceramics, polymer science, and, most recently, biology to become a rich source of technological advancement.[54] Indeed, advanced materials are enablers of many of the applications listed above under biotechnology and nanotechnology trends. A recent review article describes the role that biomaterials have played in the success of medical devices and drug delivery systems and discusses current research challenges in tissue engineering, implants and prostheses, and diagnostic and therapeutic applications.[55] Nanomaterials including nanoparticles, carbon nanotubes, semiconductor or metallic nanowires, composites with one component at the nanoscale, and fabricated or self-assembled nanostructures are integral components of every one of the applications listed above under nanotechnology trends.

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[52] Beyond simple memory and logic circuits and sensors based on carbon nanotube meshes or random networks. (Rueckes et al., 2000; Snow et al., 2005).

[53] Materials assembly using DNA has been demonstrated by several groups (Seeman and Belcher, 2002). A number of laboratory demonstrations of molecular-scale "machines" have also been reported (Sample, 2001). The time and effort required for implementing such approaches at macroscopic scale is currently impossible to predict. Moreover, the feasibility of manufacturing devices by assembling components at the molecular level is a hotly debated topic. See, for example, the dialog between Eric Drexler and (the late) Richard Smalley in Baum (2003).

[54] For example, the range of topics at the Materials Research Society's fall and spring meetings (http://www.mrs.org) includes most of the areas discussed under nanotechnology trends, and several of those discussed under biotechnology trends, in the previous sections.

[55] Langer and Tirrell (2004).

"Smart" materials, which were a focus area in GTR2015, continue to grow in importance, with recent demonstrations (e.g., of polymers that move in reaction to light,[56] layered elastomers that can respond to punctures by releasing efficacious agents,[57] self-healing concrete,[58] and smart textiles).[59] It is interesting to note also that recent advances in materials science have begun to address fundamental applications problems that have existed for decades. For example, the most widely used piezoelectric material in sensors and actuators is lead based. A potential lead-free (and thus potentially more environmentally friendly) alternative that appears to have equally good properties has recently been demonstrated.[60] Also, the technologically important phenomena of superconductivity and magnetism typically do not coexist in bulk materials because the electronic interactions that cause them to occur drive the material into different and incompatible states. But superconducting films have now been demonstrated on top of magnetic materials with nanoscale magnetic domain structures.[61] This raises the possibility of linked superconducting and magnetic components within electronic circuits, which, by allowing the combination of very-low resistance, high-current carrying capability, and magnetic switching, could provide circuit designers and electrical engineers with new flexibility for miniaturization and performance, and even new properties.

Based on the continued developments in materials science and engineering and manufacturing, our foresight suggests that the following may be feasible by 2020:

- Fabrics that incorporate power sources, electronics, and optical fibers
- Clothes that respond to external stimuli, such as temperature changes or the presence of specific substances
- On-demand manufacturing of components and small products to individual personal or corporate specifications (initially limited to low-complexity items)
- Widespread adoption of "green" manufacturing methods that substantially reduce the introduction of hazardous materials into commerce and the volume of hazardous waste streams
- Nanostructured coatings and composite materials with greatly enhanced strength, toughness, wear resistance, and corrosion resistance
- Organic electronics for increased brightness of lighting systems and displays
- Mass-producible solar cells using composite materials based in part on nanostructured, organic, or biomimetic materials
- Water purification and decontamination systems based on nanostructured, activated membranes and filters
- Designed catalysts for chemical processes based on combined rapid computation and materials screening
- Engineered multifunctional tissues grown in vivo from biodegradable scaffolds (likely limited initially to selected tissue and organ types)

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[56] Pientka et al. (2004).
[57] Sonntag et al. (2004).
[58] Vernet (2004).
[59] Johnson (2004b); Catchpole (2004); "Nanotech in Fashion" (2004).
[60] Saito et al. (2004); Cross (2004).
[61] Coleman (2004).

Information and Communications Technology Trends and Applications to 2020

The increasing availability of information and the growth of communication networks have been major factors in the globalization of the 20th century. The Institute of Electrical and Electronics Engineers (IEEE) recently sought the opinions of 40 leading technology developers concerning the most important technology of the past 40 years and the most important technology of the coming decade. The vast majority of the responses to the former question included the integrated circuit, the computer, or the Internet, and many of the answers to the latter included either the Internet or wireless communication, with several respondents noting the likely impact of biology and a few mentioning nanotechnology.[62] Our foresight study of information and communications technology focused on the integrated development over the next 15 years of semiconductor materials processing and fabrication, mathematical algorithms, MEMS, nanoelectromechanical systems (NEMS), smart materials, and biomaterials and biomedical devices, suggesting that the following may be feasible by 2020:

- Wireless Internet available worldwide to middle and upper classes, including developing countries and rural areas
- Wearable computers expanded to control medical devices, appliances, and entertainment systems
- Massive databases (hopefully with robust security) holding personal information such as history and log of information viewed or processed, as well as such items as medical records and genomic information
- Small and inexpensive devices storing massive data such as voice, video, and Web pages
- Increasingly improved search capabilities to locate not only text phrases but semantic phrases, pictures, and video through both meta representations and exemplars (without which the data storage would be useless)
- RFID tags to track commercial goods, consumer buying patterns, and even individual movement for security and targeted advertising[63]
- Biometrics (e.g., fingerprints, iris scans) widely required for travel, for security access to computers and locations, and, perhaps, for commerce
- Small ubiquitous cameras and widespread sensor networks with increasingly small size and unobtrusiveness
- Hands-free machine interfaces and input devices (e.g., light scanned directly to the retina).

In addition, we view the following as wildcard applications for 2020:

- Robots that look and move in very human fashion
- Implants that connect directly to the brain and nervous system

[62] Applewhite (2004).

[63] The use of RFID tags for commercial logistics is already in full swing, which will likely enable subsequent possible applications and innovations as RFID tags become ubiquitous. RFID in employment identification badges is also becoming commonplace.

The Integrated Effect of Technology Development

The previous sections identify likely developments in biotechnology, nanotechnology, materials science and engineering and manufacturing, and information and communications technology by 2020. But it is the *integration* of these developments that can have the most profound impact on society by providing multifunctional technologies to meet specific application needs. For example, wide availability of Internet access required a combination of mathematical algorithms for transmission and recognition of information packets, sufficient computing speed and memory, materials and engineering capability for wired networks, and software to allow nonengineers the use of electronic mail and Web sites. Maintaining the Internet's use as a state-of-the-art data transmission network and one with worldwide reach, even into rural areas, is now requiring, for example, broadband optical fiber and wireless networks and encryption algorithms. As technology increases in capability and sophistication, it continues to integrate new developments, often from diverse areas of science. Thus, the integration of developments in biotechnology, nanotechnology, materials, and information and communications is essential to the maturation of the technologies we are describing to achieve their full functionality and impact. We note, however, that each increase in sophistication comes at a price, which must be justified by an increased market—that is, the new development needs to serve some group of users.[64] Table 2.1 gives some examples of integration of technologies that may be feasible by 2020, along with possible applications and user groups.

The Potential Effects of Technology Applications in 2020

Table 2.2 lists the range of TAs that our foresight studies suggest may be feasible in 2020. To illustrate the assessment method we used, and for purposes of comparison, we added a pervasive and important current TA—the Internet—to the table. We considered the potential impact of each of these applications on 12 societal sectors—water, food, land, population, governance, social structure, energy, health, economic development,[65] education, defense and conflict, and environment and pollution. Each row of the table represents a specific application and indicates which sectors that application is anticipated to influence, as well as the total number of sectors influenced. By influencing a sector, we mean that if the application is adopted, it will significantly affect the operation or characteristics of that sector. For example, the Internet affects governance through its use by both citizens (e.g., for filing taxes) and government agencies (e.g., for posting of regulations and contracting opportunities). It affects social structure through its use by social, political and religious nongovernmental organizations for research, fund raising, recruiting, and communications. It is used by both energy suppliers and consumers for data collection and transfer and system control. It is routinely used as a

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[64] Technological innovation is as much about serving markets as it is about developing capabilities. Older technologies are often used in developing economies. When a new capability serves a disenfranchised group of users, it causes disruption in the marketplace. For example, see Christensen (2003).

[65] For economic development, we include rural economic development, significant increases in economic indicators of developing countries, and significantly increased business for countries, regions, industries, or companies.

source of medical information. It has become an instrument of economic development as e-commerce has flourished. Distance learning via the Internet is helping to bring education to individuals worldwide who previously had limited educational opportunities. Finally, net-centric military technologies are being aggressively pursued in many countries. Thus, seven sectors are identified as being influenced by the Internet in Table 2.2. We recognize that analysts may disagree about the extent of influence of a TA in a particular sector and have provided text to explain our assignments for each TA in the body of this section and in Appendix G.

Table 2.2 also indicates the results of our foresight assessment in three other areas: (1) technical feasibility—that is, the likelihood that the application is available for commercialization on a significant basis by 2020, which is based principally on the technical foresight papers in Appendices A through F; (2) implementation feasibility—that is, the net of all nontechnical barriers and enablers, such as market demand, cost (above and beyond that included in demonstrating technical feasibility), infrastructure, policies, and regulations,[66] which we based on rough qualitative estimates of the size of the market for the application in 2020 and whether it raises significant public policy issues; and (3) an estimate, based on both the technical foresights and our discussions with RAND regional experts, of whether the application will be diffused globally in 2020, or will be moderated in its diffusion—that is, restricted by market, business sector, country, or region.

For technical feasibility in Table 2.2, ++ indicates highly likely by 2020; + indicates likely by 2020; *U* indicates that our 2020 foresight is *uncertain*; - indicates unlikely by 2020; and -- indicates highly unlikely by 2020. For implementation feasibility, ++ indicates that the TA satisfies a large market need and does not raise significant public policy issues; + indicates that the technology application satisfies a strong need for a medium-sized market and does not raise significant public policy issues; - indicates that the TA may satisfy a need for a medium-sized or large market, but raises significant public policy issues; and -- indicates that the TA satisfies a need for a niche market only.

G in the diffusion foresight column of Table 2.2 denotes *global* diffusion, while *M* indicates *moderated* diffusion. In addition, we have included in Table 2.2 a net assessment for each TA, which is simply derived by combining the sector total with the pluses and minuses for technical and implementation feasibility in that row (treating *U* as a zero) and then adding one if there is a *G* in the diffusion foresight column. While this net assessment does not measure the magnitude of impact on specific sectors, it does highlight feasible TAs with multi-sectoral impact and global reach, and thus provides a very rough index of the overall impact in 2020 of each TA, based on our foresight assessments.

With direct impact on seven of the 12 sectors, and serving a large global market, the Internet has the largest net assessment value at 12.[67] The text below discusses the reasons for the assignments in Table 2.2 for the 16 TAs with a net assessment value of 6 or higher. We believe that these provide a representative and workable set of technically

[66] See additional discussions on the effects of markets and public policy issues on technology development in Anderson et al. (2000) and Hundley et al. (2003).
[67] In assigning ++ for implementation feasibility, we note that negative social impacts (such as cybercrime; use by terrorist and hate groups; and cultural objections) have not prevented global implementation.

feasible applications with the potential for broad societal impact by 2020, incorporating key aspects of each of the technology foresight areas addressed in this study. With just a few exceptions, these include all TAs that significantly affect more than two sectors and that were judged positive for either technical or implementation feasibility. While not comprehensive, this group captures the essence of our foresight of global trends in TAs by 2020 and will form the principal basis for our analysis of international variation in technology application and implementation. After discussing these "top 16" TAs individually, the text below provides a general discussion for the remaining applications. Further information on all the TAs in Table 2.2 may be found in the appendices and in the references.

Table 2.1
Integration Trend of Technology Developments

Area	Single Disciplines	Multiple Disciplines: Partially Integrated	Multiple Disciplines: Fully Integrated	User Group/Application
	Traditional →	*Transitional* →	*Evolved*	
Materials	Solid state physics or chemistry	Solid state physics or chemistry of complex materials	Physics, chemistry, engineering of complex materials	Engineers/ design of biomaterials, catalysts, structural materials
Solar collectors	Semiconductors	Organic semiconductors	Chromophores, dendrimers, nanostructured organic semiconductors	Consumers/ mass-producible and affordable solar energy
Pharmaceuticals	Designer drugs	Time-release designer drugs	Encapsulated, targeted, self-regulated drug delivery	Patients/ less invasive treatment with less side effects
Water purification	Filters and catalysts	Catalytic membranes	Functionalized, controlled pore size, selective catalytic filters and membranes	General populace/ cleaner water, safer from disease
Genetic modification in agriculture	GM crops	Climate-tailored GM crops	Adaptive GM crops (e.g., controlled germination, self-regulated nutrient uptake)	Farmers and general populace/ higher yield, greater availability of food, nutrition

Table 2.2
Impact of 2020 Technology Applications

Title	Water	Food	Land	Population	Governance	Social Structure	Energy	Health	Economic Development	Education	Defense/Conflict	Environment/Pollution	SECTOR TOTAL	2020 Technical Feasibility	2020 Implementation Feasibility	2020 Diffusion Foresight	Net Assessment
Internet (for purposes of comparison)					X	X	X	X	X	X	X		**7**	+ +	+ +	G	12
Cheap Solar Energy	X	X	X		X	X	X	X	X	X		X	**10**	+	+	M	12
Rural Wireless Comms					X	X		X	X	X	X	X	**7**	+ +	+ +	G	12
Ubiquitous Information Access					X	X		X	X	X	X		**6**	+ +	+	M	9
GM Crops	X	X	X	X			X	X	X			X	**8**	+ +	–	M	9
Rapid Bioassays					X			X	X		X		**4**	+ +	+ +	G	9
Filters and Catalysts	X	X	X					X	X		X	X	**7**	+	+	M	9
Targeted Drug Delivery				X	X	X		X	X				**5**	+ +	+	M	8
Cheap Autonomous Housing					X	X	X	X	X		X		**6**	–	+ +	G	8
Green Manufacturing	X		X				X	X	X			X	**6**	+	+	M	8
Ubiquitous RFID Tagging					X	X			X		X		**4**	+ +	+	G	8
Hybrid Vehicles							X					X	**2**	+ +	+ +	G	7
Pervasive Sensors					X	X			X		X		**4**	+ +	–	G	6
Tissue Engineering				X	X			X	X				**4**	+	+	M	6
Improved Diagnostic and Surgical Methods								X		X			**2**	+	+ +	G	6
Wearable Computers						X		X	X	X	X		**5**	U	+	M	6
Quantum Cryptography									X		X		**2**	+	+ +	G	6
Hands-free Computer Interface									X		X		**2**	U	+ +	G	5
In-silico drug R&D								X	X				**2**	U	+ +	G	5
Smart Textiles						X		X	X		X		**4**	U	+	M	5
Resistant Textiles				X				X					**2**	U	+ +	G	5
Electronic Transactions						X			X				**2**	U	+ +	G	5
Genetic Screening				X				X					**2**	+ +	–	G	4
GM Insects		X		X				X	X			X	**5**	U	–	M	4
Unconventional Transport					X	X	X		X			X	**5**	+	– –	M	4
Commercial UAVs	X	X	X						X		X	X	**6**	U	– –	M	4
Drug Development from Screening								X		X			**2**	+	+	M	4
Monitoring and Control for Disease Management						X		X					**2**	+	+	M	4
Enhanced Medical Recovery						X		X	X				**3**	U	+	M	4

Table 2.2 (continued)

Title	Water	Food	Land	Population	Governance	Social Structure	Energy	Health	Economic Development	Education	Defense/Conflict	Environment/Pollution	SECTOR TOTAL	2020 Technical Feasibility	2020 Implementation Feasibility	2020 Diffusion Foresight	Net Assessment
Secure Data Transfer					X				X				**2**	U	+ +	M	4
Print-to-Order-Books									X	X			**2**	–	+ +	G	4
Therapies based on Stem Cell R&D					X	X		X	X	X			**5**	U	–	M	4
CBRN Sensor Network in Cities					X			X			X	X	**4**	U	–	M	3
CBRN Sensors on ERT								X			X		**2**	+ +	– –	G	3
Immunotherapy				X				X					**2**	U	+	M	3
Improved Treatments from Data Analysis								X		X			**2**	U	+	M	3
Smart Systems									X				**1**	+	+	M	3
Hydrogen Vehicles							X					X	**2**	– –	+ +	G	3
Implants for Tracking and ID					X	X					X		**3**	+	–	M	3
Gene Therapy				X				X					**2**	U	–	G	2
Chip Implants for Brain						X		X	X		X		**4**	–	–	M	2
Drugs Tailored to Genetics				X				X					**2**	–	+	M	2
Secure Video Monitoring					X	X					X		**3**	U	–	M	2
Biometrics as sole ID					X	X					X		**3**	U	–	M	2
Hospital Robotics								X	X				**2**	U	–	M	1
Military Nanotechnologies									X		X		**2**	U	– –	G	1
Military Robotics					X						X		**2**	U	– –	G	1
Xenotransplantation								X					**1**	+	–	M	1
Artificial Muscles and Tissue								X			X		**2**	– –	+	M	1
GM Animals for R&D				X				X					**2**	+	– –	M	1
High-Tech Terrorism					X	X					X		**3**	U	– –	M	1
Memory Enhancing Drugs						X		X		X			**3**	–	– –	M	0
Super Soldiers					X						X		**2**	–	– –	M	-1
Genetic Selection of Offspring				X				X					**2**	– –	–	M	-1
Proxy-bot						X			X		X		**3**	– –	– –	M	-1
Quantum Computers									X	X	X		**3**	– –	– –	M	-1
Robotic Scientist								X					**1**	–	– –	M	-2

Cheap Solar Energy Collection, Conversion, and Storage

Definition: Solar energy systems cheap enough to be widely available to developing and undeveloped countries and economically disadvantaged populations.

Sectoral Impact: The direct impact of this application is in the energy sector. However, it has important ramifications for several other sectors, especially in developing economies. By providing power for water pumping and irrigation, solar energy application affects agriculture and, thus, water, food, and land. By improving food and water availability in rural areas, it can contribute to improved health; by providing energy without fuel combustion, it reduces environmental emissions. Combined with the availability of highly efficient solid state lighting technology,[68] it also provides a mechanism for the rural populace to educate their children and participate in cottage industries. The development of rural cooperatives will contribute to rural economic development and can also provide an alternative to the urban migration that often leads to poor living conditions in areas just outside major cities. By providing an alternative to subsistence farming and building local economies, this application can also contribute to the relaxation of tensions resulting from the rich-poor gap in developing economies and thus can affect governance and social structure.[69] In fact, concerns about unrest in rural regions in response to rapid development of localized affluent areas have been reported recently by observers of both China and India.[70]

Technical Feasibility: The principal barrier to widespread use of solar energy for electricity generation is cost, and the principal drivers of solar cell cost are the efficiency with which the cell converts sunlight to electricity and the manufacturing cost of the collection system, including provision for storage of energy during periods without sufficient sunlight.[71] Recent technical advances are addressing both of these issues, and hence our assessment is that this application will be feasible by 2020. Solar collector designs using composites based on nanoscale organic conductors, as well as those using large polymer molecules that mimic biological processes, promise cheap large-scale manufacturing,[72] and efficiency targets consistent with application needs seem achievable within five to ten years. Moreover, developments in battery technology—in particular, the emergence of higher-energy-density batteries using nanoparticles and nanostructures—have the potential to provide the cheap, small-scale storage needed to support distributed solar collectors.[73]

Implementation Feasibility: This TA does not raise significant public policy issues. We characterize the market (the local electricity component of the energy market need that it satisfies) as medium-sized.

Diffusion Foresight: Diffusion assessment is moderated, because it will be more difficult for this TA to penetrate the electricity market where a working electricity grid already exists and where conventional fuels are readily available.

Rural Connection to Telephones and the Internet Using Wireless Communications

Definition: Widely available telephone and Internet connectivity without wired network infrastructure.

Sectoral Impact: The "last mile" problem (i.e., the expense of bringing wired networks from backbones into individual dwellings) has been a major factor impeding the development of rural areas. The availability of wireless communications to solve this problem would, in addition to facilitating economic development, have major impacts on

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[68] Light Up the World Foundation (2002). Semiconductor light-emitting diodes are currently more efficient than incandescent bulbs but less efficient than fluorescent lights. They are already in widespread use in applications requiring durability and compactness (e.g., traffic lights). For a detailed discussion of the status and objectives of international R&D, see the Sandia National Laboratories home page on solid-state lighting at http://www.lighting.sandia.gov.

[69] "200,000 Households to Get Solar Cells" (2004); "Fresh Efforts to Tap Solar Energy" (2004).

[70] Eckholm (2001).

[71] National Renewable Energy Laboratory (undated).

[72] Fairley (2004).

[73] Chung et al. (2002); Curtright (2004); Lucent Technologies (2004); Arico et al. (2005).

society through the rapid diffusion of information and ideas. Specific examples include the empowerment of women and their changing role in society, as well as the increased enabling of nongovernmental organizations to recruit, raise funds, and plan and accomplish actions rapidly and even with some degree of covertness. It would also influence health and education through access to medical information and record keeping and through the availability of Web-based classes in localities where students or teachers are unable to travel regularly to schools. Rural wireless communications could enable both local and national governments to monitor resources (e.g., on wildlife reserves) and environmental conditions and pollution, thus contributing to resource conservation and environmental protection. In addition, widely available encrypted wireless connectivity would likely raise the bar for government security and intelligence operations, impeding tracking and surveillance by law enforcement organizations.

Technical Feasibility: In some developing economies today, wireless communication systems are growing so rapidly that they are in fact replacing landlines as the preferred means of connectivity.[74] By 2020, wireless communication, including both wide-area networks and satellite connectivity, will likely enable middle- and upper-class people anywhere on the globe to access telephones and the Internet, with bundled packages including television, computing, and other entertainment options also available on a specialized basis.[75]

Implementation Feasibility: The current rate of growth of wireless communication worldwide testifies to the large market need for this TA.

Diffusion Foresight: This TA will be implemented globally.

Communication Devices for Ubiquitous Information Access Anywhere, Anytime

Definition: Communication and storage devices that provide agile access to information sources anywhere and anytime—operating seamlessly across communication and data storage protocols. Devices may be either wired or wireless and will have increasing local data storage cache capabilities for not only text but for meta-text with layered contextual information, images, voice, music, video, and movies.

Sectoral Impact: Beyond the effects from rural wireless communications, advanced communication and access devices will continue the evolution of our social structure by allowing individuals to not only communicate wherever they are (including on the move) but to remain connected wherever and whenever they want. Cellular phones and wireless text messenger personal digital assistants (PDAs) are already changing the way we interact with others. Governance will continue to evolve to enable citizens to access rich information and also enable tele-involvement in government interactions with bureaucratic and elected officials. Health information will expand to include not only ready access to information but to facilitate information exchange about our physical state with health care providers. Economic development will be affected by productivity improvements, new avenues for commerce on-the-fly, and continued economic expansion from global Internet commerce. Seamless, multimedia information access will provide rich information on educational topics and expand Internet-based remote

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[74] "Russian Cell Phone Boom Helps Connect People" (2004); "Experts: China's Cell Phone Users to Reach 600mn by 2010" (2005); "China's Cell Phone Users Hit 300m" (2004).

[75] Earlier discussions by Anderson et al. (2000) talked about the possibility of ubiquitous digital access to communications and the Internet, but the recent global expansion of wireless infrastructure appears to make this trend more likely to be globally available, even to rural areas.

educational opportunities. Military exploitation of information access on the move will improve combat planning and execution, logistics, and support functions. Intelligence effects will be mixed. Information sharing, access to and processing of multimedia information, and some tracking of individual activities will be improved, but expanded use of encryption plus the increased numbers of communication channels will increase the volume of information needed to watch.

Technical Feasibility: Visions for seamless data, voice, and video sharing with universal connectivity have been around for a few years now,[76] with some progress already being made in commercial products (e.g., the integration of voice, text, image, and even video sharing on cellular phones and PDAs). While all challenges in seamless, multimedia access will not have been solved by 2020, a workable set of technological advances is likely to provide usable TAs during this period.

Implementation Feasibility: The market for these devices will be large but will be focused in developed countries where large populations and business can afford to pay for their services and where wireless, flexible broadband capabilities are available and updated often.

Diffusion Foresight: This TA will be moderated by the cost to acquire and pay for information devices and services.[77]

Genetically Modified Crops

Definition: The capability to genetically modify crops to improve the nutritional value of food (e.g., by adding vitamins and micronutrients), increase production (e.g., by tailoring crops to local conditions), and reduce pesticide use (e.g., by increasing pest resistance).

Sectoral Impact: This application would directly address the global problem of malnutrition, one of the leading causes of infant mortality, by providing enhanced nutrition, thus influencing food, population, and health. In addition, it would conserve natural resources used by the agricultural sector, increase productivity, and eliminate sources of pollution, thus influencing water and land, energy, and environment, respectively. Depending on the cost and availability of the GM seeds,[78] it could also contribute to economic development by providing opportunities to improve the economics of local agriculture.

Technical Feasibility: By 2020, it is estimated that it will be possible to modify staple food crops genetically so as to make them more robust against environmental damage, repel pests without using polluting pesticides, and improve their nutritional value.

Implementation Feasibility: Currently, there is substantial resistance to GM crops in some developed countries,[79] and an ongoing debate about potential negative impacts on agriculture and the environment. A recent National Academies panel on the safety of GM foods could not rule out the possible introduction of unintended compositional changes to GM foods that may have adverse effects on human health. The panel pointed out that genetic modification has a higher risk than some traditional modification

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[76] See, for example, Anderson et al. (2000) and Hundley et al. (2003).

[77] See, for example, Anderson et al. (2000).

[78] Wu and Butz (2004).

[79] "Canadians Increasingly Uneasy About GM Food" (2004); Jones (2004c); "Anti-GM Feeling Hardens" (2004); "Public Opposition to GM Crops Is Growing" (2004); Ho and Ching (2003).

techniques, such as crossbreeding, but a lower risk than other traditional modification techniques, such as irradiation (which causes random variations). The panel recommended improvements for monitoring the safety of GM foods, which could go a long way to improving the actual and perceived safety of GM foods. Reducing the chance of adverse health effects requires the use of appropriate scientific methods to predict and identify unintended compositional changes that may result from genetic modification of plants, animals, and microorganisms intended for use as food.[80] However, the needs of poorer countries may well drive wide acceptance of this technology for staples such as rice and soybeans. A turning point may be reached when the emphasis shifts from crops that are commercially attractive to the technology developers to crops that are needed to feed large populations.[81]

Diffusion Foresight: This TA will be moderated by public debate and its possible unforeseen consequences.

Rapid Bioassays

Definition: The capability to rapidly perform tests to verify the presence or absence of specific biological substances and to perform multiple tests simultaneously.

Sectoral Impact: This application would allow rapid screening to identify or eliminate threats to public health and would provide governments with new tools to limit the spread of diseases, thus influencing both health and governance. It could also significantly improve patient outcomes and increase use of correct medicines to limit the spread of antibiotic and drug resistance. Finally, it would allow the identification of pathogens in the environment, for use by both civilians and military personnel, and could enable economic development by providing a means to ensure the safe movement of people and materials.

Technical Feasibility: Current bioassay methods (e.g., using lab-on-a-chip microarrays),[82] together with recent progress in gene sequencing and monitoring chemical reactions in living organisms,[83] promise rapid development in bioassay capabilities. For example, the speed of current sequencing technologies enabled analyses of the severe acute respiratory syndrome (SARS) virus barely a year after the recognized outbreak of the disease.[84] By 2020, the combination of available data from genomics and proteomics with developing testing methods and systems should enable rapid and highly accurate bioassays.

Implementation Feasibility: The public health market need should be a strong driver for the implementation of this TA.

Diffusion Foresight: This TA will be implemented globally.

Filters and Catalysts to Enable Water Purification and Decontamination

Definition: The capability to filter, purify, and decontaminate water with great efficacy and high reliability locally using unskilled labor.

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[80] National Research Council (2004).
[81] Kurup (2004).
[82] Jung and Stephanopoulos (2004); Freedman (2004).
[83] Venter et al. (2001); Lok (2004).
[84] Chinese SARS Molecular Epidemiology Consortium (2004).

Sectoral Impact: Since water is a critically scarce resource in several areas of the world under conflict, especially in the Middle East,[85] this application can have enormous influence on conflict, as well as resource (e.g., water and land) use, by enabling the cleaning of wastewater for reuse and by making currently unfit water sources usable. This will benefit the environment by conserving resources and reducing waste streams. Access to clean water will also improve local hygiene—benefiting health—and enable agriculture and manufacturing to increase food production and enhance economic development. The same filter and catalyst technologies will also be available to military personnel and first responders for problems that involve chemical or biological contaminants.

Technical Feasibility: Advances in nanotechnology have increased the likelihood that by 2020 we will have the ability to design and manufacture filters and catalysts that selectively separate and act against pathogens and chemical agents, both through pore size and chemical and biological functionalization.[86]

Implementation Feasibility: This TA does not raise significant public policy issues. We characterize the market need it satisfies, the local availability of clean water, as medium-sized in 2020. However, this market could grow substantially in size as the technology matures and can also be used to improve water quality in developed areas.

Diffusion Forecast: This TA will be moderated because it will initially apply only to areas where water quality or availability is a major issue.

Targeted Drug Delivery for Tumor and Pathogen Location and Destruction

Definition: The capability to design and implement drug therapies that preferentially attack specific tumors or pathogens, without harming healthy tissues and cells.

Sectoral Impact: Limiting damage to healthy tissue is one of the main concerns in cancer therapy decisions.[87] This application would first appear in specialized clinics or treatment centers, probably for specific therapies. However, as experience becomes more widespread, it could ultimately enable treatment of cancers and other diseases on-site in remote areas, addressing public health problems in developing countries and potentially influencing population. Reduction of major health problems would free up government resources to address other social and economic development goals and might also contribute to reduction of tensions, especially when they stem from public health issues, with major potential influence on governance and social structure.

Technical Feasibility: Several techniques exist today to target certain tumor locations based on biological markers, as well as to encapsulate drugs in biomaterials for later delivery.[88] Developments anticipated by 2020 will likely extend this capability to many important tumors and pathogens and provide accurate and reliable means for delivering planned doses or agents of destruction.[89] See Appendix E for a detailed discussion of possible advances enabled by nanotechnology.

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[85] Rudge (2004).
[86] Cotriss (2004); Bradbury (2004); "Project Designed to Promote Cooperation" (2004); Zhong et al. (2003); Campbell (2004).
[87] National Cancer Institute (2003).
[88] Gao et al. (2004); Robinson (2004).
[89] Lurie (2004).

Implementation Feasibility: This TA does not raise significant public policy issues, although there is the possibility of conflict over insurance coverage and priority for treatment. We characterize the market need that it satisfies, which is an important sector of the health care market, as medium-sized in 2020.

Diffusion Foresight: This TA will be moderated, because it is anticipated that its capability may be more readily available in developed countries. However, we estimate that it will be sufficiently developed by 2020 to address important global health problems on a case-by-case basis.

Cheap Autonomous Housing

Definition: Locally self-sufficient and affordable housing that provides shelter adaptable to local conditions, as well as energy for heating and cooling, and cooking.

Sectoral Impact: This application would provide for the basic energy and shelter needs of rural populations at minimal cost, improving on or replacing inadequate or antiquated methods, materials, and systems. It would increase the efficient use of local resources and improve quality of life. Principal sectors influenced would be energy, health, and economic development. It could contribute to relieving stress on government institutions and social structures, although the net impact would depend strongly on the nature of the local situation and government response. This type of housing would also be useful in response to natural disasters, power grid failures, and other emergencies, and to support military troops in the field.

Technical Feasibility: Recent developments in biotechnology, nanotechnology, and materials technology, and their integration, provide several different possibilities for this TA, including lightweight and environmentally resistant structural materials,[90] nanostructured batteries and fuel cells,[91] bio-based fuel cells],[92] nanoparticle energetic materials and catalysts,[93] and solar energy harvesting polymers.[94] While all of these areas will progress, and it is likely that small demonstration energy systems and innovative building materials will be available by 2020, we believe that it is unlikely that this TA will be widely available by 2020. Cost is probably the principal barrier to this application.

Implementation Feasibility: This TA does not raise significant public policy issues.

Diffusion Foresight: This TA will be implemented globally.

Green Manufacturing

Definition: Redesigned manufacturing processes that either eliminate or greatly reduce waste streams and the use of toxic materials.

Sectoral Impact: This application would reduce the burden of pollution cleanup on local governments, as well as the volume of toxic materials in the environment. The net effect on economic development will be country specific, depending on whether the improved environment attracts investment and increases economic growth and trade and whether there are increased costs. The cleaner environment would have positive impacts

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[90] Scrivener and Van Damme (2004); Cassar (2004).
[91] Curtright et al. (2004); Arico et al. (2005).
[92] Sandia National Laboratories (2002).
[93] Jacoby (2004); Harrison (2004); Brown (2002).
[94] Adronov et al. (2000).

on health, and the reduction of waste streams would increase the productivity of energy, water, and land use.

Technical Feasibility: The increasing cost of remediation, as well as the increasing public awareness of environmental problems and interest in resource conservation and environmental protection, has driven the development of "green" manufacturing processes based on the substitution of raw materials and the design of processes to either eliminate waste streams or ensure that they are nontoxic and environmentally friendly.[95]

Implementation Feasibility: By 2020, this trend should encompass most significant industrial pollutants in developed countries, although for cases in which there are increased costs, developing economies may be less likely to use these processes.

Diffusion Foresight: This TA will be moderated by the likelihood that it will be applied on a case-by-case basis either where there are strong regulations in place or where there are clear economic benefits.

Ubiquitous Radio Frequency Identification Tagging of Commercial Products and Individuals

Definition: Widespread use of RFID tags for tracking retail products from manufacture through sale and beyond, as well as the tracking of individuals and their movements.

Sectoral Impact: The capability to tag, identify, and characterize commercial products throughout the supply chain will allow manufacturers, distributors, and retailers to control their inventory to reduce losses by theft; rapidly identify and respond to mishaps; ensure that perishable or time-sensitive goods are delivered when needed; and increase efficiency through just-in-time inventory. Data recorded at time of sale could aid marketers and, if the tags are not removed or deactivated at point of sale, in combination with cell phones could allow marketers to track consumers and trigger targeted advertisements.[96] The principal influence of this TA will be on economic development of the retail sector through improved inventory control and more efficient marketing. It will also enable improvements in logistics for the military. RFIDs in personal identification (ID) cards, such as those used by employers, provide another way to track individuals beyond the intended application in company access readers. If this truly becomes ubiquitous, governments will have to deal with privacy concerns. Moreover, nonvisual identifiers could lead to new ways of social groupings and self-organized communities not necessarily based on conventional characteristics, such as physical appearance, race, style of dress, or economic station.

Technical Feasibility: Currently, RFID tags[97] are being developed and tested for labeling many different products to aid functions such as making purchases at a store, confirming inventory, and combating theft,[98] as well as for use in employee ID cards. These tags label a product or person with a specific code and transmit its information a short distance away (from 1 to 10 meters, but possibly farther). Grocery stores and larger

[95] Lempert et al. (2003).
[96] While RFID tags on products are already in use, and cell phones can be monitored, whether a sufficient quantity of accurate and detailed information to assist marketing will be able to be gathered is uncertain.
[97] Bonsor (undated); Langheinrich (2004).
[98] Kumagai and Cherry (2004); Knowledge@Wharton (2004).

retailers such as Wal-Mart have begun to use them to track pallets of products.[99] This TA is highly likely to be technically feasible in 2020.

Implementation Feasibility: The key issue affecting implementation is whether the technology will evolve to address privacy concerns sufficiently enough to enable widespread adoption. Despite its potential impact on privacy, this application is already in use by Wal-Mart, the largest retailer in the United States, and seems to be gathering momentum.[100] RFID for personal identification is expanding. Corporations already widely use RFIDs in their company ID cards for building access. Several methods have been suggested to protect the privacy of consumers.[101]

Diffusion Foresight: Given the need for extensive infrastructure, there may be some moderation of individual tracking, but, given commercial globalization demands and current trends, logistics tracking of products will likely be implemented globally.

Hybrid Vehicles

Definition: Automobiles available to the mass auto market with power systems that combine internal combustion with other power sources.

Sectoral Impact: This application has the potential to initiate the transformation of the transportation sector from reliance on internal combustion engines to other power sources such as electric motors and fuel cells. By providing a hybrid option that is more efficient, and hence less polluting, it could form a bridge to less-polluting power sources, especially in urban areas with currently high levels of air pollution.

Technical Feasibility: Gasoline-electric hybrids, such as the Toyota Prius and the Honda Insight and Civic, have been on the market for some time, and new hybrids are appearing with each new model year.[102] "Plug-in" hybrids with larger banks of batteries and a plug-in system operate like electric rechargeable vehicles during their first tens of miles of operation (using current battery technologies) but switch to conventional gas-electric hybrids when the batteries get low. Plug-in hybrids may fill the time gap between current production hybrids and alternative (hydrogen) fueled vehicles.[103] The cooperative research program between the U.S. government and automotive industry, Partnership for a New Generation of Vehicles, developed several diesel-electric and diesel-fuel cell concept cars,[104] and the current FreedomCar initiative is working on R&D for hydrogen-fueled vehicles.[105] By 2020, a variety of options for hybrid vehicles should be technically feasible and widely available.

Implementation Feasibility: The hybrid vehicle market has taken off impressively, with more than a million gasoline-electric hybrids already sold, and more and more companies around the world planning to release new hybrid vehicles.[106] This trend is clearly satisfying a large market, with no apparent negative social impacts. The only questions are whether the vehicles will be sustainable in five to ten years, when, for

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[99] Kumagai and Cherry (2004); Knowledge@Wharton (2004).
[100] Landy (2005).
[101] Kumagai and Cherry (2004).
[102] See, for example, http://www.fueleconomy.gov for the latest news and information about hybrid vehicles.
[103] Jones (2005).
[104] National Research Council (2001).
[105] National Research Council (2004).
[106] Buban (2004); "Japan Leads the Hybrid Charge" (2002); Porretto (2004).

example, batteries need replacement,[107] and how long it will take before the next-generation power system that is not a hybrid will be available.[108]

Diffusion Forecast: This technology is already being implemented globally.

Pervasive Sensors

Definition: Presence of sensors in most public areas and the ability to network sensor data to accomplish real-time surveillance.

Sectoral Impact: This application will provide governments with a powerful tool for law enforcement but, at the same time, raise serious privacy issues with respect to both surveillance and the collection and handling of data, thus influencing governance and social structure, respectively. Companies and countries with expertise in sensor development, network design and implementation, and data management will have expanded opportunities for economic development. The sensor networks may have dual-use (i.e., military and civilian) applications as well.

Technical Feasibility: The availability of very small cameras,[109] together with the increasing miniaturization (using microtechnology and nanotechnology) of combined sensing and data collection and transmission platforms and analysis software,[110] suggests that by 2020 it will be feasible to implement widely and network together sensors small enough to be unrecognizable to nonspecialists.[111]

Implementation Feasibility: This application has already raised significant public policy issues—for example, through cell phone cameras being a potential abuse of privacy.[112] As sensors become more pervasive, continued battles between government and private organizations seeking to implement surveillance and privacy advocates should be anticipated.

Diffusion Foresight: This TA will be implemented globally.

Tissue Engineering

Definition: The design and engineering of living tissue for implantation and replacement.

Sectoral Impact: Engineering of living tissue can provide options for treatment of wounds, disease, and injuries that would minimize rejection and reoccurrence. It might allow classes of individuals who are currently chronically ill or untreatable (e.g., those with damaged corneas or damaged spinal cartilage) to become more productive members of society, thus affecting population. It could also create governance issues involving sources of biological and nonbiological materials, bioengineering methods, and access to and cost of treatment. Companies and countries with required technical or medical expertise, intellectual property, or manufacturing capability could see increased economic development.

Technical Feasibility: Tissue engineering has already succeeded in growing skin cells that are being used for wound closures, and engineered tissues for corneas, cartilage,

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[107] Peckham (2003a); Peckham (2003b).
[108] Cohn and Heywood (2002); Sustainable Mobility Project (2004).
[109] Geier (2004).
[110] Goldstein (2004a); Rosenblatt (2004).
[111] See also prior discussions on ubiquitous smart sensors in Anderson et al. (2000).
[112] Nishi (2004); Barr (2004).

bone, and liver are in clinical trials.[113] These developments have resulted from a combination of engineered materials and structures, some based on biomimetic approaches, and the use of biological materials and methods to provide the necessary conditions for cell and tissue growth. Perhaps the ultimate goal is the use of engineered tissue to repair damage done by a heart attack. This is a currently active research area, with several promising approaches.[114] Whether or not it is yet viable for treating heart attacks, we anticipate that by 2020 tissue engineering will be a feasible option for addressing a wide variety of medical problems.

Implementation Feasibility: This TA does not raise significant public policy issues. We characterize the market need that it satisfies, which is an important sector of the health care market, as medium-sized in 2020.

Diffusion Forecast: This TA would be moderated, because it is anticipated that this capability may be more readily available, at least initially, in developed countries and to affluent populations.

Improved Diagnostic and Surgical Methods

Definition: Use of technologies to improve the precision of diagnoses and greatly increase the accuracy and efficacy of surgical procedures, while reducing invasiveness and recovery time.

Sectoral Impact: Increased precision of diagnoses and efficacy of surgical procedures will improve patient health, and reduced invasiveness and reduced recovery time will make surgery available to a wider group of patients. Education of medical practitioners will also be affected as the new methods are developed and adopted in teaching hospitals.

Technical Feasibility: Advances in biotechnology and nanotechnology, as well as their integration, continue to provide more accurate and less invasive diagnostic methods and nonsurgical options for treatment of some conditions.[115] Three-dimensional displays of bodily organs or drug interactions could enable improved diagnoses.[116] Approaches such as microneedles[117] and nanomaterials functionalized with biological agents[118] may offer low-impact treatment methods following such precise diagnoses. Nanostructured or nanocomposite materials[119] may offer combinations of properties (e.g., hardness, biocompatibility) that will improve performance as surgical instruments. By 2020, the combined developments in diagnostics and nanoscale design and functionalization of biomaterials should enable the widespread adoption of improved surgical methods.

Implementation Feasibility: This TA does not raise significant public policy issues, and a large market exists.

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113 Langer and Tirrell (2004).
114 Cohen and Leor (2004).
115 For example, see Hotraphinyo and Riviere (2001); Lurie (2004); Gao et al. (2004); "Dots Pinpoint Cancer" (2004); Ang, Reviere, and Khosla (2000); "Electronic Nose Device Proves Effective for Diagnosing Pneumonia and Sinusitis" (2004); and Shen et al. (2005); the discussion in this chapter under "Targeted Drug Delivery"; and Appendix E.
116 Rider et al. (2003).
117 Peplow (2004b); McAllister (2003).
118 Day (2003); Pilcher (2004a).
119 Peplow (2004b).

Diffusion Forecast: This TA will be implemented globally, although the specific methods used in different countries and regions may vary according to local needs and desires.

Wearable Computers

Definition: Computational devices embedded in clothing or other wearable items such as handbags, purses, or jewelry.

Sectoral Impact: This application, coupled with current and developing sensor capabilities, could enable continuous health monitoring. Together with miniaturized communication devices, it could enable on-demand distance learning or the ability to send and receive instructions in military or conflict situations. It would also contribute to the continued development of economic sectors based on computation and could enable new uses of personal computational devices (e.g., instant messaging via accessories) with the potential to influence social structure.

Technical Feasibility: Several different groups have already developed fabrics that incorporate electrical circuits and demonstrated them for health monitoring, function switching, and art and design.[120] The integration of developing trends in functional nanoscale fibers,[121] microsystems that include integrated circuits,[122] and small communications devices[123] should facilitate the inclusion of computational capability in an increasingly broader range of wearable fabrics and accessories. The level of computational capability and consequent breadth of application available by 2020 is, however, uncertain.

Implementation Feasibility: This TA does not raise significant public policy issues. It is judged to appeal to a medium-sized market that might include both high-end entertainment and recreational and specialized medical and government users.

Diffusion Foresight: This TA will be moderated, because it will likely be used only in countries and regions with the specialized markets described above.

Quantum Cryptography

Definition: The use of quantum mechanical methods to encode information for secure transfer.

Sectoral Impact: This TA would provide a means for reliably secure transfer of information with the ability to detect any attempt at interception. It would be extremely attractive to both military and civilian organizations (e.g., intelligence, mission control, banking and finance), thus influencing both defense and economic development.

Technical Feasibility: This application is based on the use of the state of a quantum mechanical system (e.g., the polarization state of light) to encode information. Recent research has demonstrated that pairs of quantum states can be coupled, or "entangled," so that a measurement of the state of one determines the state of the other.[124] Furthermore, because it is well known that any measurement of a quantum state disturbs

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[120] Clothier (2004); Bowie (2000); Wahl (2004); "Infineon Presents Concept for 'Smart' Industrial Textiles" (2003); Park and Jayaraman (2003); Warneke and Pister (2002).

[121] Thomson (2003a); Thomson (2003b).

[122] Manjoo (2001).

[123] Hoover (2004).

[124] Albert Einstein discussed this theoretically, calling it "spooky action at a distance." See, for example, Spotts (2001).

that state,[125] information so encoded sent from one place to another will be noticeably changed if it is intercepted en route. Two different companies have already designed and manufactured quantum encoding devices and demonstrated their use over relatively short distances.[126] By 2020, it may well be feasible to use such methods for secure information transfer over distances needed for the applications mentioned above.

Implementation Feasibility: This TA does not raise significant public policy issues and satisfies a large market need in the banking and finance sector.

Diffusion Forecast: This TA will be implemented globally.

Other Technology Applications

The remaining 40 TAs listed in Table 2.2 fall into three general categories: health and medical applications, commercial applications, and government and military applications. We summarize these by topical area below. Appendix G provides a definition and describes the sectoral impact assignments for each of these TAs.

Health and Medical Applications

Medical diagnostics and drug development will continue to improve by advances in the sensitivity of instrumentation and computational capabilities to model the effects of proposed drugs and to screen drugs for development. Although technical feasibility by 2020 is uncertain, applications such as computational or "in silico" drug discovery will likely be implemented on a global basis once available. Other possibilities in this area that are less likely to be implemented by 2020 involve the widespread use of robotics in hospitals and the development and use of robotic scientists to perform experiments.

Continued developments in genetics are likely by 2020 to make genetic screening, which is already available today on a limited basis,[127] into a powerful tool for disease prevention and perhaps treatment, although its widespread use may be impeded by government or public objections in some countries or regions. Genetic selection of offspring—for example, for strength or intelligence—although highly unlikely to be feasible by 2020, is an application that will likely generate much opposition in some parts of the world, but perhaps be welcomed in others.[128] The use of biotechnology to develop GM insects (e.g., sterile versions of agricultural pests or disease carriers) or GM animals (e.g., as a source of organs for xenotransplantation), both with uncertain technical feasibility by 2020, would likely lead to similar mixed reactions and implementation.

Table 2.2 also lists a number of therapeutic or prosthetic applications that could potentially begin to appear by 2020, as a result of combined developments in biotechnology, nanotechnology, materials, neuroscience, and biomedical engineering. They include devices to enhance recovery after injury, illness, or stroke; drugs that use the recognition capabilities of the immune system to target organs or tumors; computer chip implants linked directly to the brain; and drugs to enhance or selectively eliminate

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[125] A manifestation of Heisenberg's Uncertainty Principle. For a discussion of the relationship to quantum information transfer, see Ouellette (2005). The ability to control entangled quantum states could lead to further applications such as secure long distance information transfer at very high data rates.

[126] Johnson (2004a); Emery (2004).

[127] "Future Visions" (2003).

[128] For example, the greater desirability of male offspring in some Asian countries, together with current capability to determine sex in the womb, has already had significant demographic effects (Sharma, 2004). The capability to select sex through in vitro fertilization is available today (Stein, 2004b).

memories. The authored papers in the appendices discuss the factors affecting the uncertainty of such developments.

Commercial Applications

Commercial applications that are likely to be feasible in 2020 include unconventional means of transport to satisfy some of the needs currently met by today's automobiles. Electric rickshaws in India [129] and minicars in Europe[130] may be forerunners of such transport systems that could, for example, be powered by very small electric motors or bio-based fuel cells. Hydrogen vehicles, though apparently attractive to a large market, are highly unlikely to be available by 2020 because of the magnitude of remaining technical and infrastructure problems.[131] Unmanned aerial vehicles (UAVs) and systems, which are currently used mostly for military surveillance, could see a variety of commercial uses by 2020 (e.g., by farmers or forest rangers) and could even see functional use in such activities as firefighting.

Continued developments in materials, as well as miniaturization and integration of computation, memory, and communication capability, are likely to enable by 2020 "smart" systems (e.g., buildings and roads that respond to environmental change,[132] kitchens that cook with wireless instruction).[133]

Table 2.2 also lists a number of potential applications based on advances in information technology, such as hands-free computer interfaces, anonymous transactions with digital credentials and electronic cash, print-to-order books, and secure video monitoring. The factors affecting the uncertainty of such developments are discussed in the authored papers in the appendices.

Government and Military Applications

As illustrated throughout the discussions of technology application and implementation in this chapter, the integrated development of bio-, nano-, materials, and information technology presents both governance challenges and new potential threats. These technology developments, together with the increased diffusion of information and technical expertise worldwide, may enable terrorists or rogue nations to develop or obtain, sooner or more easily, chemical, biological, radiological, or nuclear (CBRN) weapons.[134] However, the development of smaller, more sensitive nanostructures and highly selective sensors using functionalized nanomaterials and nanostructures,[135] together with miniaturized sensing and communications platforms, could by 2020 provide for networks for early warning of attacks and is likely to enable highly functional protection for soldiers and emergency responders. Advances in drug development may also accelerate the development of medicines to counter the threat. The ability to develop autonomous networked systems with dedicated power sources may also allow the implementation of parallel, redundant, or more robust infrastructures.

Other military TAs that could be feasible by 2020 include increased use of robotics for intelligence, surveillance, and reconnaissance—as well as combat

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[129] "Macneill Plans Battery-Operated Auto-Rickshaws" (2005).
[130] Weernink (2004).
[131] U.S. Department of Energy (2003).
[132] Vernet (2004); Cassar (2004); Scrivener and Van Damme (2004).
[133] Ju et al. (2001).
[134] Mintz (2004); Smith, Inglesby, and O'Toole (2003).
[135] Cui et al. (2001).

operations[136]—and technologically enhanced capabilities of individual soldiers.[137] A specialized technology that is under development for its potential to greatly accelerate code-breaking capabilities and perhaps revolutionize the field of encryption[138]—quantum computing (i.e., the use of quantum mechanical states as bits of information in computation)—is unlikely to be available by 2020.

Biometric data (e.g., fingerprints, iris scan, facial recognition software) are beginning to be used in specialized applications, such as entry to government facilities and validation of certain transactions.[139] For example, the use of a standard ID card for U.S. government employees that includes biometric data has been mandated.[140] How this TA will develop, and whether a wider use of biometric ID in the commercial and public sectors will emerge by 2020, is uncertain,[141] with substantial opposition anticipated from privacy advocates.[142]

Summary of Technology Applications

Table 2.3 summarizes the results of our foresight assessment of the TAs considered in this chapter. Each TA is placed in the table according to its 2020 technical feasibility (rows) and implementation feasibility (columns). The number of sectors that it impacts and whether its diffusion foresight is *global* (*G*) or *moderated* (*M*) is also shown in the table in parenthesis for each technology. The darker lines divide the table into quadrants based on technical and implementation feasibility, which facilitates identification of the TAs most likely to be important in 2020.

[136] For example, the Joint Unmanned Combat Air Systems program is a collaboration between DARPA, the Air Force, and the Navy. See http://www.darpa.mil/j-ucas/.

[137] For example, the Massachusetts Institute of Technology–based Institute for Soldier Nanotechnologies is developing an integrated battle suit using nanotechnologies to increase strength and endurance and automatically respond to certain threats. See the MIT Institute for Solder Nanotechnologies' Web site, http://web.mit.edu/isn/, for more information.

[138] It has been demonstrated that a quantum computer could so rapidly factor the large strings of random numbers currently used in encryption that this method would become infeasible.

[139] "Government of Malta Selects Bioscrypt V-Station Finger Scan Reader" (2004); "Emerging Homeland Security Surveillance Company Unveils Digital Video Recording Technology" (2004).

[140] The National Institute for Standards and Technology (NIST) is developing standards for a single government ID card based on biometrics. See NIST (2003) for a description of current biometric standards and NIST (2005) for the latest information on the progress of the Personal Identification Verification Project.

[141] See Appendix D for a discussion of the uncertainties associated with biometric identification.

[142] O'Harrow (2004b); Leach (2005).

Table 2.3
Technical and Implementation Feasibility of Illustrative 2020 Technology Applications

Technical Feasibility	*Implementation Feasibility*: Niche market only (– –)	May satisfy a need for a medium or large market, but raises significant public policy issues (–)	Satisfies a strong need for a medium market and raises no significant public policy issues (+)	Satisfies a strong need for a large market and raises no significant public policy issues (+ +)
Highly Feasible (+ +)	• CBRN Sensors on ERT (2,G)	• Genetic Screening (2,G) • GM Crops (8,M) • Pervasive Sensors (4,G)	• Targeted Drug Delivery (5,M) • Ubiquitous Information Access (6,M) • Ubiquitous RFID Tagging (4,G)	• Hybrid Vehicles (2,G) • Internet [for purposes of comparison] (7,G) • Rapid Bioassays (4,G) • Rural Wireless Comms (7,G)
Feasible (+)	• GM Animals for R&D (2,M) • Unconventional Transport (5,M)	• Implants for Tracking and ID (3,M) • Xenotransplantation (1,M)	• Cheap Solar Energy (10,M) • Drug Development from Screening (2,M) • Filters and Catalysts (7,M) • Green Manufacturing (6,M) • Monitoring and Control for Disease Management (2,M) • Smart Systems (1,M) • Tissue Engineering (4,M)	• Improved Diagnostic and Surgical Methods (2,G) • Quantum Cryptography (2,G)
Uncertain (U)	• Commercial UAVs (6,M) • High-Tech Terrorism (3,M) • Military Nanotechnologies (2,G) • Military Robotics (2,G)	• Biometrics as sole ID (3,M) • CBRN Sensor Network in Cities (4,M) • Gene Therapy (2,G) • GM Insects (5,M) • Hospital Robotics (2,M) • Secure Video Monitoring (3,M) • Therapies based on Stem Cell R&D (5,M)	• Enhanced Medical Recovery (3,M) • Immunotherapy (2,M) • Improved Treatments from Data Analysis (2,M) • Smart Textiles (4,M) • Wearable Computers (5,M)	• Electronic Transactions (2,G) • Hands-free Computer Interface (2,G) • *In-silico* drug R&D (2,G) • Resistant Textiles (2,G) • Secure Data Transfer (2,M)
Unlikely (–)	• Memory-Enhancing Drugs (3,M) • Robotic Scientist (1,M) • Super Soldiers (2,M)	• Chip Implants for Brain (4,M)	• Drugs Tailored to Genetics (2,M)	• Cheap Autonomous Housing (6,G) • Print-to-Order-Books (2,G)
Highly Unlikely (– –)	• Proxy-bot (3,M) • Quantum Computers (3,M)	• Genetic Selection of Offspring (2,M)	• Artificial Muscles and Tissue (2,M)	• Hydrogen Vehicles (2,G)

NOTE: For each technology, the parenthetical information indicates the number out of 12 societal sectors (water, food, land, population, governance, social structure, energy, health, economic development, education, defense and conflict, and environment and pollution) that can be impacted by the technology, and if the diffusion will be *global* (G) or *moderated* (M). For example, hybrid vehicles affect two sectors and will have global diffusion.

Technically Feasible Technology Applications That Are Likely to Be Implemented Widely

(*Four upper-right boxes in Table 2.3*) The TAs that appear to be both technically feasible and likely to be implemented widely in 2020, because they serve at least a medium-sized market and raise little to no significant public policy issues, are as follows (in order by the number of the 12 sectors they affect):

- Cheap solar energy (10 sectors)
- The Internet (for purposes of comparison) (7 sectors)
- Filters and catalysts for water purification (7 sectors)
- Rural wireless communications (7 sectors)
- Ubiquitous information access (6 sectors)
- Green manufacturing (6 sectors)
- Targeted drug delivery (5 sectors)
- Rapid bioassays (4 sectors)
- Tissue engineering (4 sectors)
- Ubiquitous RFID tagging (4 sectors)[143]
- Hybrid vehicles (2 sectors)
- Improved diagnostic and surgical methods (2 sectors)
- Quantum cryptography (2 sectors)
- Drug development from screening (2 sectors)
- Body monitoring and control for disease management (2 sectors)
- Smart systems (1 sector)

Technically Feasible Technology Applications That Are Less Likely to Be Implemented Widely

(*Four upper-left boxes in Table 2.3*) The TAs that appear to be technically feasible, but are less likely to be implemented widely in 2020 either because they raise significant public policy issues or because they serve only a niche market, are as follows (in order by the number of the 12 sectors that they affect):

Significant Public Policy Issues:

- GM crops (8 sectors)
- Pervasive sensors (4 sectors)
- Implants for human tracking and identification (3 sectors)
- Genetic screening (2 sectors)
- Xenotransplantation of organs and tissues (1 sector)

[143] Despite the potential impact on privacy, this application is already in use by Wal-Mart, the largest retailer in the United States, and seems to be gathering momentum (Landy, 2005), so implementation appears to be feasible. Several methods have been suggested to protect the privacy of consumers (Kumagai and Cherry, 2004).

Niche Market:

- Unconventional transport (5 sectors)
- GM animals for R&D (2 sectors)
- CBRN sensors on emergency responders (2 sectors)

Technology Applications for Which Technical Feasibility Is Uncertain in 2020 but That Would Be Implemented Widely If Available

(*Right two middle boxes in Table 2.3*) The TAs for which technical feasibility is uncertain, but that appear to appeal to large markets and thus would likely be implemented widely in 2020 if available, at least in developed countries, are as follows (in order by the number of the 12 sectors that they affect):

- Wearable computers (5 sectors)
- Smart textiles (4 sectors)
- Enhanced recovery from disability, illness, injury, or stroke (3 sectors)
- Hands-free computer interface (2 sectors)
- Anonymous transactions with digital credentials and electronic cash (2 sectors)
- Computational ("in-silico") drug R&D (2 sectors)
- Resistant (e.g., to dirt, contaminants, pests) textiles (2 sectors)[144]
- Secure personal data transfer through identity removal (2 sectors)
- Immunotherapy (2 sectors)
- Improved medical treatment from data analysis (2 sectors)

Technology Applications for Which Technical Feasibility Is Uncertain in 2020 and That Are Less Likely to Be Implemented Widely If Available

(*Left two middle boxes in Table 2.3*) The TAs for which technical feasibility is uncertain, and that are less likely to be implemented widely in 2020, either because they raise significant public policy issues or because they serve only a niche market, are as follows (in order by the number of the 12 sectors that they affect):

Significant Public Policy Issues:

- GM insects (5 sectors)
- Therapies based on stem cell R&D (5 sectors)
- CBRN sensor networks in cities (4 sectors)
- Secure video monitoring (e.g., by electronically altering facial images so that they can be recovered only with a specific algorithm) (3 sectors)
- Biometrics as sole personal identification (3 sectors)[145]
- Gene therapy (2 sectors)

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[144] Clothing with some of these capabilities is already available. What is meant here is widespread availability of textiles that resist dirt and pathogens. See Appendix G for definition and sectoral impact.

[145] Technical uncertainties for biometric identification include error rates (both false positives and false negatives), and secure backup for individuals whose biometric fails. While biometrics such as fingerprints on passports and iris or retina scans for entry to secure facilities are already in limited use, biometrics as a primary means of identification remains a challenging objective (Phillips and Newton, 2002).

- Robotic tools for hospitals (2 sectors).

Niche Market:

- Commercial unmanned aerial vehicles (6 sectors)
- Military robotics (2 sectors).

Wildcards:

- High-tech terrorism (3 sectors)[146]
- Military nanotechnologies (2 sectors)[147]

Technology Applications That Are Unlikely to Be Technically Feasible in 2020 but That Would Be Implemented Widely If Available

(*Four lower-right boxes in Table 2.3*) The TAs that are unlikely to be technically feasible in 2020, but that would be implemented widely if available, because they serve at least a medium-sized market and raise no significant public policy issues, are as follows (in order by the number of the 12 sectors that they affect):

- Cheap autonomous housing (6 sectors)
- Print-to-order books (2 sectors)[148]
- Genetically tailored drugs (2 sectors)
- Hydrogen-powered vehicles (2 sectors)
- Artificial muscles and tissue (2 sectors)

Technology Applications That Are Unlikely to Be Technically Feasible in 2020 and That Are Less Likely to Be Implemented Widely If Available

(*Four lower-left boxes in Table 2.3*) The TAs that are unlikely to be technically feasible in 2020 and that are less likely to be implemented widely, either because they raise significant public policy issues or because they serve only a niche market, are as follows (ordered by the number of the 12 sectors that they affect):

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[146] Technological advances certainly provide both new points of societal vulnerability (e.g., cyberattack) and new potential terrorist weapons (e.g., custom-designer pathogens). Major uncertainties relating to technical feasibility by 2020 include the level of technical sophistication needed to plan and carry out attacks, the efficacy of security systems and countermeasures, and the extent to which new technological capabilities might be used in unintended or disruptive ways with significant societal impact even if they do not perform fully as designed. These issues are discussed in Appendix E. Terrorist efforts and possibilities to acquire CBRN weapons are discussed in a recent series of articles ("The World After 9/11," 2004a; 2004b; 2004c).

[147] Military applications of nanotechnologies such as improved power systems, armor, sensors, medical treatments, and explosives are currently under R&D (see, for example, the MIT Institute for Solder Nanotechnologies' Web site, http://web.mit.edu/isn/). By "military nanotechnologies," we mean technologies with the potential to change the nature of warfare (see, for example, Altmann and Gubrud, 2004).

[148] Desktop publishing and print-on-demand for specialized applications currently exist. By "print-to-order books," we mean publisher printing of individual books only in response to specific orders.

Significant Public Policy Issues:

- Chip implants for the brain (4 sectors)
- Genetic selection of offspring (2 sectors)

Niche Market:

- Memory-enhancing drugs (3 sectors)
- Quantum computers (3 sectors)
- Humanlike robot (“proxy bot”) for individuals (3 sectors)
- Soldiers with greatly enhanced capabilities (“super soldiers”) (2 sectors)
- Robots to perform experiments (“robotic scientists”) (1 sector)

CHAPTER 3
INTERNATIONAL VARIATION IN TECHNOLOGY APPLICATIONS AND IMPLEMENTATION

The net assessment in Chapter Two took us a step further in understanding sectors that might benefit from use of technology applications that might be technically feasible and ready for use in the year 2020. In this chapter, we will take our analysis a step further to examine what might determine implementation of these TAs, by different countries and across a number of problems and issues. Nations have different priorities. The resources they can command to implement TAs also differ.

This chapter has five major sections. The first begins with a reporting of regional variation of technology application and implementation based on input from technology and regional and country experts. This section is followed by three sections that together lay out our approach to understanding the adoption and use of TAs by individual countries. These sections, respectively, describe drivers and barriers to technology adoption and use, discuss eight major problems and issues and the TAs relevant to addressing them, and report our assessment of country capacity to acquire TAs, taking into consideration the influence of drivers and barriers. The final section of this chapter examines the capacity of these countries to implement TAs to address each of the eight problems and issues.

Regional Variation of Technology Application and Implementation

We consulted experts within and outside RAND for their assessment of the impact of TAs in different regions of the world. For each region, they identified important problems and issues and relevant TAs.

For Africa, HIV/AIDS is seen to have a devastating effect on public health and the workforce. Africa also has large land areas with porous borders, which makes its populations more vulnerable to the transmission of infectious diseases and spillage from ethnic and other types of conflicts. Poor governance is a pervasive problem, and the lack of infrastructure seriously hinders development efforts.[149] Technologies that enable HIV drug development and treatment for a large number of people with little means and technological sophistication will be critical. GM crops might alleviate hunger and improve nutrition and also increase output, while providing jobs. UAVs might improve

[149] See United Nations Economic Commission for Africa (2004). This study surveyed 28 out of 53 African countries, assessing corruption, political representation, economic management, and respect for human rights in these countries. Chad and Kenya were ranked at the bottom. Although some experts dispute the causes of corruption and poor governance (mainly that poverty breeds poor governance, or vice versa), there is widespread agreement that corruption and poor governance are serious and widespread problems hindering development and stability in many African countries. Consequently, tackling corruption and poor governance is considered essential to improving livelihood and stability in Africa. See, for example, LaFraniere (2005) and Kaufmann (2005).

resource monitoring for conservation and resource use management.[150] Biometrics might be applied to secure border control. Rural wireless communications, cheap solar energy, and water purification were all seen as important to improving the standard of living for the vast majority of people in Africa.

For Asia, the lack of infrastructure outside national capitals and other developed areas was seen as a problem for technology implementation. Experts were also worried about the impact on the environment of rapid urban migration, industrial pollution, and land use decisions resulting from strong economic growth. Finally, most Asian countries are energy resource poor—except China, which has a large coal reserve—so that their dependence on imported oil is a major concern. TAs such as cheap solar energy for rural electrification, filters and catalysts for water purification, green manufacturing, hybrid vehicles, unconventional transport, GM crops, and rural wireless communications were all considered important to addressing the problems cited. RAND's regional experts also felt that genetic screening would likely be adopted if available, especially in China and India.

For Europe, there are important differences between East and West. Many advanced economies of Western Europe have rapidly aging populations. This demographic trend will affect all facets of life in these countries and should influence their decisions on technology adoption. In Eastern Europe, the bigger issue affecting technology adoption is poor and unreliable infrastructure. For virtually all countries in Europe, except Russia, dependence on energy imports will also affect decisions on technology adoption. In response to these problems and issues, Western European countries will likely welcome accelerated drug discovery methods and targeted drug delivery. For countries in Eastern Europe, cheap solar energy, water purification, and rural wireless communications should be important. Hybrid vehicles and unconventional means of transport should also be attractive to Europeans to alleviate dependence on energy imports. The European Union (EU) will also be a factor in the way Europeans acquire and implement technology. EU funding for R&D activities is increasing, and more open markets within the Union and with the global trade community can spur innovation. The EU's funds and policies are also pushing the less-developed economies in the Union to improve their infrastructure, institutions, and human capital. This will make more European economies ready producers and consumers of TAs.

For countries in Central and South America, the large disparity between rich and poor is a major problem. Lack of reliable infrastructure—common to most developing countries—is another barrier to implementing the TAs examined in this study. Modern health care is not widely available, and security remains a problem. As is the case for other developing countries, the experts interviewed thought that cheap solar energy, rural wireless communications, and ultra-fuel-efficient vehicles would be important TAs for countries in this region. In addition, they underlined the importance of TAs that could provide affordable health care delivery methods. RFID, CBRN sensors, biometrics, and UAVs were also thought to offer benefits to strengthen security and promote economic development.

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[150] A 2004 report by the Food and Agriculture Organization of the United Nations said that the use of genetic engineering to increase crop yields could help reverse a trend to slowing yield growth and significantly reduce world hunger.

For the Middle East, the last of five regions examined, experts underscored the need to have adequate water supply for personal and industrial use. Rapid urban migration also exacerbates the problem of waste management, which, if improperly handled, pollutes valuable clean water supplies and damages environmental and human health. TAs that can offer relief include filters and catalysts for water purification, cheap desalination, green manufacturing, and cheap solar energy.

Drivers and Barriers to Implementing Technology Applications

Input from regional experts clearly suggested that many TAs can help to alleviate problems confronting countries around the world but that technology adoption and implementation will not be easy for most countries; for example, the lack of infrastructure will be a critical hurdle. Thus, technical maturity and feasibility are necessary, but not sufficient, conditions for the implementation of TAs. Many other factors will determine whether a TA will be implemented, how it will be implemented, whom it benefits, and whether its use can be sustained over time and can produce expected outcomes.

This section will delineate and describe the drivers and barriers to the implementation of TAs—and the relationships among them—to illustrate the complex policy, political, social, and economic landscape in which technology implementation occurs.

Drivers are the motivations or forces that will enable policymakers, as well as individual users, to choose a technology to meet a certain need and to acquire capacity to sustain the application of that technology. Barriers are the opposites of drivers: They are hindrances to the implementation of TAs. Drivers and barriers frequently stem from the same sources. Their main difference lies in whether the source is available or absent (e.g., funding and a technologically savvy population), its nature relative to the technology (e.g., public opinion and laws), the problem(s) that the TA is expected to address in that particular decision environment, and the potential for negative or unanticipated consequences.

Knowing the drivers and barriers and the relationships among them will better enable decisionmakers to implement beneficial TAs in a manner that fully addresses significant ethical, safety, and public concerns. In this study, we identified ten major types of drivers and barriers to technology implementation:

1. Cost and financing
2. Laws and policies
3. Social values, public opinion, and politics
4. Infrastructure
5. Privacy concerns
6. Resource use and environmental health
7. R&D investment
8. Education and literacy
9. Population and demographics
10. Governance and political stability.

Drivers and barriers can be (and often are) present simultaneously, reflecting progress in some aspects and problems in other aspects. In these cases, it is important to understand the relative magnitude and importance of each aspect for each type of driver and barrier. However a detailed analysis of where on each driver-barrier continuum particular countries fall was beyond the scope of this study. In the analysis below, we identify which drivers and barriers are present in specific countries, but discuss their importance only qualitatively. We do, however, highlight cases in which one or more of the ten areas listed above is *both* a driver and a barrier for a particular country.

Although these major drivers and barriers have no order of hierarchy or sequence, they are often related in complex ways. For example, a country might lack the necessary funds to acquire a TA because poor governance and political instability does not make it attractive to lenders and investors. Technology implementation might also require a certain level of comfort with S&T, as well as the capacity to understand certain technical concepts, among policymakers and the general population. Thus, public investment in education and R&D, as well as social values or a culture that takes a positive view of S&T, can also make a society more receptive to technology.

Knowing the drivers and barriers to technology implementation and understanding the complex relationships between them is critical, particularly to policymakers. This section provides a general discussion of drivers and barriers and highlights how they might influence implementation of the TAs described in the previous chapter.

Cost and Financing

An obvious driver and barrier to the application of any technology is money, whether it is available to acquire the technology, construct the physical infrastructure to support its use, or build the human capacity to deliver, apply, and sustain its use. How much a technology costs is only one of many considerations for government, commercial, and individual decisionmakers. Analogous to this is the ability to access funds and the costs of those funds. The economically advanced countries certainly have more resources available than the less-developed ones to enable their acquisition and use of technologies. At the same time, they have superior ability to access funds. The banking and financial sectors in these countries are well developed and regulated. They have numerous mechanisms through which governments, companies, and individuals can access funds at mutually agreed costs and risks. For example, governments can issue long- and short-term treasury bonds; private firms can borrow from commercial banks or raise capital on the stock market; and individuals can take out private commercial loans. For most less-developed economies, the types of mechanisms available to acquire funds are much more restricted, which further hinders their ability to deploy technologies. Therefore, although cost and financing can generally be barriers to most countries, mechanisms to access funds represent drivers. And those countries that have these mechanisms will be more able to adopt the TAs described in this study.

In addition, the cost of funds also goes up for countries that are more politically and economically volatile. Their government bonds have to pay a higher interest to lure buyers—if there are any buyers at all—and typically do not cover as long a period for repayment. When borrowing from the international financial market, these countries also have to pay more for their loans because they are considered higher-risk borrowers. Hence, most developing countries, particularly those that are politically and economically unstable, will find it a lot more difficult to access funds from the international market because lenders do not want to lend to them or would only do so at a very high cost to the borrowing country.

Laws and Policies

Laws and policies can create friendly or hostile environments that can promote or hinder technology implementation and exploitation. The passage of laws and enunciation of policies that explicitly promote or prohibit the use of a technology will significantly influence government, commercial, and individual decisions. For example, restrictive human embryonic stem cell research legislation in the United States has created a more hostile environment for researchers and pharmaceutical companies. The United States prohibits the use of federal funding for human embryonic stem cell research that destroys an embryo. Federal funding is restricted to established human embryonic stem cell lines that were in existence before August 9, 2001.[151] State laws, however, can fund or prohibit such research through state-level legislation. In November 2004, for example, California voters approved a proposition to provide $3 billion in state funds over the next decade for human embryonic stem cell research.[152] In Brazil, the government's recent approval for commercial planting of GM soy will likely make the country a more competitive international exporter of soy. In October 2004, Brazil's president issued an executive order to allow commercial planting of GM soy. Brazil is the second largest soy producer in the world, after the United States.[153] This decision came about after many years of domestic debate over potential environmental impact and amid anxieties about how adopting genetic modification might jeopardize Brazil's agricultural exports to European markets, which are largely hostile to this technology. China and India, too, are legalizing commercial use of GM crops. China, for example, is expected to commercialize GM rice before the end of 2006. China has four varieties of GM rice in the final stages of field trials, two of which were found to decrease pesticide use by 80 percent, thus benefiting the health of farmers and the environment.[154]

By comparison, many African countries continue to prohibit the planting of GM crops and the import of GM foods, despite the threat of famine and widespread malnutrition and research pointing to significant health, social, economic, and environmental benefits.[155] Their reason for rejecting genetic modification in agriculture is

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[151] This effectively prevents use of federal money for human embryonic stem cells derived from blastocysts. However, no federal laws restrict privately funded research using human embryonic stem cells, except by demanding compliance with human subject protection regulations.

[152] This initiative is the biggest state-supported scientific research in the country, and San Francisco was chosen as the site for this new stem cell agency in May 2005. For more on this topic, see Hall (2005). In May 2005, concerns about effects of federal funding restrictions on science and health prompted a majority of the U.S. House of Representatives to call for a repeal of these measures. See Allen and Connolly (2005).

[153] See "GM Soy Approved by EO in Brazil" (2004). The Brazilian parliament followed up with legislation allowing the planting and sale of GM crops on March 2, 2005. The law was approved with a 353-to-60 vote in favor of allowing GM crops. See Massarani (2005).

[154] See "A Boost for Genetically Modified Crops" (2004); "India Becoming Major GM Crop Hub" (2004); and Cyranoski (2005b).

[155] For example, the Nuffield Council on Bioethics in the United Kingdom issued a major study in 1999 on benefits of GM crops for developing countries (Nuffield Council on Bioethics, 1999). The World Health Organization's (WHO's) *Modern Food Biotechnology, Human Health, and Development*, published in June 2005, acknowledges the potential of GM food to enhance human health and development. The report

a complex mix of pressure from development assistance donor country governments and nonprofit organizations, domestic anxieties about potential human health and environmental dangers of GM crops, and lack of institutional, human, and physical capacity to use this technology. Zambia, for example, continues its ban on import of GM foods, including food assistance, and rejects the use of genetic modification for agriculture despite suffering its third severe drought since 2000. In May 2005, the Norwegian government announced assistance to Zambia to build a high-tech laboratory for detecting GM foods.[156]

Implementation of any TA examined in this study will be affected by laws and policies at the national and international levels. Some TAs (e.g., hybrid vehicles, cheap solar energy, rural wireless communications, filters and catalysts, and wearable computers) will likely find acceptance without much controversy. Others, such as GM crops, green manufacturing, and pervasive sensors, will likely be subject to heated debate.

While laws and policies can be drivers and barriers to technology implementation, they are products of government decisions that are influenced by a host of factors. These factors include national goals and priorities; divergent political, economic, and social interests; and existing legal and policy environments. In more-open and -democratic societies, transparent mechanisms are usually available to support public debates and other activities that shape laws and policies. In less-open and -democratic societies, elites in government, military, and business, or traditional religious and tribal leaders, might exercise power to assert their preferences and have them reflected in laws and policies. In societies characterized by conflict between secular and religious values, the nature and outcome of that conflict can have significant impact on implementation of TAs. Poor governance that is frequently characterized by widespread corruption and abuse of power can hinder the adoption and implementation of laws and policies and other actions necessary for productive application of technologies. Nevertheless, vibrant public debates for new or revised laws and policies can also be absent in more-open societies when a problem becomes set in an issue framework that does not encourage more-open debate and when elected officials do not provide leadership to examine the need for a new approach to the problem or issue.

Social Values, Public Opinion, and Politics

Religion, traditions, customs, and social mores can affect how technologies are perceived, and compatibility of a new technology with the values and beliefs of a society can affect its adoption.[157] Such perspectives can shape public opinion and the politics behind debates to define problems and acceptable technological solutions. For example, populations in Europe tend to take a dim view of genetic modification in agriculture. They worry far more about the uncertain human health and environmental effects of GM crops and foods than their American counterparts do. The result is two very different approaches to regulating the application of genetic modification in agriculture. The EU favors a “precautionary approach” to genetic modification in agriculture that emphasizes

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indicated that premarket assessments done so far have not found any negative health effects from consuming GM foods (World Health Organization, Food Safety Department, 2005).

[156] See Ngandwe (2005). The controversy over GM crops in Africa is captured in *The Economist* article, “Better Dead Than GM Fed?” (2002).

[157] For more on compatibility, see Rogers (2003).

the presence of "uncertainties" and imposes a very high bar for its implementation. This perspective contrasts sharply with the U.S. approach, which stresses the nutritional value of GM crops and foods—for example, if the GM crops are the same as their non-GM varieties, they are regulated the same.[158] Another example is xenotransplantation, which some people might find objectionable because animal parts are used as transplants for humans. Others might object on the basis of religion—for example, Muslims and Jews reject the use of organs or DNA from pigs (considered an "impure" animal according to their religious beliefs) in any drugs or medical procedure. Also, pervasive sensors and other TAs used for identification and tracking—for example, biometrics as sole personal identification and ubiquitous RFID tagging of commercial products and individuals—might elicit strong public objection in some societies on the basis of concerns about invasion of privacy and expanding government control of personal data.[159]

On the matter of stem cell research, for example, the Brazilian attorney general is seeking to repeal a law that allows the use of human embryos for research purpose. He argues that life begins at fertilization of an egg by a sperm, a view supported by many prominent scientists in Brazil. This runs counter to the perspective of the Brazilian health minister, and that of WHO, which asserts that life begins only when an embryo attaches itself to a woman's womb.[160]

While traditions, religion, and customs are some major sources of social values and public opinions, there are other sources that affect whether societies embrace new technologies, including economics, the visions of a charismatic leader, knowledge, foreign opinions, civil society groups, past experience in technology adoption, and observations of foreign technology adoption successes and failures. For example, many African countries have refrained from adopting genetic modification in agriculture, and even accepting GM corn for hunger relief, for fear of contaminating local crops and losing access to markets in Europe.

Infrastructure

Having such infrastructure as airports, seaports, roads, electrical power and water supply, and telecommunications at a threshold of quality (e.g., no frequent and large scale sudden power interruptions or intermittency in water supply) can be critical to the implementation of TAs. Building infrastructure is a first step, which in many developing countries is carried out with bilateral and multilateral development grants and loans. However, the more important task is to make infrastructure produce payoffs for the nation, which requires its maintenance and continuous upgrade and expansion over time.

In many economically developing countries, absence of funds and expertise to maintain infrastructure has meant broken roads and water filtration plants, sometimes

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[158] The U.S. Food and Drug Administration is responsible for regulating food safety relative to new plant varieties, dairy products, seafood, food additions, and processing aids. The key factors in assessing food safety are the characteristics of the food and its intended use, rather than that new methods have been used in its production. This sharply contrasts with the European Union's assessment criteria, which emphasize the process of genetic modification in food production. See, for example, information provided by the National Centre for Biotechnology Education (undated). See also the final report of the EU–U.S. Biotechnology Consultative Forum (2000).

[159] See, for example, "UK Home Office to Press Ahead with ID Cards" (2004); Kiley (2005); and Rohde (2005). Also, see Chapter Three in the report for the OECD workshop, "Human Genetic Research Database" (2004).

[160] Lemle (2005).

within months of their completion. Lack of political stability in many of these countries has also meant that infrastructure is damaged by violence. Corruption and official abuses also add to the cost of infrastructure construction and maintenance. A worse situation is when infrastructure building is motivated by political rather than economic objectives.[161] Very large infrastructure projects that take many years to complete can be "white elephants" that waste valuable resources and serve no one except the regime in power. Although economically advanced countries have more resources, they too face competing resource allocation priorities. Furthermore, infrastructure building frequently comes with its complex webs of laws and regulations (e.g., the "not-in-my-backyard" syndrome, land use, zoning, and emission standards), which is often the subject of public debate. All this can add to the time and cost required to put infrastructure in place to support technology adoption.

TAs such as cheap solar energy and rural wireless communications might be particularly attractive to countries that cannot afford to expand their electric and communications grids to their rural hinterlands. However, TAs such as GM crops, technologies for identification and tracking, and many medical technologies will require infrastructure to house, disseminate, and support their use. Kenya, for example, has acquired capacity to develop GM crops specific to local environmental conditions and agricultural pests and diseases. The Kenya Agricultural Research Institute's Biotechnology Center opened a $12 million biosafety greenhouse in 2004, where Kenyan scientists have conducted experiments with insect-resistant GM maize. This facility is only the second one of its kind in sub-Saharan Africa (the first being in South Africa). In May 2005, maize seeds modified to resist stem borers were planted at this greenhouse, making Kenya the second country in Africa, after South Africa, to conduct field trials for GM crops. Critics opposed these experiments, citing that Kenya lacks a robust regulatory framework to regulate GM crops and monitor food safety.[162]

Privacy Concerns

Knowledge is power. The moveable printing press made it possible to share information with a number of people and at a cost affordable to a large number of people. Steamships, railroads, the telegraph, the telephone, and the Internet are all technological advances that hastened the speed of data transmission and expanded the reach of information to an ever-growing number of people. Many people welcome the quicker and cheaper access to more information made possible by new technologies, but there are also many others wary of personal data falling into the wrong hands and the risk of compromises to personal privacy, freedom, and security. These concerns range from a "Big Brother" government keeping tabs on its population to enterprises collecting and selling personal data to commercial marketers, political campaigns, and advocacy groups that aim to market products and services or to seek donations and support from individuals. Personal data can also land in the hands of criminals, who can use the information for illegal purposes (e.g., credit card fraud, fake identity documents, extortion).

Advances in information and communication technologies in the past several decades, particularly Internet and computing technologies, have allowed personal data to be documented in a digital format that can be copied many times over and sent across the

[161]See, for example, Bandow and Vasquez (1995) and Hotland and Hudiono (2005).
[162] Chege (2004); Ogodo (2005).

world to multiple recipients—all by the click of a button and completed within a matter of seconds. Together with advances in software, information technologies have made the collection, collation, and analysis of data easier, faster, and cheaper than ever before. For those concerned about the privacy of personal data, technological advances (e.g., RFID tagging of commercial products and individuals, implants for tracking and identification, and secure video for security) are threats to personal privacy because they render personal identification data, consumption habits, and movements increasingly subject to electronic tracking or surveillance. TAs for sole personal identification, such as biometrics, raise significant concerns about what would happen when personal identification using unique personal physical characteristics such as fingerprints and retinal patterns are stolen or are corrupted due to technical or human errors. Unlike changing an ID number, a person cannot simply cancel the existing assigned identifier and be granted a new one, as is the current practice with passports, driving licenses, credit cards, or other types of identity documentation.[163]

Although the desire to protect privacy is a personal preference, it is shaped as much by social values toward privacy as an individual's experience and ideological inclinations. How society views privacy can significantly affect national discussions on the implementation of TAs that have ramifications for privacy protection. Societies that are more open and free and have greater respect for individual rights will likely have more-vibrant debates on the impact of technology on privacy than those that are less open and free, or where assertions of collective good take precedence. It is also important to note that privacy concerns can be a driver for the development of technologies to increase the security of personal information (e.g., through anonymity) or to enable the use of surveillance methods while protecting personal identities. The "Privacy and Anonymity" section of Appendix D provides examples of such technologies.

Resource Use and Environmental Health

The availability and accessibility of natural resources and concerns about environmental health and its impact on humans are important drivers and barriers to technology implementation. Soil that is high in acidity and communities that have restricted access to water might not be able to grow certain crops or employ certain farming techniques, respectively. Absence of grid electricity and lack of access to kerosene and other fuels compel households to rely on wood and charcoal for cooking and heating. In many such communities, this can mean the rapid clearing of forests for firewood, which exacerbates erosion of topsoil and contributes to massive mudslides that destroy homes and lives when heavy rain falls. For individual households, lack of access to reliable and affordable energy can mean spending hours every day foraging for firewood, instead of pursuing more economically profitable activities. Cooking with firewood can also generate severe indoor air pollution, which victimizes women more than men because women are customarily responsible for cooking in virtually all societies, but especially in those using firewood.[164]

TAs such as cheap solar energy and filters and catalysts for water purification hold enormous potential to help improve environmental and human health in

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[163] See Appendix D for a more detailed discussion of biometric technologies, as well as privacy issues associated with information technologies.

[164] See, for example, Rong (2005).

economically developing countries. GM crops that are better adapted to the distinctive environmental conditions in these places might also increase crop yields and improve diets and livelihoods. Cleaner TAs (e.g., hybrid vehicles and green manufacturing) can reduce resource input in production, as well as emissions that harm the environment and human health. Such relatively expensive TAs, however, might find more ready markets in the economically developed countries.

Many other forces (e.g., social values and politics) shape a society's perspectives and decisions toward resource use and environmental health. In the United States, increasing awareness of the effects of chemicals on wildlife, the land, and, since the 1960s, human health, as well as a tradition of establishing national parks and conservation areas, has established environmental health as a high priority among the list of voter concerns. In Japan, industrial pollution in the 1960s spawned a strong civil society movement to advocate food safety. Recent incidents involving mad cow disease and tainted foods have further eroded public confidence in government officials. All this has increased Japanese consumer resistance to GM crops and foods, even in a society that is in general keen to embrace new technology.[165] In places where environmental degradation threatens health and livelihood, tensions rise and open conflicts frequently follow. Competition for land and water has sparked violence in many places, especially where institutional capacity is lacking to mediate and find nonviolent solutions.[166]

R&D Investment

Technology implementation requires know-how and capacity to adopt, disseminate, and implement for practical uses. Scientific knowledge, technical skills, and means to provide sustainable access to and use of technology are essential. Those societies with a higher level of science and technology (S&T) capacity will be better able to implement TAs and to produce their own technological innovation or advance technology to offer better solutions to their problems.

Building S&T capacity requires investment in R&D. Funding for the education and training of scientists and engineers, scientific research and technology development activities, promotion of technology transfer to commercial applications, and dissemination of technology into the marketplace might come from public or private sources. However, R&D investment does not exist in a vacuum. It must compete with other spending priorities of the state and of private investors, who look for opportunities with high return on investment. Countries in which government policies are hostile to economic activities, politics are unstable, and the level of R&D capacity is extremely low generally are not attractive places for investment that would promote R&D capacity building. Development assistance groups might step in to transfer technology, but their efforts to make technology implementation sustainable and to produce the expected outcomes for the intended beneficiaries would likely be constrained by political and economic hurdles.

Indeed, S&T capacity building is a long-term and cumulative process that requires not only financial investment, but also a host of other inputs and conditions to establish,

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[165] See "Food Safety Citizens' Watch Proposed Continuing of Import Ban of Beef from U.S. to PM Koizumi" (2005); GMR Watch Center (2001); and Wong (2001).

[166] A UN assessment of ecological hotspots in Africa found a suggestive link between areas of ecosystem degradation and social conflict. See Stoddard (2005).

maintain, and generate benefits for society. Country statistics in Appendix H indicate the current R&D spending of countries selected for analysis in this study.[167] A positive correlation is evident between those that spend a larger share of their gross national product (GNP) in R&D and those that are more able to acquire and implement the TAs of Table 2.2 described in this study. A RAND study for the World Bank produced an S&T index based on a number of S&T indicators.[168] Table 3.1 presents the values from the RAND S&T Capacity Index scores for the selected countries.

It is quite clear that a positive correlation exists between a country's rank in the S&T Capacity Index and its level of economic development. The RAND S&T Capacity Index was compiled taking into consideration the number of scientists and engineers in a country, its R&D investment relative to GNP, and many other factors. Building S&T capacity requires a sustained level of investment over time, as well as supportive political, economic, and social conditions. Many countries that ranked low according to the RAND S&T Capacity Index will have to do a great deal to create these conditions and garner the resources to raise their S&T capacity level.

A great number of the TAs examined in this study will require societies to invest considerable resources to bring these technologies to technical maturity, disseminate them, and develop an environment conducive to their implementation. These R&D investments range from building world-class research laboratories, high-speed computers, and hospital facilities to training service technicians and technology extension officers.

Education and Literacy

Education is critical to cultivating a population that is literate and comfortable with, and a workforce able to interface with, S&T. For example, China has made enormous strides in its economic development because it has a literate workforce and a sizable number of R&D personnel, in addition to cheap and abundant labor. This has allowed China to move up the technology scale in manufacturing, from clothing and plastic Christmas trees to electronics, household appliances, and computers. This sharply contrasts with such places as Thailand, where a shortage of technically proficient workers has hurt the country's ability to move into higher-technology and value-added manufacturing.[169] Consequently, to bolster the country's long-term economic competitiveness, the Thai government is actively working to raise the general level of education, promote technical training, and expand higher education in the sciences.[170]

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[167] Individual analysis of the 200-plus nation-states of the world was beyond the resources and time available for this study. However, we selected for analysis 29 countries that we believe are representative of the most important international variations in capacity to acquire and implement TAs. A discussion of the country selection process is presented in the section below on country capacity.

[168] Appendix H shows the complete RAND S&T Capacity Index.

[169] See the UN education indicators for East Asia and the Pacific at http://www.unesco.org.

[170] See Ministry of Education, Thailand (2004).

Table 3.1
RAND S&T Capacity Index Scores for Selected Countries

	Selected Countries	S&T Index Score
1.	United States	5.03
2.	Japan	3.08
3.	Germany	2.12
4.	Canada	2.08
5.	Israel	1.53
6.	South Korea	1.49
7.	Australia	1.33
8.	Russia	0.89
9.	Poland	0.19
10.	China	0.10
11.	Brazil	0.10
12.	South Africa	0.04
13.	India	0.04
14.	Chile	–0.11
15.	Mexico	–0.14
16.	Pakistan	–0.15
17.	Turkey	–0.17
18.	Colombia	–0.22
19.	Iran	–0.22
20.	Egypt	–0.29
21.	Indonesia	–0.30
22.	Jordan	–0.35
23.	Nepal	–0.40
24.	Georgia	–0.44
25.	Kenya	–0.46
26.	Dominican Republic	–0.48
27.	Cameroon	–0.49
28.	Chad	–0.51

SOURCE: Wagner et al. (2001).
NOTE: Fiji, a selected country in this study, is not a country listed in the RAND S&T Capacity Index. For this reason, there is no S&T index score for Fiji in Table 3.1.

But, of course, like other drivers and barriers examined, education and literacy are a necessary, but not a sufficient, requirement for technology implementation. A society must have other elements in place to provide incentives for people to acquire education and opportunities for people to use their knowledge and skills. In the Philippines, thousands of doctors, nurses, computer engineers, and other professionals leave their country to work overseas every year because there are not enough jobs for them and the pay is very low compared with what they would receive in the United States, Britain, and elsewhere. In fact, many Philippine doctors are now going to nursing school to better their chances for a job abroad, because the demand for nurses is greater than that for physicians. Between 1995 and 2000, nearly 34,000 Philippine nurses left the country.[171] This exodus is fast creating a shortage crisis in the Philippines. While one might argue that remittances sent by Philippine workers overseas benefit their families and thus the country, these trained personnel are not there to serve the Philippine population and to maintain a healthy workforce that can attract investments and support economic growth.

At a minimum, having a population that is literate, comfortable with technology, and able to interface with technology will be critical to the implementation of TAs that require even the lowest level of technical know-how. Users also have to welcome the potential benefits of technology and be willing to accept the risks and uncertainties associated with it. Such sentiments are necessary to encourage acceptance and to push for acquiring and applying new technologies. In their absence, potential users are unlikely to embrace new technologies, even if they are supplied free of charge. Also, ignorance, prejudice, and alienation can prevent these potential users from accepting new technologies.

Population and Demographics

Population size and demographics can be a strong driver or barrier to policy decisions. For countries with large and rapidly aging populations, policymakers will want to look for technological solutions that can help to provide care and reduce the cost of medical and health care services. Countries with large young populations, however, will need to generate jobs and economic growth, for which technologies might provide options. Countries with rapidly growing populations, shrinking arable land, or harsh climatic conditions might also seek technological solutions to improve food production and nutrition.

In many sub-Saharan African countries and Russia, HIV/AIDS has become devastating for the 20s and 30s age groups.[172] As those infected become debilitated and die, not only do economies lose farmers, technicians, managers, soldiers, and police officers, but children are left without parents and the elderly without someone to care for them. Moreover, these age cohorts are a conduit for traditional knowledge between generations and citizens whose voices are important to social and political debates. Therefore, their demise has serious economic, social, political, and security implications for societies. Other new and reemerging diseases (e.g., avian flu and polio, respectively) also pose serious threats. Old diseases have in some cases become harder to treat and curb—for example, multidrug-resistant strains of tuberculosis, which attack many in Russia. All this intensifies the demand for technologies to detect, treat, and stop these diseases before pandemics occur and millions of lives are taken. Some TAs (e.g., rapid bioassays, targeted drug delivery, GM crops) might provide some relief. However,

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[171] This number was cited by the Philippine Overseas Employment Administration in Quan (undated).

[172] In the case of Russia, experts are particularly concerned by the high rate of HIV/AIDS and tuberculosis infections among this age group. Without drastic actions to curb these diseases, Russia could lose as much as 10 to 15 million of its population by 2015. Premature deaths among those between 15 and 30 years of age, the workers of tomorrow, will severely cut productivity and threaten long-term economic growth in Russia. See National Intelligence Council (2000b). In South Africa, for example, about 6 million of the country's 40 million people are estimated to be infected with HIV/AIDS. See "Big Jump in S African HIV Cases" (2005) and Cohen (undated). The challenge of dealing with HIV/AIDS in South Africa and Russia's low birth rates, poor medical care, and widespread HIV/AIDS infection are also noted in the National Intelligence Council's *Mapping the Global Future* report (2004, pp. 10, 54, and 56).

whether any TA is implemented will also be influenced by many of the other drivers and barriers described in this section.

Governance and Stability

Governments that are corrupt and in which abuse of power is rife pose a significant hindrance to development. Countries in which corruption is severe perform poorly economically compared with those in which corruption is limited. A World Bank study measured quality of governance in 209 countries and territories between 1996 and 2004 and found a strong correlation between income and governance.[173]

Corruption can add to the cost of technology acquisition and implementation. One example comes from India, where high-tech towns created to attract foreign investment were unable to take off because of a lack of the necessary infrastructure such as roads, sewage treatment, and uninterrupted power supply. Corruption among officials took precious dollars needed to provide this infrastructure. Worse, government purchases of farmland to convert into this high-tech zone at low market price and the absence of job opportunities for the rural poor have engendered considerable dissatisfaction toward the authorities and foreign investors.[174] In Cameroon and Turkey, Transparency International reported that 70.8 percent and 77.8 percent of respondents, respectively, think that corruption has a very significant impact on the business environment. Respondents in Turkey also think that corruption very significantly affects the culture and values of society (76.1 percent) and personal and family life (66.4 percent).[175]

Corrupt officials might also demand bribes for government licenses, fees, and registration requirements for technology imports and their dissemination. Or they might use their authority to influence access to technology, which can potentially deny those who need it most or would benefit most from it. For example, a township official might decide to locate an Internet access point near his home or his major supporters rather than near the market or school, where local town folk can more conveniently have access.[176]

Table 3.2 compares country scores in Transparency International's Corruption Perception Index (CPI) to their per capita GDP and Human Development Index rank. Countries that have higher CPI scores are deemed less corrupt and in general have higher GNP per capita and a higher quality of life, as reflected by their higher rankings in the HDI.[177]

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[173] Six governance indicators were used in this World Bank study. They are voice and accountability, political stability and violence, government effectiveness, regulatory quality, rule of law, and control of corruption. See Kaufman, Kraay, and Mastruzzi (2005).
[174] See Lakshmi (2005).
[175] Transparency International (2003).
[176] For more on the importance of good governance to development, see various reports on governance at World Bank Group's "Governance & Anti-Corruption" Web page (undated). See also Bhargava and Bolongaita (2004) for detailed case studies on Indonesia, Korea, Thailand, and the Philippines.
[177] The HDI is based on a country's performance in a number of areas—for example, health, education, S&T, population size, gross domestic product (GDP)—to reflect the well-being of societies. More on the HDI can be found at United Nations Development Programme (undated a).

Table 3.2
Corruption Perception Index Scores for Selected Countries

Countries	CPI 2005 Score[a]	GDP Per Capita Value in 2003 (Purchasing Power Parity in US$)[b]	HDI Rank in 2003[b]
Australia	8.8	29,632	3
Canada	8.4	30,677	5
Germany	8.2	27,756	20
United States	7.6	37,562	10
Chile	7.3	10,274	37
Japan	7.3	27,967	11
Israel	6.3	20,033	23
Jordan	5.7	4,300	90
South Korea	5.0	17,971	28
South Africa	4.5	10,346	120
Colombia	4.0	6,702	69
Fiji	4.0	5,880	92
Brazil	3.7	7,790	63
Mexico	3.5	9,168	53
Turkey	3.5	6,772	94
Poland	3.4	11,379	36
China	3.2	5,003	85
Egypt	3.4	3,950	119
Dominican Republic	3.0	6,823	95
Iran	2.9	6,995	99
India	2.9	2,892	127
Nepal	2.5	1,420	136
Russia	2.4	9,230	62
Georgia	2.3	2,588	100
Cameroon	2.2	2,118	148
Indonesia	2.2	3,361	110
Kenya	2.1	1,037	154
Pakistan	2.1	2,097	135
Chad	1.7	1,210	173

SOURCES: [a]Transparency International Corruption Perception Index 2005. [b]UNDP Human Development Index 2005.

NOTE: The CPI ranks countries in terms of the degree to which corruption is perceived to exist among public officials and politicians. It is a composite index, drawing on corruption-related data in expert surveys carried out by a variety of organizations. It reflects the views of business people and analysts from around the world, including experts who reside in the countries evaluated. Countries with higher CPI scores are deemed less corrupt.

Stability is another important factor in development. Investors are discouraged from investing in places where leadership is uncertain, an open and accountable political system is absent, and internal strife and external aggression are constant threats, because political instability increases the risks of economic and social instability. Many multinational firms and investment companies have political risk divisions in-house to advise their own staff and investors. Deutsche Bank and the Eurasia Group, for example, created a stability index to monitor political stability in emerging markets.[178] Not only

[178] The Deutsche Bank Eurasia Group Stability Index (DESIX) uses 20 composite indicators to monitor political and economic risks in more than 20 emerging markets that include China, India, Nigeria, South Africa, Hungary, Poland, Egypt, Turkey, Brazil, Mexico, Russia, and Ukraine. Stability in this instance is

does foreign capital not flow into a country that is beset by instability, but domestic entrepreneurs and skilled workers frequently take their capital and expertise elsewhere to seek better pay and a greater sense of personal security. Without political and social stability, policymakers will be more engaged in political battles for power and dealing with immediate security threats, rather than in policy debates about long-term development goals and how to allocate resources to pursue them. Investors, too, will look for quick turnaround profit opportunities rather than investing in capacity building for long-term profits, and individuals will seek livelihoods elsewhere through legal or illegal migration.

Political instability can also directly disrupt scientific R&D activities. Violence might destroy laboratories, make research sites inaccessible and dangerous to researchers, and force researchers to leave their work and the country. For example, armed conflict recently forced the closure of the Africa Rice Center, an agricultural research center, in Cote d'Ivoire. One researcher affiliated with this institute was killed in a bomb attack, and many have fled to Benin. Since November 2004, fighting has been intense in the area where the institute is located.[179]

Problems and Issues and Relevant Technology Applications

Technology development is not a goal in and of itself. In addition to being driven by their quest to push S&T to new frontiers, scientists and engineers develop new technologies to meet established or perceived needs of society. Comments received from regional experts with whom we consulted clearly linked TAs to specific problems and issues that are important in different parts of the world.

This section examines which of the top 16 TAs of Table 2.2 might be relevant to the problems and issues listed below that will likely confront societies in the future. Our choice of these problems and issues was significantly influenced by the fact that they are both present-day concerns and will likely continue in the future to be fundamental to the well-being of societies across the globe, although their specific characteristics and importance might differ across time and space:[180]

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defined as the capacity of countries to withstand shocks and crises and to avoid generating shocks and crises. The indicators are grouped into four weighted subcategories—namely, government, society, security, and economy. Political factors represent about 65 percent of the total weight and economic factors for the rest. See Eurasia Group (undated).

[179] Shanahan and Cockburn (2005).

[180] These problems and issues are reflected in policies and goals of many nation-states and multilateral organizations. For examples, see the United Nations Millennium Development Goals to end human poverty (United Nations Development Programme, undated b); initiatives to promote financing for development and improve global governance, global health, and access to water and IT by the World Economic Forum; the goals of promoting good governance, investment in people, and economic freedom in the Millennium Challenge Account (White House, undated); the major sectoral foci of development assistance of the U.S. Agency for International Development; the UK Department for International Development (DFID, undated); and various multilateral development banks such as the World Bank, the Asian Development Bank, and the African Development Bank. Also, technology is a major emphasis in the U.S. Department of Defense's efforts to build the fighting force of the future, from high-tech protective gear for soldiers to network-centric warfare (U.S. Department of Defense, 2001).

- Promote rural economic development
- Promote economic growth and international commerce
- Improve public health
- Improve individual health
- Reduce resource use and improve environmental health
- Strengthen the military and warfighters of the future
- Strengthen homeland security and public safety
- Influence governance and social structure

Table 3.3 shows our assessment of the relevance of the TAs of Chapter Two to these problems and issues. This table is based on a crosswalk between the 12 sectors of Table 2.2 and the eight problems and issues. In some cases (e.g., reducing resource use and improving environmental conditions, strengthening the military and warfighters of the future, and influencing governance and social structure), there is a one-to-one correspondence between sectors in Table 2.2 and problems and issues in Table 3.3. However, some sectors in Table 2.2 (e.g., health and economic development) have more than one counterpart in Table 3.3 (i.e., health may involve public health, individual health, or both)[181] and economic development may refer to rural development, international commerce, or both. Finally, some problems and issues in Table 3.3 have no direct sectoral counterpart in Table 2.2, and vice versa (e.g., strengthen homeland security and public safety, water, food, land, population, energy, and education). The crosswalk between the tables is shown explicitly in Table 3.3, in which each "X" is accompanied by parenthetical notes that identify sectors in Table 2.2 from which that assignment was derived. For example, the contribution of cheap solar energy to economic development is associated with rural electrification and hence rural economic development, whereas its contribution to providing power for improving local hygiene will affect both public health and individual health. Also, its contribution to the global energy system may have impacts on economic growth and international commerce.

In addition to these direct impacts, we also considered how each TA might contribute to problems and issues that have less-obvious linkages. For example, filters and catalysts will benefit rural economic development and homeland security, respectively, by providing clean water to rural populations that lack access to reliable and safe water supply, as well as to communities after terrorist attacks or hazardous materials spills that damage their regular drinking water source. In some cases, a sector identified in Table 2.2 is not reflected in this evaluation of relevant TAs because the impact is not considered significant enough to make a significant difference in addressing the highlighted problems and issues. Those cases are indicated by a sector shown in parentheses without an "X" in the corresponding box in Table 3.3.

[181] Public health experts define public health as "an organized community effort aimed at the prevention of disease and promotion of health." For a succinct guide to public health in the United States, see Hooker and Speissegger (2002).

Table 3.3
Relevant Technology Applications for Highlighted Problems and Issues

	Technology Applications	Promote Rural Economic Development	Promote Economic Growth and International Commerce	Improve Public Health	Improve Individual Health	Reduce Resource Use and Improve Environmental Conditions	Strengthen the Military and Warfighters of the Future	Strengthen Homeland Security and Public Safety	Influence Governance and Social Structure	Total Number of Problems and Issues (Sectors) Affected
1	Cheap solar energy	X (food, econ dev, edu)	X (energy)	X (health)	X (health)	X (water, land, energy, environ)			X (govern, social)	6 (10)
2	Rural wireless communications	X (econ dev, edu)	X (econ dev)	X (health)	X (health)	X (environ)	X (defense)	X (defense)	X (govern, social)	8 (7)
3	Ubiquitous information access		X (econ dev, edu)	X (health)	X (health)		X (defense, edu)	X (defense)	X (govern, social)	6 (6)
4	GM crops	X (food, econ dev, edu)		X (health)	X (health)	X (water, land, energy, environ)				4 (8)
5	Rapid bioassays		X (econ dev)	X (health)	X (health)		X (defense)	X (defense)	X (govern)	6 (4)
6	Filters and catalysts	X (food, water, econ dev)		X (health)	X (health)	X (water, land, energy, environ)	X (defense)	X (health)		6 (8)
7	Targeted drug delivery		(econ dev)	X (pop, health)	X (health)			X (defense)	X (govern, social)	4 (6)
8	Cheap autonomous housing	X (econ dev, energy)		X (health)	X (health)		X (defense)	X (defense)	X (govern, social)	6 (6)
9	Green manufacturing		(econ dev)	X (health)	X (health)	X (water, land, energy, environ)				3 (6)
10	Ubiquitous RFID tagging		X (econ dev)				X (defense)		X (govern, social)	3 (4)
11	Hybrid vehicles					X (environ, energy)				1 (2)
12	Pervasive sensors		X (econ dev)				X (defense)	X (defense)	X (govern, social)	4 (4)

	Technology Applications	Promote Rural Economic Development	Promote Economic Growth and International Commerce	Improve Public Health	Improve Individual Health	Reduce Resource Use and Improve Environmental Conditions	Strengthen the Military and Warfighters of the Future	Strengthen Homeland Security and Public Safety	Influence Governance and Social Structure	Total Number of Problems and Issues (Sectors) Affected
13	Tissue engineering		X (econ dev)		X (pop, health)				X (govern)	3 (4)
14	Improved diagnostic and surgical methods				X (pop, health)					1 (2)
15	Wearable computers		X (econ dev, edu)		X (health)		X (defense)	X (defense)	X (social)	5 (5)
16	Quantum cryptography		X (econ dev)				X (defense)	X (defense)		3 (2)
17	Hands-free computer interface	X (econ dev)	X (econ dev)				X (defense)		X (econ dev)	4 (2)
18	In silico drug R&D		X (econ dev, health)		X (health)					2 (2)
19	Smart textiles		X (econ dev)				X (defense)		X (econ dev, health)	3 (3)
20	Resistant textiles		X (health)					X (health)		2 (1)
21	Electronic transactions		X (econ dev)							1 (1)
22	Genetic screening			X (health)	X (health)				X (pop, health)	3 (2)
23	GM insects			X (food, pop, health)		X (food, energy, environ)		X (health, environ)		3 (5)
24	Unconventional transport	X (econ dev)	X (econ dev)			X (energy, envion)				3 (3)
25	Commercial UAVs		X (econ dev)			X (water, food, land, environ)	X (water, food, land, defense,	X (defense)		4 (6)

	Technology Applications	Promote Rural Economic Development	Promote Economic Growth and International Commerce	Improve Public Health	Improve Individual Health	Reduce Resource Use and Improve Environmental Conditions	Strengthen the Military and Warfighters of the Future	Strengthen Homeland Security and Public Safety	Influence Governance and Social Structure	Total Number of Problems and Issues (Sectors) Affected
							environ)			
26	Drug development from screening			X (health)	X (health)					2 (1)
27	Monitoring and control for disease management	X (social)		X (health)	X (health)	X (health)		X (health)	X (social)	6 (2)
28	Enhanced medical recovery				X (health)		X (health)	X (health)		3 (1)
29	Secure data transfer		X (econ dev)							1 (1)
30	Print-to-order books		X (econ dev)							1 (1)
31	Therapies based on stem cell R&D		X (econ dev)	X (health)	X (health)				X (govern, social)	4 (4)
32	CBRN sensor network in cities			X (health)		X (environ)	X (defense)	X (health, defense, environ)	X (govern)	5 (4)
33	CBRN sensors on emergency response technicians						X (heath, defense)	X (health, defense)		2 (2)
34	Immunotherapy			X (pop, health)	X (pop, health)			X (pop, health)	X (pop, health)	4 (2)
35	Improved treatments from data analysis			X (health)	X (health)					2 (1)
36	Smart systems		X (econ dev)							1 (1)
37	Hydrogen vehicles					X (energy)				1 (1)
38	Implants for tracking and ID						X (defense)	X (defense)	X (govern, social)	3 (3)

	Technology Applications	Promote Rural Economic Development	Promote Economic Growth and International Commerce	Improve Public Health	Improve Individual Health	Reduce Resource Use and Improve Environmental Conditions	Strengthen the Military and Warfighters of the Future	Strengthen Homeland Security and Public Safety	Influence Governance and Social Structure	Total Number of Problems and Issues (Sectors) Affected
39	Gene therapy				X (pop, health)					1 (2)
40	Chip implants for brains				X (health)		X (defense)		X (social)	3 (3)
41	Drugs tailored to genetics				X (health)				X (govern)	2 (2)
42	Secure video monitoring						X (defense)	X (defense)	X (govern, social)	3 (3)
43	Biometrics as sole personal ID						X (defense)	X (defense)	X (govern, social)	3 (3)
44	Hospital robotics		X (econ dev)		X (health)					2 (2)
45	Military nanotechnologies						X (defense)	X (defense)		2 (1)
46	Military robotics						X (defense)	X (defense)		2 (1)
47	Xenotransplantation				X (health)					1 (1)
48	Artificial muscles and tissue				X (health)		X (health, defense)			2 (2)
49	GM animals for R&D			X (health)	X (pop, health)					2 (2)
50	High-tech terrorism						X (defense)	X (defense)	X (govern, social)	3 (3)
51	Memory-enhancing drugs				X (health)				X (social)	2 (2)
52	Super soldiers						X (defense)			1 (1)

	Technology Applications	Promote Rural Economic Development	Promote Economic Growth and International Commerce	Improve Public Health	Improve Individual Health	Reduce Resource Use and Improve Environmental Conditions	Strengthen the Military and Warfighters of the Future	Strengthen Homeland Security and Public Safety	Influence Governance and Social Structure	Total Number of Problems and Issues (Sectors) Affected
53	Genetic selection of offspring				X (health)				X (pop)	2 (2)
54	Proxy bot						X (defense)	X (defense)		2 (1)
55	Quantum computers for code breaking						X (defense)	X (defense)		2 (1)
56	Robotic scientist			X (health)	X (health)					2 (1)
Total Number of Top 16 TAs		5	9	9	12	6	9	9	10	
Total Number of All TAs		8	21	19	30	12	26	25	25	

NOTE: Information in parentheses shows sectors indicated in Table 2.2 that TAs will likely affect and that determined the assignment to a particular problem or issue in this table. In several instances, the net assessment of Table 2.2 identified sectors that TAs will likely influence, but that determination was not considered sufficient to make a TA relevant to a highlighted problem. For example, targeted drug delivery will likely affect economic development, but it is not seen as sufficient to promote large-scale economic growth and international commerce. Econ dev = economic development; edu = education; environ = environment; govern = governance; pop = population; social = social structure. The numbers in parentheses in the far right-hand column are the number of sectors that these TAs affect.

We recognize that continuing development of these TAs, changes in laws and policies, new business models to dissemination innovation, and other factors may make a TA more or less relevant to a particular problem or issue. Thus, Table 3.3 represents our best assessment constrained by what we know today. Many more innovative uses of these TAs to address these and other problems and issues are entirely possible. Nevertheless, as we shall see below, this grouping of TAs according to the problems and issues they may address allows a useful entry to global impact assessment.

Examination of Table 3.3 shows that some TAs are relevant to more problems and issues than others. Efforts to invest in and disseminate TAs that have relevance to multiple problems and issues might bring together a larger number of stakeholders (e.g., scientists, engineers, potential users and beneficiaries, government and industry officials, and experts from nonprofit organizations). Success in managing the shared interests of these stakeholders might allow better leveraging of resources and building of partnerships to enable acquisition and implementation of these TAs. Of course, the opposite could also be true if divergent interests clash.

We summarize below the relationships between TAs and the problems and issues. However, it is important to recognize that, since the importance of problems and issues varies greatly among countries, regions, and societies, these simple counts based on Table 3.3 do not determine the priority of TAs. They merely indicate which TAs are relevant to multiple problems and issues and which problems and issues each TA can address.

Table 3.3 shows that, of the top 16 TAs, rural wireless communications is the only one with potential to affect all eight problems and issues. Cheap solar energy, ubiquitous information access, rapid bioassays, filters and catalysts, and cheap autonomous housing follow with six; wearable computers addresses five problems and issues. GM crops, targeted drug delivery, and pervasive sensors are relevant to four problems and issues; green manufacturing, ubiquitous RFID tagging, tissue engineering, and quantum cryptography to three; and hybrid vehicles and improved diagnostic and surgical methods are each considered relevant to a single problem or issue.

Looking at this from the problem and issue perspective, Table 3.3 shows that 30 of 56 TAs are potentially relevant to improving individual health. Strengthening the military and warfighters of the future follows with 26 of 56 TAs; 25 TAs are relevant to strengthening homeland security and public safety, and 25 TAs can potentially influence governance and social structure; 21 TAs are relevant to promoting economic growth and international commerce; and 19 TAs are relevant to improving public health. As for reducing resource use and improving environmental health, 12 TAs are relevant, and for rural economic development, 8 TAs are relevant.

With respect to the top 16 TAs, 12 are relevant to improving individual health. This is followed by ten for influencing governance and social structure; nine each for promoting economic growth and international commerce, improving public health, strengthening the military and warfighters of the future, and strengthening homeland security and public safety; six for reducing resource use and improving environmental conditions; and five for promoting rural economic development.

We note, however, that while most TAs are not pertinent to promoting rural economic development, the five relevant ones of the top 16 TAs do not require a high level of institutional, human, and physical capacity to support implementation, and only one (GM crops) raises significant public policy issues. Three of the other four (cheap solar energy, rural wireless communications, and filters and catalysts) receive "+" marks under both technical and implementation feasibility in the net assessment of Chapter Two and fall in the most likely upper quadrant of Table 2.3. Cheap autonomous housing was assessed in Chapter Two as highly likely for implementation but unlikely to be widely available by 2020.

Country Capacity to Acquire Technologies and Drivers, and Barriers to Implementing Technology Applications

Having identified drivers and barriers to technology implementation, a set of problems and issues that we believe will continue to be important to societies in the year 2020, as well as the relevance of specific TAs to these problems and issues, we now proceed to develop a more in-depth understanding of the complex dynamics between a nation's capacity to acquire technologies and the specific drivers and barriers that affect its capacity to implement TAs.

It is important to make a distinction between the capacity to *acquire* TAs and the capacity to *implement* them. A nation might acquire a TA through domestic R&D efforts, through technology transfer, through international R&D collaboration, or through simple purchasing via importation of commercial off-the-shelf systems from other countries. Hence, the capacity to acquire a technology reflects the S&T capacity of that nation, particularly its ability to conduct R&D activities or import know-how. However, the capacity to acquire TAs does not necessarily imply the capacity to successfully implement those TAs.

Using technology requires more than the ability to do research or import know-how. A nation must be able to match a TA to a problem and put that TA in the hands of users. Further, users must be able to sustain that use over time. This might require financing to access the TA, infrastructure to support its use, and skilled workers to maintain it. Finally, individual users and the society as a whole must be able to benefit from the use of the TA and be willing to support its implementation.

To accomplish all this, a country will need a certain level of institutional, human, and physical capacity. Institutional capacity includes the quality and reach of governance in a country, a banking and financial system that works, an honest and functioning judiciary, and working educational and health systems. Human capacity covers the quality and quantity of educated and skilled personnel available in a society. Physical capacity includes the quality and quantity of roads, airports, seaports, schools, hospitals, research laboratories and libraries, water treatment plants, grid electricity, and other infrastructure. A society's institutional, human, and physical capacity is reflected in the drivers and barriers discussed previously. For example, a society that is short of laws to promote technology use, of financial mechanisms to enable technology acquisition, and of political stability and good governance to reduce uncertainties in economic decisionmaking would present a very hostile environment for technology implementation.[182]

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[182] Research by the World Bank Institute estimates that more than $1 trillion is paid in bribes each year around the world. This does not include embezzlement of public funds or theft of public assets. This adds an enormous sum to the cost of production and consumption. Research also concluded that reducing

Furthermore, as illustrated in Table 3.4, different technologies demand different levels of capacity for acquisition and implementation. Of the top 16 TAs, cheap solar energy, rural wireless communications, GM crops, filters and catalysts, and cheap autonomous housing make the least demands on their users. These TAs do not require extensive and high-quality infrastructure, such as uninterrupted, nationwide electricity or telecommunication grids. In fact, deployment without extensive infrastructure support is a major advantage of these TAs. They also do not require highly trained experts to manage and use them. Trained technology extension officers can support diffusion and monitor use.[183] Individual farmers, small business owners, homeowners, and other users should be able to deploy these TAs with minimum instruction and capture their benefits. These TAs produce safe and reliable lighting, enable access to information and communication, producer larger crop yields, expand access to clean water, and provide safe housing, respectively. Thus, countries with even the most basic institutional, human, and physical capacity available should be able to acquire and use these TAs, albeit on a more restricted scale than societies with greater capacity.

TAs such as rapid bioassays, green manufacturing, ubiquitous RFID tagging, and hybrid vehicles demand greater capacity to acquire and use. Countries that already use bioassays (e.g., to monitor for public health problems or to diagnose individuals) will be the chief beneficiaries of this technology. Green manufacturing presumes the existence of manufacturing capacity and will require know-how to adopt its technologies. It also presumes that the presence of market demand for "green" goods exists, that productivity gains benefit users, and that there is government enforcement of environmental regulations. In many countries, laws passed are rarely enforced and rhetoric calling for increased efficiency and cleaner environment never gets translated into real action. Use of RFID tagging of commercial products and individuals implies the existence of a fairly sophisticated industrial sector, as well as employees and managers with the necessary know-how to reap the benefits of the available information.

Hybrid vehicles might be seen as a TA that has low capacity demands. Hybrid cars use gasoline, which should be available anywhere conventional combustion engine vehicles are used. Drivers do not need additional training to operate hybrid vehicles, and hybrid vehicles can be driven on the same roads used by conventional combustion engine vehicles. However, large-scale hybrid vehicle adoption has other requirements. First, the price of hybrid vehicles is higher than that of conventional combustion engine vehicles of the same class, size, and power. This reality has made hybrid vehicles less attractive even to buyers in the economically advanced countries in which per capita income is relatively high. For consumers in developing countries, the price differential is even greater because the price of a hybrid car must be compared with not only that of new cars, but also cheaper imported used cars from the United States, Japan, and other high-income countries. Second, developing-country consumers who can afford to buy hybrid vehicles might choose to spend their money on a higher-class vehicle for the perceived prestige or perhaps to fulfill a personal dream to own a particular brand and style of vehicle. Automobiles are frequently seen by buyers as extensions of themselves so that those who value energy efficiency might choose hybrid vehicles, and those who value style, speed,

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corruption has a positive effect on increasing income growth and reducing income disparity. See "The Costs of Corruption" at World Bank Group's "Governance & Anti-Corruption" Web page (undated).

[183] For more on technology diffusion, see Rogers (2003).

or other characteristics will likely choose other types of vehicles.[184] Third, special training is necessary for automobile mechanics to work on hybrid vehicles, and spare parts could be hard to obtain. Buyers might hesitate to buy hybrid vehicles unless they know they can obtain maintenance and repair service at a reasonable price.

Targeted drug delivery, improved diagnostic and surgical methods, and quantum cryptography demand even higher S&T capacity, infrastructure, training, and user sophistication for widespread implementation. Targeted drug delivery and improved diagnostic and surgical methods require detailed understanding of integrated biotechnology and biomedical nanotechnology developments and the use of advanced medical tools and training. Quantum cryptography requires support by a sophisticated information and communications technology infrastructure, hardware, and software, and users who are experienced with the latest encryption methods.

Finally, ubiquitous information access, pervasive sensors, tissue engineering, and wearable computers make the greatest capacity demand on societies. Ubiquitous information access, pervasive sensors, and wearable computers require a combination of extensive networked infrastructures and user sophistication. Tissue engineering requires precise application of sophisticated biotechnology, nanotechnology, and materials technology advances to produce biologically compatible and multifunctional materials for use in the human body. At this time, only the economically and scientifically advanced societies in North America, Western Europe, Japan, Singapore, and a few other places in Asia and Oceania possess such infrastructures and user sophistication, as a result of decades of sustained investment.

Selecting Countries for Analysis

Individual analysis of the 200-plus nation-states of the world was beyond the resources and time available for this study. However, we selected for analysis 29 countries that we believe are representative of the most important international variations in capacity to acquire and implement TAs. These countries were selected to reflect diversity in physical size, natural conditions, and location (e.g., large versus small, tropical versus temperate, land-locked versus island); population size and demographics (e.g., high versus low birthrate, rapidly aging societies versus youthful ones); level of economic development and types of economy (e.g., developed versus developing; market capitalist versus controlled economies); types of government (e.g., competitive liberal democracies versus authoritarian regimes); and S&T capacity levels (e.g., scientifically advanced versus scientifically lagging). While these criteria are not independent of each other, they together represent the principal geographical, social, economic, political, and scientific characteristics of international variation. Within each region of the world, we identified several candidate countries. We then reviewed this initial country list to eliminate highly similar countries within a region. Countries across regions were then compared with each other to remove those that might be represented by others. Table 3.5 lists our selected countries by geographical region.

[184] Indeed, if fuel economy and reliability were key selection criteria for most car buyers, there would be far fewer sport-utility vehicles, trucks, and vans on U.S. roads.

Table 3.4
Demands on Capacity of Top 16 Technology Applications

Level of Capacity Demand	Technology Applications
Low	Cheap solar energy Rural wireless communications GM crops Filters and catalysts Cheap autonomous housing
Medium	Rapid bioassays Green manufacturing Ubiquitous RFID tagging Hybrid vehicles
High	Targeted drug delivery Improved diagnostic and surgical methods Quantum cryptography
Very High	Ubiquitous information access Tissue engineering Pervasive sensors Wearable computers

Table 3.5
Selected Countries Across Regions of the World

Asia	Oceania	North Africa and the Middle East	Europe[a]	Africa	North America	Central and South America and the Caribbean
China	Australia	Egypt	Georgia	Cameroon	Canada	Brazil
India	Fiji	Iran	Germany	Chad	Mexico	Chile
Indonesia		Israel	Poland	Kenya	United States	Colombia
Japan		Jordan	Russia	South Africa		Dominican Republic
South Korea			Turkey			
Nepal						
Pakistan						

[a] We recognize that there are many ways to assign countries into regional groupings. In this instance, we put Turkey in the European group because of the country's long and sustained commitment to join the European Union. This ambition has pushed Turkey to change many of its laws and policies to meet EU admission requirements, as well as to build strong bilateral and multilateral economic and security ties with EU members and NATO.

Determining Country Capacity to Acquire Technology Applications and Their Drivers and Barriers

We assessed the capacity of these 29 selected countries to acquire the top 16 TAs.[185] This assessment used the data that determined the indicators and rankings in the United Nations' HDI, the RAND S&T Capacity Index,[186] the World Bank's Knowledge

[185] As discussed in Chapter Two, this group of TAs captures the essence of our foresight of global trends and provides a representative and workable set of TAs with the potential for broad social impact in 2020.
[186] Wagner et al. (2001).

Economy Index, and data from the Central Intelligence Agency's *World Factbook*.[187] To make a final assessment of capacity to acquire for each representative country, we combined the data from the indicators, rankings, and indices with our assessment of the relative level of capacity demanded by each of the top 16 TAs, as described above and presented in Table 3.4. This produced a basic "tool kit" of TAs that each country has to draw from to address highlighted problems and issues. For example, the United States, which has capacity to acquire all 16 TAs, will have 16 TAs with which to address problems and issues, whereas Nepal will only have five. Table 3.6 shows the number of top 16 TAs for our 29 selected countries, arranged in four groups according to the demand that these TAs make (according to Table 3.4) on S&T capacity, infrastructure, user sophistication, and other country characteristics.

Table 3.6
Groups of Selected Countries by Number of Top 16 Technology Applications

14 to 16 TAs (Very High Demand)	10 to 12 TAs (High Demand)	6 to 9 TAs (Medium Demand)	1 to 5 TAs (Low Demand)
Australia (16)	China (12)	Brazil (9)	Cameroon (5)
Canada (16)	India (12)	Chile (9)	Chad (5)
Germany (16)	Poland (12)	Colombia (8)	Dominican Republic (5)
Israel (16)	Russia (12)	Indonesia (9)	Egypt (5)
Japan (16)		Mexico (9)	Fiji (5)
South Korea (16)		South Africa (9)	Georgia (5)
United States (16)		Turkey (9)	Iran (5)
			Jordan (5)
			Kenya (5)
			Nepal (5)
			Pakistan (5)

The first group comprises countries with the capacity to acquire 14 to 16 TAs: Australia, Canada, Germany, Israel, Japan, South Korea, and the United States. As economically and scientifically advanced nations, they have the institutional, human, and physical capacity necessary to acquire all top 16 TAs.

The second group comprises countries capable of acquiring 10 to 12 TAs: China, India, Poland, and Russia. S&T capacity indicators for these countries suggest a considerable level of scientific and technological proficiency.

The third group comprises countries with the capacity to acquire six to nine TAs: Brazil, Chile, Colombia, Indonesia, Mexico, South Africa, and Turkey. These countries have more-limited S&T capacity and generally rank lower in their economic and social development indicators.

The last group of countries has the least capacity to acquire TAs described in this study. Eleven of our 29 selected countries fall into this group: Cameroon, Chad, the Dominican Republic, Egypt, Fiji, Georgia, Iran, Jordan, Kenya, Nepal, and Pakistan. A

[187] Central Intelligence Agency (2005). The HDI can be found online at http://www.undp.org, and the World Bank Knowledge Economy Index at http://www.worldbank.org/wdi/. Data for the 29 selected countries drawn from these sources are in this chapter and in the appendices.

low level of S&T capacity and poor standing in other economic development indicators suggest that they will at best be able to acquire only TAs that require a low level of institutional, human, and physical capacity to implement.

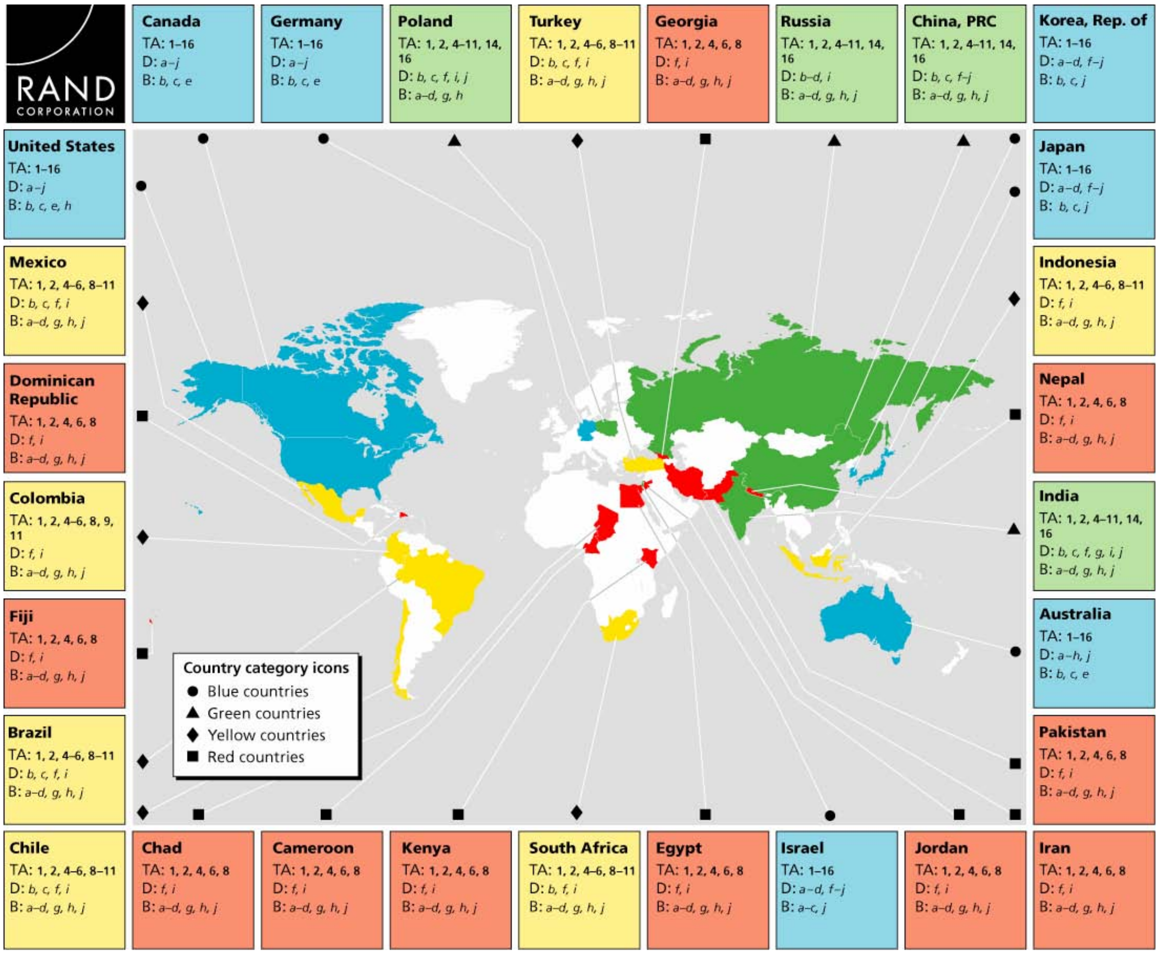
Figure 3.1 presents the specific top 16 TAs that these selected countries have the capacity to acquire. Through the 29 representative countries, Figure 3.1 illustrates regional variations in capacity to acquire TAs. The most economically advanced and scientifically developed countries (shown in blue with a circle icon) represent North America, Western Europe, Australia, and the developed economies of East Asia (e.g., Japan and South Korea). Most of the rest of Asia and Eastern Europe are represented by the next level of capacity to acquire TAs (shown in green with a triangle icon). Latin America, parts of Southeast Asia, Turkey, and South Africa represent a lower level of capacity to acquire TAs (shown in yellow with a diamond icon). Finally, the countries with the least capacity to acquire TAs (i.e., most of Africa and the Middle East, as well as the Caribbean and Pacific Island countries) are represented by the countries shown in red with a square icon. There are individual exceptions illustrated by our 29 selected countries—e.g., Georgia and Nepal ("red" countries in a "green" region) and Israel ("blue" country in a "red" region)—but Figure 3.1 provides a useful overall representation of regional variations across the globe of the capacity to acquire TAs.

Our next task was to determine the major drivers and barriers for these 29 selected countries. We referred to the same data used to determine country capacity to acquire technologies and applied expert judgment on political, economic, and social conditions in these selected countries. Figure 3.1 shows the specific drivers and barriers for each country in the country boxes. "D" stands for drivers, and "B" stands for barriers.

Our assignments indicate that the countries most capable of acquiring TAs (the economically and scientifically advanced countries in the blue group) have the highest number of drivers and simultaneously the lowest number of barriers. By comparison, all selected countries in the green, yellow, and red groups have fewer drivers and face many more barriers to technology implementation. The following pages present our analysis of country capacity to acquire TAs and the drivers and barriers to implementation.

Countries with the Capacity to Acquire 14 to 16 Technology Applications: Australia, Canada, Germany, Israel, Japan, South Korea, and the United States. These seven economically and scientifically advanced countries all have the capacity to acquire all top 16 TAs. Their capacity is built on decades or even centuries of institution building in finance, government, education, commerce, and other facets of society. These societies have stable democratic governments and open economies. Their economic competitiveness and political power are tied to their strength in S&T, and vice versa. Having greater institutional, human, and physical capacity to develop S&T and apply it has afforded these countries many more drivers and far fewer barriers than countries in the other three groups. Also, having a higher level of institutional, human, and physical capacity will enable these countries to more easily overcome barriers to implementing TAs. Table 3.7 shows the drivers for these countries.

Figure 3.1
Selected Countries' Capacity to Acquire the Top 16 Technology Applications



NOTES: Technology Application numbers correspond to those in Table 3.3. Countries in blue boxes (shown in blue on the map and with circles in the icon line) are those with the capacity to acquire 14 to 16 of these TAs. Those in green (triangle icon) have the capacity to acquire 10 to 12 TAs; in yellow (diamond icon), six to nine TAs; and, in red (square icon), one to five TAs. "D" denotes drivers for technology implementation; "B" denotes barriers to technology implementation. a—cost and financing; b—laws and policies; c—social values, public opinions, and politics; d—infrastructure; e—privacy concerns; f—resource use and environmental health; g—investment in R&D; h—education and literacy; i—population and demographics; j—governance and stability.

As described in the section introducing drivers and barriers, although cost and financing are inherently barriers to technology adoption, those countries that have mechanisms to access funds will be in a superior position compared with those that do not. The countries in this group are in a better position than all other selected countries in this study in terms of financing mechanisms available to support implementation of TAs. In general, they have well-established and well-regulated banking systems and financial markets. They also have stable governments and strong economies, so that their government-issued bonds are trusted and welcomed by institutional and individual investors.

All these countries have laws and policies in place to promote R&D, diffusion of innovation, education, and other activities critical to the implementation of TAs. For example, the South Korean government has been actively reshaping its S&T policies, laws, and regulations to spur R&D and innovation in South Korean universities and industry. There is also broad consensus that S&T is central to the country's future given South Korea's paucity in energy and other resources. In Japan, too, the government is rigorously revising its S&T policy and tying it to the nation's education and economic policies. It has created a Council of Science and Technology Policy, chaired by the prime minister, who holds monthly meetings with his S&T advisors and provides direct leadership in national S&T policies.[188]

Table 3.7
Drivers for Australia, Canada, Germany, Israel, Japan, South Korea, and the United States

Drivers	Australia	Canada	Germany	Israel	Japan	S. Korea	U.S.
a. Cost and financing	*	*	*	*	*	*	*
b. Laws and policies	*	*	*	*	*	*	*
c. Social values, public opinions, and politics	*	*	*	*	*	*	*
d. Infrastructure	*	*	*	*	*	*	*
e. Privacy concerns	*	*	*				*
f. Resource use and environmental health	*	*	*	*	*	*	*
g. Investment in R&D	*	*	*	*	*	*	*
h. Education and literacy	*	*	*	*	*	*	*
i. Population and demographics		*	*	*	*	*	*
j. Governance and stability	*	*	*	*	*	*	*
Total number of drivers	**9**	**10**	**10**	**9**	**9**	**9**	**10**

Social values, public opinions, and politics in these countries are all favorable to S&T. S&T is seen as essential to solving problems, promoting economic growth, and meeting other societal needs. Public consensus on and political leadership to advance S&T, particularly integrating them into all spheres of society, are very important to shaping national policies, ensuring resource allocation to support R&D, infusing science and mathematics in education, promoting innovation, and spurring implementation of new technologies. For example, the South Korean government and industries recognize that the South Korean economy not only has to catch up with the United States, Japan, and other leading world economic and scientific leaders, but it must also deal with China, which is moving ahead rapidly in S&T capacity and economic competitiveness.[189] Thus, South Korea invests heavily in education and R&D. Literacy is virtually universal and

[188] See Wong et al. (2004).
[189] Seong, Popper, and Zheng (2005).

science education is emphasized at all levels. South Korean universities graduate thousands of scientists and engineers each year.[190]

Another driver shared by all seven countries is the presence of modern infrastructure. South Korea, a latecomer as an economically and advanced economy, has invested heavily in the past two decades on improving electrical power, communication networks, roads, airports, and other key infrastructure. South Korean industries, in addition to significantly increasing their investment in R&D, work with the government to build a world-class infrastructure for science. Within a matter of years, for example, Internet diffusion and broadband access, by percentage of population in South Korea, grew to surpass all other countries in the world.[191]

Privacy concerns can also be a driver for the application of technologies that address these concerns in Australia, Canada, Germany, and the United States. As democratic and open societies, these countries' populations place a high value on privacy. They support laws, policies, and technologies that promise privacy protection. Such sentiments are influential in shaping public policies and individual choices toward TAs that have the potential to bolster (or weaken) privacy protection.

These countries are also motivated to reduce resource use to increase economic competitiveness and respond to popular demand for better environmental health. These countries have far more comprehensive and stricter laws and regulations to protect natural environments and reduce pollution. Such laws and regulations frequently are even more stringent at the state or local level, which is a reflection of citizen demand for greener and cleaner environments. For example, emission laws in California significantly exceed federal limits on emissions. In Japan, too, provincial authorities and local governments have pushed for much stricter pollution control laws than those introduced by the central government in Tokyo. Companies, too, are increasingly motivated to adopt green technologies to improve their public image—and bottom lines.[192]

As scientifically advanced countries, substantial public and private resources go toward R&D investment and education in all seven countries. This investment produces a rich pool of human capital and institutions to conduct science, produce innovations, and use technologies to boost economic growth, improve health, protect the environment, strengthen security, and meet other development challenges. It also enables a higher level of literacy and comfort with S&T among their populations, which are more keen to adopt new technologies and able to implement them. For example, Israel ranks third in the number of university graduates per capita, after the United States and the Netherlands. It also has the highest per capita number of scientists in the world and publishes the highest number of scientific papers per capita. This human capital drives the Israeli economy, producing world-class research and cutting-edge technologies that address problems at home and are then exported overseas.[193] In South Korea, too, a large number of

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[190] See, for example, Wagner et al. (2003).

[191] For example, a report produced by the Japan Center for Economic Research, raised Korea to 19th place for potential national competitiveness among 50 major countries. Indicators used include external trade, foreign direct investment, manufacturing productivity, college education, fiscal soundness, and inflation. See Lee (2004a).

[192] For example, British Petroleum and Shell emphasize a green image in their advertisements, emphasizing their research on renewable energy and cleaner fuels rather than their oil and gas explorations or competitive pricing. See also Gewin (2005).

[193] Sharaby (2002).

university graduates proceed to postgraduate studies at home and overseas and enter careers in academia, industry, and government. South Korea today is spending more on basic R&D than it has ever before to increase its national S&T capacity to perform cutting-edge R&D. South Korea today has some of the fastest computers in the world and some of the most advanced research facilities for stem cell research, although at the time of this writing the South Korean stem cell research program was shaken by revelations of scientific fraud.[194]

Another key driver is demographic change. These rapidly aging societies need new technologies for medical treatment and care,[195] and they need to increase the productivity of the future workforce in order to pay for these services. Thus, Germany, Japan, and the United States, for example, will be strongly motivated to implement health care–oriented TAs, such as targeted drug delivery and improved surgical methods. The high cost of health care in these countries is already seen as reaching crisis proportion, and some of these TAs offer potential for treatment, as well as cost control. In addition, the elderly represent an important constituent group in these polities, and their demand for better and affordable health care will put implementation of these TAs on national agendas. Australia is the only exception in this instance. Although the population is growing and demographics are changing, these trends are not moving in a direction that is strongly influencing national discussions on how S&T might provide solutions.

Finally, a very important driver is the presence of good governance and political, economic, and social stability in these seven countries. Good governance enables the implementation of laws and policies that otherwise exist only in name. Good governance acts to prevent abuse and corruption, ensuring that resources are allocated fairly and spent efficiently to achieve national goals and objectives. A stable environment encourages long-term investment and capacity building so that development becomes sustainable. In these democratic societies, the demand for increasing transparency, increasing accountability, and expanding participation in public life will spur implementation of technologies to support these objectives.

Figure 3.8 indicates the barriers to technology implementation for these scientifically advanced countries, showing that some of the drivers listed in Table 3.7 are also barriers. In this table and the following tables of barriers for other countries, we indicate barriers that are also drivers with an "X."

Among these barriers, there are three major ones: laws and policies; social values, public opinion, and politics; and privacy concerns. While laws and policies supporting implementation of TAs exist in these countries, many TAs will require new laws and policies—or revisions to existing ones—to make possible their development and implementation. Politics are highly competitive in such democratic societies, and minority opinions can matter just as much as majority preferences. In this connection, the complex interplay of social values, public opinions, and politics surrounding a TA and the issue it is associated with will influence the shaping of laws and policies. Indeed, the power of social values and public opinions in shaping public policy toward science cannot be underestimated. Public perception of risks associated with a TA and the level of risk citizens can tolerate can strongly influence that society's acceptance and

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[194] Cyranoski and Check (2005).

[195] For description of technologies to help the elderly to live independently, see, for example, "Home Alone" (2005).

implementation of that TA. In the United States, public debates on when life begins have shaped current laws and policies governing human embryonic stem cell research. Another example is genetic modification in agriculture. The United States and Europe hold different regulatory approaches and public perceptions. Consumers in the United States are much less apprehensive about the potential negative effects of GM crops and foods on human health and the environment than their peers in Europe are. Europe's rejection of GM crops and food products has caused some countries (e.g., Brazil and India) to hesitate implementation of this technology for fear of losing access to export markets in Europe.[196] In Japan, consumer confidence in GM crops and food is also colored by its citizens' perception of what is pure, as well as declining public trust in the government to ensure food safety.[197]

Table 3.8
Barriers for Australia, Canada, Germany, Israel, Japan, South Korea, and the United States

	Barriers	Australia	Canada	Germany	Israel	Japan	Korea	U.S.
a.	Cost and financing				X			
b.	Laws and policies	X	X	X	X	X	X	X
c.	Social values, public opinions, and politics	X	X	X	X	X	X	X
d.	Infrastructure							
e.	Privacy concerns	X	X	X				X
f.	Resource use and environmental health							
g.	Investment in R&D							
h.	Education and literacy							X
i.	Population and demographics							
j.	Governance and stability				X	X	X	
	Total number of drivers	*3*	*3*	*3*	*4*	*3*	*3*	*4*

NOTE: X indicates that this barrier is also a driver.

Also, in Australia, Canada, Germany, and the United States, individual freedom is highly valued so that privacy concerns represent the third major barrier. (The exceptions are Japan and South Korea, which are collective, group-oriented societies, and Israel, where privacy concerns are not as prominent because the society is more apprehensive about internal security and survival in a regional environment that is hostile to Israel's existence.) Privacy concerns in these four countries will affect national debates on laws and policies on TAs that are perceived to have the potential to compromise privacy. Pervasive sensors, for example, might find considerable public opposition based on the fear of government or commercial control of vast amounts of private personal data. In the

[196] See James (2004).

[197] Mercury poisoning from industrial emissions in the 1960s and poor government response was a major catalyst for a new civil society movement in Japan that challenged the authority of central and local governments and compelled the Japanese government to adopt new environmental legislation in the 1970s. For a history of environmental pollution, civil society movements, and Japanese government responses, see Wong (2001). More recently, concerns about mad cow disease (bovine spongiform encephalopathy) had pushed the Japanese government to tighten meat inspection procedures in Japan and ban the import of U.S. beef. See "Japan Close to Lifting Beef Ban" (2005) and Sharaby (2002).

United States, government attempts to use commercial databases for aviation security have received considerable public criticism. The European Union has also responded to public privacy concerns by introducing a personal data privacy protection directive, with which all member nations must comply.

On other barriers, commanding resources to implement TAs will, by comparison, likely be more difficult for Israel than for other countries in this group. First, Israel has a smaller economy, and more importantly, it has internal security threats and external dangers posed by many neighboring countries that are hostile to its existence. Israel's military spending, as percentage of GDP, consistently ranks among the top 10 in the world. In 2002, 8.7 percent of the GDP went to defense, putting Israel seventh in the world after North Korea, Jordan, Eritrea, Oman, Qatar, and Saudi Arabia. At its peak in 1976–1977, Israel's military spending was more than 30 percent of its GNP. In addition to direct military expenditures, there are also other costs of defense—for example, special construction costs due to laws requiring that every residential building have a bomb shelter and every home a sealed-off room to protect against biological-chemical attacks. The military also holds much land that could otherwise be used for economic purposes. Traffic diversions due to emergencies and violent attacks destroying existing infrastructure add yet another burden to the national economy.[198]

In the United States, the future of literacy in science and mathematics will affect future public attitudes toward S&T and its determination to implement TAs. One indicator is the continuing decline in mathematics and science scores among students in U.S. international comparison surveys that consistently show students in Asian countries such as Japan, South Korea, China, and Singapore performing better than their counterparts in the United States.[199] Also, the number of U.S. students pursuing advanced degrees in science and engineering is falling relative to the growing number of foreign students in university science and engineering departments.[200] If fewer students at the primary and secondary levels take interest in S&T, and society does not value and reward its scientists and engineers, fewer young people will choose careers in S&T. Top technology firms such as Microsoft complain that difficulties in finding enough scientists and engineers have pushed them to set up research operations in China, India, and other overseas locations. Microsoft's research laboratory in Bangalore, India, the John F. Welch Technology Centre, will be Microsoft's third outside the United States;[201]the center has filed 240 patents and has had 25 granted.[202] Another worrisome sign is public school board decisions in many parts of the country to alter their science education curriculum.[203] All this raises concern about the future quality and quantity of scientists

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198 See Central Intelligence Agency (2005) and Sharaby (2002).

199 "U.S. Students Lag in Math, Science Scores" (2000); "American Students Above Average, but Still Lag in Science and Math" (2004); Plisko (2004).

200 Freeman and Jin (2003). See detailed statistics on U.S. and foreign science and engineering graduates from U.S. universities in National Science Board (2004).

201 See "Microsoft Research Launches Operations in India" (2005).Focal areas of research will include geographic information systems, technologies for emerging markets, multilingual systems, and sensor networks. Microsoft Research India and the Indian Ministry of Science and Technology and Ocean Development also signed an agreement to partner in S&T research projects. For example, the Birla Institute of Technology and Science will receive funding to conduct research on for wireless sensor–based water resource management network for monitoring and control of irrigation.

202 Cookson (2005a).

203 See, for example, MacDonald (2004).

and engineers in the United States and the general public's ability to understand the importance of S&T for their lives. These trends represent a potential barrier for the United States to implement TAs and hold serious ramifications for U.S. economic competitiveness and leadership in world science.

Finally, governance and stability are potentially important barriers for Israel, Japan, and South Korea. For Israel, internal security threats and dangers from attacks by external enemies have the potential to destabilize the country politically, economically, and socially. Internal security problems in the past several years, for example, have brought about several changes in government, deepened partisanship, and created a more difficult environment for investors. In Japan and South Korea, political reforms toward greater transparency and accountability have made significant headway, but much still has to be done to enable their governments to optimize the building and use of their institutional, physical, and human capacity. Proximity to North Korea and the potential for increased political instability, or even outright conflict, is another force that can potentially bring instability to these countries.

Countries with the Capacity to Acquire 10 to 12 Technology Applications: China, India, Poland, and Russia. This group comprises four countries, each having the capacity to acquire 12 TAs. These countries have a high level of S&T capacity, which is a reflection of their considerable institutional, human, and physical capacity for S&T. Table 3.9 lists the TAs these countries have the capacity to acquire.

Table 3.9
Technology Applications for China, India, Poland, and Russia

Cheap solar energy	**x**	Green manufacturing	**x**
Rural wireless communications	**x**	Ubiquitous RFID tagging	**x**
Ubiquitous information access		Hybrid vehicles	**x**
GM crops	**x**	Pervasive sensors	
Rapid bioassays	**x**	Tissue engineering	
Filters and catalysts	**x**	Improved diagnostic and surgical methods	**x**
Targeted drug delivery	**x**	Wearable computers	
Cheap autonomous housing	**x**	Quantum cryptography	**x**

Cheap solar energy, rural wireless communications, GM crops, filters and catalysts, and cheap autonomous housing will be particularly important to China and India to increase rural economic development and improve public health. Income disparity is great between rural and urban areas, as is the gap in health, education, and other development indicators. Much of the rapid economic growth the world has witnessed in China and India is largely confined to their urban areas. This growth has improved the livelihood of millions of Chinese and Indians, but many more millions live at or below the poverty line in the rural economies of these countries. They have scarce arable land and fresh water, and more of these valuable resources are lost each day to land degradation, industrial pollution, and urban development. (For example, experts project that China's water supply is likely to reach its limit by 2030, when the country's population reaches 1.6 billion people.[204]) Also, China and India lack infrastructure (e.g.,

[204] For example, see "Experts Warn of Water Crisis" (2005).

grid electricity, national highways) to deliver electricity, clean water, and other services that are critical to economic development. Despite the decline in birthrate, their populations, the two largest in the world, will continue to grow in real terms in the decades to come. As rural areas grow, they will have to deal with typical problems associated with urban development (e.g., sanitation, transportation, and housing). Electrical power supply, fresh water, and housing are also stressed in many urban communities throughout China and India, so that these technologies will also be significant in more-developed areas.[205]

Cheap solar energy, rural wireless communication, and filters and catalysts can reduce the need for large investments in infrastructure building and maintenance. Genetic modification in agriculture can increase production and make farm produce more resilient to disease, cold, heat, and handling when temperature-controlled warehouses and cargo containers are not available or too expensive for use by farmers. Genetic modification in agriculture can also be applied to help delivery of particular nutrients and drugs to consumers, thereby improving public health. China and India are investing significant resources in biotechnology, including GM crops, and both are proceeding cautiously to avoid domestic opposition and backlash from overseas markets. The desire to master this technology is clear: These countries need to feed their large and growing populations.[206]

Another important TA for rural and urban development is cheap autonomous housing, which helps to meet demand for housing and provide an innovative alternative to existing housing design and materials. This TA has the potential to significantly improve the quality of life for the poor, as well as to build more energy-efficient homes for the growing middle class. In times of emergency, when natural or man-made disasters strike, cheap autonomous housing could provide temporary living quarters for victims and relief workers.

All four countries will also have the capacity to acquire rapid bioassays, targeted drug delivery, and improved diagnostic and surgical methods. Rapid bioassays will help these countries to curb the spread of contagious diseases to protect public health and avert negative economic consequences. Outbreaks of SARS and avian flu in recent years and the spread of HIV/AIDS, in addition to other old and new diseases, have caused the Chinese government to face up to the critical need to improve public health if the country is to continue as a magnet for investors and to avoid the negative economic and social effects that widespread diseases can cause.[207] By comparison, application of targeted drug delivery and improved diagnostic and surgical methods will likely be constrained, perhaps limited to urban areas because of high cost, as well as limited infrastructure and human capacity beyond the urban centers.

In the case of Russia, political instability and economic difficulties in the decade following the dissolution of the Soviet Union have further eroded its already crumbling infrastructure and institutions.[208] The Russian economy has recovered from its nadir in recent years largely because of rising oil prices, but it is not clear that earnings have been

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[205] For more on statistics, see Alhous (2005) and Feng (2005).

[206] Feffer (2004). Indeed, biotech capacity is increasing in the developing world. For example, see "Southern Comfort, Eastern Promise" (2004).

[207] See for example, Cyranoski (2005a) and Jia (2005a). Officials in China reported that bird flu had killed 1,000 wild birds and that foot-and-mouth disease had infected cattle in China.

[208] Burger (2002);Wagner et al. (2002); Watkins (2003).

invested into upgrading the existing infrastructure and strengthening institutional and human capacity in science, health, or administration.[209] The exodus of Russian scientists, engineers, and other professionals throughout the 1990s and their continuing departure to seek better livelihoods overseas also raise serious questions about the future of Russian S&T capacity. Those who stay often struggle with meager pay—if any—and deteriorating laboratories and empty libraries, or they switch to other professions for better pay. Thus, while Russia has substantial scientific assets, it is not on par with Japan, the United States, and other scientifically advanced nations. Furthermore, rapidly developing and scientifically proficient countries such as China and India will soon surpass Russia in S&T capacity unless Russia puts a stop to the deterioration of its S&T enterprise and reinvigorates it with new funding and leadership.[210]

All four countries will have the capacity to acquire ubiquitous RFID tagging, as well as quantum cryptography. China, which is rapidly becoming the manufacturing hub for industries around the world, would be particularly motivated to adopt RFID tagging. It will do so either voluntarily to become more economically competitive or in response to demands by international buyers to support the latter's logistics and market research.

China and India are already using advanced cryptography for their IT-based businesses, and they are expected to exploit quantum cryptography to support international commerce and business services in the future.[211] Both countries are emerging high-technology powers, hosting research operations set up by top multinational technology firms such as Motorola, Microsoft, and Hewlett-Packard.[212] For example, domestic research companies, like CapitalBio, a four-year old company in Beijing, are emerging as world leaders. CapitalBio, which builds biochips for biological testing and medical diagnostics, now sells its instruments to U.S. drug companies and in May 2005 entered into a partnership with California-based Affymetrix, the world's largest biochip maker.[213]

Poland's membership in the European Union will push it to complement and compete more effectively with other economies in the European Union. The use of RFID tagging, as well as an advanced information TA such as quantum cryptography, could enhance its economic competitiveness. It is less clear how Russia will use the benefits of RFID tagging and quantum cryptography to promote economic growth and address other policy goals, because of uncertainties about future Russian S&T capacity and how the Russian government views the priority of S&T in national policies.

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[209] Whalen (2004).

[210] For more on Russia, see the National Intelligence Council report (2000a) on Russia's physical and social infrastructure and its implication for future development. For more on Russia's S&T capacity since the collapse of the Soviet Union, see Wagner et al. (2002). Experts interviewed for the study spoke about their experience with and observations of Russia's S&T capacity.

[211] The Indian government announced a tightening of cybersecurity laws just days after a sting operation carried out by a British tabloid managed to buy passwords and other confidential details of British bank customers from Indians working in business process outsourcing companies in India. See "Tighten Cyber Security Laws" (2005).

[212] The Motorola China R&D Institute in Beijing employs about 650 researchers. Lucent Technologies runs Bell Labs in Bejing and Shanghai, and the Bell Labs' Asia Pacific China headquarters is in Bejing. Other U.S. companies with research laboratories in China include General Motors, IBM, Proctor & Gamble, and Texas Instruments. See Larson (2000).

[213] Cookson (2005a).

Finally, all four countries will have the capacity to acquire TAs for green manufacturing and hybrid vehicles. For Poland, its membership in the European Union might provide a greater impetus to adopt green manufacturing technologies to meet EU environmental requirements. For the other three countries, the primary motivation to adopt green manufacturing will be costs and market demand. Businesses aim to reduce input cost, and green manufacturing technologies might help them accomplish this. However, the cost of emissions, or pollution, is not always accounted for in production costs, and low wages relative to the leading world economies ease the urgency to adopt new manufacturing processes to increase efficiency and profits.

Government subsidies on water and energy also distort cost calculations. Antipollution laws with costly penalties and rising labor cost might change the cost equation for business and spur adoption of green manufacturing technologies. Consumer demand will also promote adoption of green manufacturing technologies. In China, a better understanding of the cost of pollution on human and environmental health is pushing the central government to impose stricter fines on polluters. In 2005, the Chinese government announced the opening of the world's first international research center dedicated to addressing cumulative environmental problems, such as global warming, deforestation, and desertification, in the northwestern Chinese city of Lanzhou.[214] However, enforcement of environmental regulation remains weak. Hence, capacity to apply green manufacturing technologies even at a small scale without substantial investments is far from sufficient to motivate implementation.

The same can be said of hybrid vehicles. Continuing high gas prices—which appear likely in the decades to come—will be one factor driving the diffusion of hybrid vehicles.[215] Stricter emission reduction requirements, increased public awareness, change in consumer preference, engineering improvements, and competitive pricing will also help to promote hybrid vehicles in the years to come. However, the extent to which they are adopted will depend on economic and social factors in each country.

As for ubiquitous information access, pervasive sensors, tissue engineering, and wearable computers, the current and anticipated S&T capacity level of these four countries for the year 2020 does not strongly suggest that these four countries will acquire these TAs. Ubiquitous information access will require a sophisticated IT infrastructure, which is missing in these countries. Pervasive sensors might be desired by the regimes in China and Russia to increase government power in surveillance. However, deployment of pervasive sensors for this purpose again will require a sophisticated IT network, and the cost might not justify the benefits, considering that less-expensive means for government control are available—for example, a judiciary that is controlled by the state and intimidation of the media and populace by the police and military. Widespread use of wearable computers might also require more networked infrastructure than these countries can provide. Finally, tissue engineering requires a level of interdisciplinary scientific capacity and focused funding commitment well beyond that for other advanced medical TAs such as targeted drug delivery and improved diagnostic and surgical methods.[216]

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[214] Jia (2005c).

[215] See energy price forecasts prepared by the U.S. Energy Information Administration (2004).

[216] See, for example, Cohen and Leor (2004) and Lavik and Langer (2004).

In short, these four countries have basic S&T capacity to acquire all 16 TAs, but the institutional, human, and physical capacity available to these countries will not likely allow them to acquire all 16 TAs at a high level and on a broad scale—as is the case for the economically and scientifically advanced countries in the first group.

Furthermore, China, India, Poland, and Russia have fewer drivers and more barriers to implementation of TAs than the economically and scientifically advanced countries in the first group. For these four countries, overcoming the barriers will not be easy, but it will not be insurmountable, because certain fundamentals are in place. The drivers, shown in Table 3.10, reflect a considerable level of institutional, human, and physical capacity in these four countries.

Table 3.10
Drivers for China, India, Poland, and Russia

Drivers	China	India	Poland	Russia
a. Cost and financing				
b. Laws and policies	*	*	*	*
c. Social values, public opinions, and politics	*	*	*	*
d. Infrastructure				*
e. Privacy concerns				
f. Resource use and environmental health	*	*	*	
g. Investment in R&D	*	*		
h. Education and literacy	*			
i. Population and demographics	*	*	*	*
j. Governance and stability	*	*	*	
Total number of drivers	7	6	5	4

There are three major drivers for implementing TAs in these four countries. First, their governments either have laws and policies that promote technology development and implementation or are working to put them in place. In China and India, in particular, their political and business leaders explicitly underscore the importance of S&T to national development.[217]

Although social values, public opinions, and politics support technology development and implementation in Poland and Russia, they appear less intense when compared with the situation in China and India. Leaders in these two countries, in particular, recognize that S&T will be important to their country's future. Furthermore, their governments, in the view of some experts, are keen to achieve technological success (e.g., acquiring capacity for nuclear weapons and establishing a space program) as instrumental to increasing their domestic credibility and legitimacy.[218] Populations in China and India appear to embrace S&T. Both countries have seen technology

[217] For example, in March 2005, Chinese Premier Wen Jiabao said that S&T is critical to China's national strength and international competitiveness at a national S&T awards ceremony in Beijing. See "Chinese President, Premier Attend Science Award Meeting" (2005).
[218] See, for example, Feigenbaum (2003) and Havely (2005).

implementation bring significant economic growth and much positive benefit to their lives. For example, China is now the leading exporter of lower- and middle-priced electronic goods, from electric fans to television sets and mobile telephones, and India is now the world's leading back office, processing checks and insurance claims, transcribing medical records, and answering technical support calls. These manufacturing and service businesses have created millions of jobs and expanded their middle class. Their populations are also avid consumers of the competitively priced manufactured goods and services that they produce, buying television sets, obtaining mobile phone services, and accessing the Internet at a very low cost.

Poland, too, is keen to use S&T to increase economic competitiveness and deliver social benefits, but it does not appear to be driven by the same level of fervor as in China and India. Improving governance, strengthening its newly established democratic institutions, expanding welfare, modernizing its military for greater compatibility with security partners, and other issues are more prominent national concerns for its citizens and politicians.

Russia, by comparison, is keen to preserve its world power status, and advanced capacity in S&T is critical to its military power. Hence, social values, public opinions, and politics will likely be important drivers for TA implementation in these countries, but the motivation will be less intense or more narrowly focused than in China and India.

The third major driver for these four countries is population and demographics. These governments will need to find ways to create jobs and provide nutrition, health, and security to their populations. Like several countries in the first group, the population in these countries is either shrinking in real terms (in Russia) or rapidly aging in the coming decades. As a result, these countries, like countries in the first group, will look to new TAs for cost-effective medical treatments and ways to boost productivity and add value to their products and services.

As for other drivers for these four countries, cost and financing is not a driver because there will be very strong competition for resources. Moreover, because they are less developed than countries in the first group, these four countries will have much to do to construct the requirements to turn themselves into economically and scientifically advanced nations. As for infrastructure, China, India, and Poland still have to significantly improve their infrastructure in breadth and depth; thus, it is not currently a driver for these countries. By comparison, infrastructure in Russia today, particularly for R&D, might still be considered world-class, and this currently is a driver. However, this infrastructure is rapidly deteriorating, and a few strong indications suggest that Russian government or business is interested in upgrading this infrastructure, including that portion necessary for R&D. Privacy concerns are not a major driver in these countries. Privacy concerns are not traditionally valued and widely shared by their populations or upheld in their political systems.

Resource use and environmental health will be an important driver in China, India, and Poland. There is considerable political and public awareness of the negative effects of environmental destruction and pollution. These negative effects include human health impacts and environmental degradation and their associated economic costs on society. Public pressure and international criticisms also persuade these governments concerning the political value of improving efficiency in resource use and improving environmental health.[219] By comparison, Russia will be less motivated to implement TAs that reduce resource use and improve environmental health. A strong sense of environmental awareness is lacking among the leadership and population in Russia, and the country's domestic environmental movement is an insignificant voice. The Russian government pays scarce attention to environmental issues, and resource use to improve international economic competitiveness is not high on the official agenda or in the minds of Russian entrepreneurs. This might be due to the fact that Russian economic growth is fueled by energy, mineral, and other raw material exports rather than manufactured goods and services. These are not economic activities that require cutting-edge technologies. There are no strong signs that suggest a significant change in this situation in the coming years.

R&D investment will be an important driver in China and India, but not in Poland and Russia. As described above, China and India have benefited much from the implementation of technology, and their political and business leaders are committed to sustaining this phenomenon. Both the Chinese and Indian governments are increasing funding for R&D. For example, in March 2005 the Indian government announced a 24 percent increase in public allocations, from $3.06 billion to $3.8 billion for S&T in fiscal years 2005–2006. India also announced plans to expand biotechnology research through increased public spending and tax incentives and start-up grants to promote innovation by private enterprises.[220] The Chinese government said it will increase public funding for nanotechnology research in the next several years, up from $25.5 million for the 2001–2005 period. Research projects will focus on six fields, including energy, medical materials, and microelectronics.[221]

Education and literacy will be a major driver for technology implementation in China but not in India, Poland, or Russia. China stands out because the government is strongly committed to expanding access to learning for all peoples across the country. Although spending on education in actual dollars is low measured by population size, adult literacy in China reached 90.9 percent for persons over 15 years of age and 86.5 percent for females over 15 years of age in 2002.[222] These numbers compare favorably with those of the most economically and scientifically advanced countries in the first group, and it is remarkable that these numbers were achieved in a matter of decades since the communist victory in 1949 and *despite* the cultural revolution and other turmoil in Chinese modern history. The Chinese government is eager to use the Internet to deliver education to remote corners of the country, as well as to improve education and information access for urban populations. A population that is literate and comfortable with technology will provide workers who are more able to interface with technology and consumers who are more eager to implement technology.

By comparison, in 2002, India's adult literacy was only 61.3 percent for persons over 15 years of age, and only 46.6 percent for women over 15 years of age. Both Poland

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[219] Public grievance and protests against the human and environmental health impacts of industrial development have become more common in China. See, for example, French (2005b).
[220] See Cookson (2005b) and Padma (2005).
[221] Jia (2005b).
[222] See HDI figures for China at http://hdr.undp.org/statistics/data/cty/cty_f_CHN.html (as of December 2005).

and Russia have high literacy rates in general and specifically among women as well.[223] However, high literacy alone is not a driver for technology implementation in the absence of broad interest in using TAs to improve livelihood and achieve national goals.

Finally, governance and stability are assessed as major drivers for China, India, and Poland but not for Russia. In China, rapid economic growth has enabled a level of political and social stability and some improvements in governance. India is in a similar position. In Poland, democratic reforms and economic opening in the past decade have facilitated the country's admission to the European Union and NATO. Poland appears to be on a steady path toward continuing improvement in governance and stability. However, governance and stability are not drivers for Russia. There has been little improvement in governance in Russia since the collapse of the Soviet Union. Official corruption and organized crime are pervasive. Widespread unemployment and public dissatisfaction with the government's ability to stop corruption and organized crime, as well as internal security issues (e.g., in Chechnya), are potent sources of instability.[224] These weaknesses in governance and stability are better represented as barriers to technology implementation for Russia.

We present the barriers to technology implementation for these four countries in Table 3.11.

Cost and financing are clearly important challenges because these four countries have less economically advanced economies. Reforms in banking and financial sectors will likely help to introduce new mechanisms to fund implementation of TAs. However, success in these reforms will depend on improvements in governance.

With respect to laws and policies, more needs to be done to reconcile contradictions in existing laws and policies that might hinder implementation of TAs. Although these four countries are establishing laws and policies promoting technology implementation, simply having laws and policies on the books is not enough to bring about change. Resources need to be allocated and implementation strategies designed and executed, and countries frequently fall short in the necessary follow-through. Political and financial commitments are essential, and the quality and reach of implementation will also depend on having the right people, institutions, and processes.

Social values, public opinions, and politics serve as a third major barrier. Although there is considerable support for technology development and implementation by leaders and the general population in these countries, it is not clear that they will support the implementation of technologies that do not have explicit and immediate payoffs to their societies or technologies that do not match those identified as national priorities. Leaders and populations in these countries might also reject technologies that they perceive to clash with their values. For example, devoted Hindus, who are vegetarians, might reject GM crops out of concern that genes from animals were introduced to new bioengineered plant varieties. Also, the potential for the Internet to expand public participation in political processes and increase freedom of speech and media freedom have prompted many governments to impose strict controls on access to this technology. In China, the central authorities have established a large cadre of Internet

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[223] See HDI figures for India at http://hdr.undp.org/statistics/data/cty/cty_f_IND.html (as of December 2005), and for Poland at http://hdr.undp.org/statistics/data/cty/cty_f_POL.html (as of December 2005).

[224] The destabilizing effects of these problems are noted in National Intelligence Council (2004, pp. 10, 54).

police to monitor Internet postings and exchanges and have built a sophisticated firewall to block access to Web sites that are critical of the Chinese government.[225]

Table 3.11
Barriers for China, India, Poland, and Russia

Barriers	China	India	Poland	Russia
a. Cost and financing	*	*	*	*
b. Laws and policies	X	X	X	X
c. Social values, public opinions, and politics	X	X	X	X
d. Infrastructure	*	*	*	X
e. Privacy concerns				
f. Resource use and environmental health				
g. Investment in R&D	X	X	*	*
h. Education and literacy	X	*	*	*
i. Population and demographics				
j. Governance and stability	X	X		*
Total number of barriers	**7**	**7**	**6**	**7**

NOTE: X represents barriers that are also drivers.

The voices of dissent toward technology implementation might be more prominent and influential in India and Poland, which have more-open political systems. However, even in China, public opinion has become powerful enough that the government cannot entirely ignore popular sentiment. For example, Chinese farmers and urban populations have protested the damages to health and the environment caused by industrial activities.[226] Also, many Chinese citizens have complained that they were recruited to participate in clinical trials without full information on the potential harmful effects of trial treatments or the possibility of receiving placebos. Their grief, voiced through local and international media, has forced the Chinese government to admit weaknesses in government oversight and the low level of awareness of ethical regulations and informed-consent procedures among Chinese medical researchers.[227]

The lack of infrastructure is another significant barrier. Infrastructure (e.g., highways, broadband IT, research laboratories, hospitals, reliable power and water supply) is still in short supply in these four countries. Modern and high-quality infrastructure is mainly limited to their capitals and a few other major cities, although improvements are slowly expanding into other parts of these countries. Although Russia's infrastructure is considered a driver, it is also important to note that infrastructure improvements are largely limited to Moscow. Elsewhere in Russia, deterioration is the norm. This raises serious questions about Russia's future capacity to implement such TAs as those examined in this study.

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[225] See MacKinnon (2005).
[226] Simons (2005). The strains of new technologies on government are also noted in National Intelligence Council (2004, p. 12).
[227] See Cyranoski (2005c).

Another major barrier to TA implementation in these countries is R&D investment. Although their investment in R&D in general is increasing to varying degrees—in fact, it was identified as a driver in China and India—expenditures are still very low when measured in actual dollars or by population size, as well as when considering how far these countries have to go to establish a level of S&T capacity in breadth and depth that matches that of the advanced scientific nations.

Improving education systems and increasing literacy in breadth and depth present another major barrier for these four countries. As noted in the previous section, literacy is high in China, but this is only a measure of basic literacy. Having a population that is literate in science and comfortable with technology will be essential for China to move up the technology scale in its economic activities. Although tens of thousands of new science and engineering graduates are produced by Chinese universities annually, their numbers are still insufficient to meet domestic demand. Another important issue is improving the quality of education. Beyond increasing education budgets to improve and increase facilities and personnel for education, there still remains the issue of the quality of education. Pedagogy in these countries generally does not emphasize independent and innovative thinking. Some leaders in these countries are beginning to recognize how this can handicap their country's future in expanding S&T capacity and using technologies in society. While these governments look for solutions to this problem, there will be limits to what they will choose to do because of political considerations and public perspectives on the role of education in promoting economic development, and sustaining cultural values, as well as religious beliefs and political ideologies.

Finally, governance and stability are important barriers, particularly for China, India, and Russia. Rapid economic growth in China has helped to sustain political, economic, and social stability. Whether such stability will persist in the years to come is open to debate.[228] The standard of living has improved dramatically for millions of Chinese, particularly those in the booming economic centers in coastal regions, but hundreds of millions of people in other parts of China continue to live in poverty. Also, widespread public dissatisfaction with the widening income gap and pervasive corruption continues. Thousands of small-scale protests by farmers and workers in rural townships now occur annually in China.[229] Rapid economic growth has also brought new wealth to a small segment of the Indian population. Politics in India is more competitive than in China and Russia, but the system is no less corrupt. Its institutions of governance, such as its courts, bureaucracy, and police, are also not known for being effective or efficient in settling disputes and enforcing laws and regulations. For Russia, as mentioned earlier, there has been little improvement in governance since the fall of the Soviet Union. Official corruption and organized crime are pervasive, and internal security problems (e.g., dealing with armed opposition in Chechnya) are sources of instability. In recent years, the Russian government has tightened its restrictions on the exercise of political rights and civil liberties, and there are few signs that a more open, competitive, and accountable political system will emerge and take hold in the near future.[230]

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[228] A World Bank study found governance in China worsening. See Kaufman, Kraay, and Mastruzzi (2005).

[229] See, for example, "Chinese Farmers Protest Against Government Land Grab" (2005).

[230] Freedom, defined by political rights and civil liberties, in Russia and other selected countries is measured in the Freedom Rating produced by Freedom House. See Appendix H for the 2005 scores and

Indeed, one of the more complex issues in governance and stability is how implementation of TAs described in this study might alter the balance of power and models of governance in these societies. For example, China has eagerly embraced IT, becoming the world's top consumer of mobile telephones and using satellite technology to bring education to rural communities. The central authorities in Beijing are also keen to use such IT as the Internet to improve communication with the rural masses, curb abuses by local governments, and strengthen central control over provincial government. Yet, wary of any threat to its authority, the government sponsors development of technologies to censor the Internet and to screen text messages on mobile telephones, and it exercises tight control on access to the Internet to stifle criticisms of the regime.[231] For example, an Internet police force of between 30,000 and 50,000 officers monitors Internet traffic across the country.[232] In March 2005, the Chinese government passed a new law that requires bloggers and owners of personal Web sites to register with the government or be forced offline. Users of Internet cafes must show identification and are issued user numbers.[233] Upgrades to China's Internet, specifically the installation of new routers for all email messages, will allow the authorities more effective monitoring and censorship of the Internet.[234]

Countries with the Capacity to Acquire Six to Nine Technology Applications: Brazil, Chile, Colombia, Mexico, Indonesia, South Africa, and Turkey. Seven countries comprise this group. Table 3.12 shows the TAs they have the capacity to acquire.

Compared with countries in the first and second groups, these countries have the capacity to acquire fewer technologies. On the whole, they are less economically competitive and scientifically proficient. The institutional, human, and physical assets available in these countries for S&T capacity building and implementing TAs are more restricted. Furthermore, building S&T capacity for economic growth and development has not been as prominent on their national policy agendas, as compared with most of the countries in the first and second groups. Nevertheless, they will have the capacity to acquire a considerable number of TAs. Of course, many factors will determine whether they will choose to implement them, as well as their ability to do so in a sustainable manner.

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ratings for these 29 selected countries. Russia is considered "partly free" and less so in 2004 than 2003. See also Freedom House (2005) for full details.

[231] See Chase and Mulvenon (2002) and The OpenNet Initiative studies Internet censorship worldwide at http://www.opennetinitiative.net/.

[232] Applebaum (2005); Cherry (2005).

[233] See "China Tightens Internet Controls" (2000); French (2005a); and Jesdanun (2005).

[234] See MacKinnon (2005).

Table 3.12
Technology Applications for Brazil, Chile, Colombia, Indonesia, Mexico, South Africa, and Turkey

Technology Applications	Brazil	Chile	Colombia	Indonesia	Mexico	South Africa	Turkey
Cheap solar energy	x	x	x	x	X	x	x
Rural wireless communications	x	x	x	x	X	x	x
Ubiquitous information access							
GM crops	x	x	x	x	X	x	x
Rapid bioassays	x	x	x	x	X	x	x
Filters and catalysts	x	x	x	x	X	x	x
Targeted drug delivery							
Cheap autonomous housing	x	x	x	x	X	x	x
Green manufacturing	x	x	x	x	X	x	x
Ubiquitous RFID tagging	x	x		x	X	x	x
Hybrid vehicles	x	x	x	x	X	x	x
Pervasive sensors							
Tissue engineering							
Improved diagnostic and surgical methods							
Wearable computers							
Quantum cryptography							
Number of technology applications	9	9	8	9	9	9	9

Similar to the countries in the second group, these seven countries all have the capacity to acquire cheap solar energy, rural wireless communications, GM crops, filters and catalysts, and cheap autonomous housing. These TAs do not demand a great deal of S&T capacity to benefit rural economic development, improve public health, and manage urban growth, which are important issues in these countries.[235] A significant percentage of the population in these countries lives in rural areas. Many live at or below the poverty line. Like the countries in the second group, these seven countries' infrastructure is typically poor outside their capital cities. Good roads, cheap and stable electricity and water supply, health services, schools, and other items essential to support development are frequently lacking. These five TAs can help rural populations to increase their capacity for development in myriad ways:

[235] See, for example, "Clean Water Supplies Can Help Development Says UN Health Chief" (2001).

- Cheap solar energy can provide lighting for study; energy to preserve and process crops, foods, and medicines; and energy to run filters and to power mobile phones and computers.[236]
- Rural wireless communication can improve access to information (e.g., for weather reports, prices of crops).[237]
- GM crops can increase productivity and profits, because produce stays fresh longer, looks better, and delivers nutrients to consumers.
- Filters and catalysts can increase access to clean water and reduce death and illness due to water-borne diseases.
- Cheap autonomous housing can provide innovative housing alternatives that are cheaper, sturdier, and more environmentally friendly than current options.

Like China, India, Poland, and Russia, these seven countries are experiencing rapid urban population growth, and these TAs hold potential to ease pressure on electrical power, fresh water and nutrition, transportation, communication, and housing needs.

These countries will also have the capacity to acquire TAs for rapid bioassays, which demand only a moderate level of S&T capacity to adopt and implement. Again, like countries in the second group, these seven countries will be motivated to apply this TA—if only in their major air and maritime ports, international checkpoints, and cities—to detect and stop the spread of infectious diseases. High urban density, increasing movement of people internally and externally, poor sanitation, and weak public health systems will help spread infectious diseases and impose a significant cost on human lives and the economy.

Targeted drug delivery, tissue engineering, and improved diagnostic and surgical methods, however, will likely be beyond the institutional, human, and physical capacity of these countries to acquire and implement, except perhaps in a very limited manner. For the developing countries with large populations that have little access to basic health care, improving public health will be a greater priority.

As for exploiting ubiquitous RFID tagging, all countries in this group except Colombia will have the capacity to acquire this TA. All these countries, except Colombia, are, to a varying extent, active participants in the global economy. They are promoting economic growth through exports of timber, clothing, fruits and vegetables, electronics, and other products to markets in Western Europe, Northeast Asia, and North America. Adopting this TA will make them more economically competitive as suppliers in the international marketplace. Corporate buyers of their products (e.g., home improvement chains and warehouse stores) might be catalysts for the adoption of this TA as they work to cut costs in logistics and improve awareness of consumer preferences. By comparison, Colombia's economy is much less involved in international trade, and its domestic and regional markets are unlikely to generate demand to deploy this TA.

Quantum cryptography will be beyond the reach of these countries. For Brazil and Chile, the two countries in this group with the greatest S&T capacity, use of quantum cryptography will likely be on a limited scale despite some positive signs. For example,

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[236] See examples of how photovoltaic energy is helping income generation in rural areas in Mbaiwa (2004). A success story of solar power introduced with assistance from the United States can be found in Hossain (2005).

[237] See, for example, Wilson (2004).

with respect to the RAND S&T Capacity Index, Chile ranks above all countries in this group except Brazil.[238] However, unlike China and India, the IT sector in these countries has not been an engine of economic growth. Unified IT, pervasive sensors, and wearable computers, too, are beyond the S&T capacity and needs of these countries, for similar reasons to those stated for countries in the second group.

As for green manufacturing and hybrid vehicles, these countries will have the capacity to acquire these TAs. Motivation to use them, however, will depend on a variety of factors, such as energy costs, consumer demand, and laws that promote their use through tax breaks or emission penalties. The extent of application can vary greatly. Green manufacturing might involve full end-to-end process improvements and rigorous international certification, such as that under the International Organization for Standardization.[239] This requires a great deal more institutional capacity to implement and will be difficult except for a small number of well-established businesses in these countries. Adoption of individual green manufacturing processes to make incremental improvements will require much less capital input and institutional capacity to execute, and more businesses will be able to adopt them.

The adoption of hybrid vehicles will be influenced by income growth in these countries, energy prices, consumer preference, and regulatory incentives. Hybrid vehicle production worldwide will have to increase substantially to meet demand in these markets. The major consumers of vehicles live in North America, Japan, and increasingly China, so that automobile manufacturers will likely prioritize these markets over markets elsewhere.[240] Diffusion of hybrid vehicles will also be affected by the many factors described earlier in this chapter, including price compared with new and used combustion engine vehicles, personal preferences, and availability of spare parts and services at competitive prices.

These countries share many of the same drivers and barriers to the implementation of TAs as countries in the second group—population pressure, paucity of resources, lack of infrastructure, inadequate institutional and human capacity, to name a few. In fact, these countries, which have less capacity to acquire TAs than those in the first two groups (or less institutional, human, and physical capacity for science and other enterprises) will command fewer drivers and face more barriers in their efforts to implement these TAs.

Two drivers are shared by all seven countries in this group, namely, (1) reducing resource input for greater competitiveness and (2) population growth and demographic changes. As is the case for the countries in the two preceding groups, these countries must deal with the reality of increases in energy prices, reductions in natural resources, and environmental degradation brought on by economic activities. They must

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[238] Brazil is the largest country in South America by land size, population, and economic output. Its service sector now represents 51 percent of the economy, followed by the industrial sector at 39 percent and agriculture at 10 percent. Chile has done very well to establish democratic institutions and maintain strong financial institutions and economic growth since the fall of the military regime in 1990. It is upgrading its physical infrastructure, from maritime ports and roads to educational institutions, to support its economic growth. See the HDI data for Chile and other selected countries in Appendix J.

[239] For information on the ISO14000 Environmental Management standard that is widely adopted in Europe and Japan, see International Organization for Standardization (2002).

[240] See numbers for car sales in the United States and related news on hybrid vehicles at HybridCars.com (undated).

simultaneously deal with demands imposed by growing populations and demographic changes, which if unattended might fuel political tensions, economic stress, and social instability. All this provides motivation for policymakers and entrepreneurs to implement TAs to increase resource use efficiency and protect environmental health, as well as to create jobs, provide nutrition and health, and meet other needs of their populations. Table 3.13 shows the major drivers for the implementation of TAs in these countries.

In addition to increasing efficiency in resource use and improving environmental health and meeting demands of population and demographic changes, other drivers will push the implementation of TAs in these countries. Governments in Brazil, Chile, Mexico, South Africa, and Turkey know that development will require the implementation of new technologies to increase economic competitiveness and enable improvements in nutrition, health, education, and other areas. Further, they recognize that implementation of new technologies will require the presence of appropriate laws and policies to promote the development and diffusion of these technologies. Although they have considerable distance to go toward putting in place laws and policies to promote implementation of new technologies, national debates have started and initial attempts are already visible (e.g., Brazil's decision to approve GM soy planting). In addition, institutions of governance are improving in these countries so that laws and policies adopted will more likely be enforced. By comparison, the current and foreseeable political situation in Colombia and Indonesia toward the year 2020 does not encourage great optimism. In these countries, the threat of political and military coups, rampant official abuse and corruption, and aggressive partisan competition dominate national politics. Consequently, laws and policies to promote implementation of emerging TAs are unlikely to rank high in the national agenda, and are unlikely to be backed by sufficient commitment in political will and material resources to be enacted.

Table 3.13
Drivers for Brazil, Chile, Colombia, Indonesia, Mexico, South Africa, and Turkey

Drivers	Brazil	Chile	Colombia	Indonesia	Mexico	South Africa	Turkey
a. Cost and financing							
b. Laws and policies	*	*			*	*	*
c. Social values, public opinions, and politics	*	*			*		*
d. Infrastructure							
e. Privacy concerns							
f. Resource use and environmental health	*	*	*	*	*	*	*
g. Investment in R&D							
h. Education and literacy							
i. Population and demographics	*	*	*	*	*	*	*
j. Governance and stability							
Total number of drivers	**4**	**4**	**2**	**2**	**4**	**3**	**4**

Social values, public opinions, and politics serve as another major driver, one that Brazil, Chile, Mexico, and Turkey all share. National leaders in these countries emphasize economic competitiveness as a national goal, and they underscore the importance of S&T toward this end. These countries are experiencing increasing international trade, cross-border travel, and free flow of information. These things encourage their populations to be more aware of the potential benefits of TAs and increase their desire to implement them. Public opinions and the visions of national leadership thus echo each other and help push S&T into national discussion. In the three remaining countries in this group—Colombia, Indonesia, and South Africa—this driver is weak. Political instability and military insurgencies in Colombia and Indonesia dominate politics and the minds of national leaders and ordinary citizens alike. Without stable governments, peaceful environments, and commitments to S&T by their national leaders, S&T is rarely emphasized in national discussions, particularly in their importance to broader national development. Instead, any emphasis given might only be focused on tackling immediate emergencies (e.g., vaccinations to prevent the spread of disease in the Indonesian province of Aceh following the December 2004 tsunami disaster and use of satellite technologies to track narcotics smugglers in Colombia). In the case of South Africa, refusal by top South African leaders to accept international scientific consensus on the relationship between the HIV virus and AIDS infections delayed adoption of national laws and policies to control spread of the disease and to offer medical treatment to the afflicted.

With respect to the barriers to implementing TAs, these seven countries, like the countries of the preceding group, face many more than countries in the first group. Moreover, these barriers are strong in all seven countries. All these countries suffer from a lack of funding to implement TAs. They also either lack laws and policies that promote technology implementation or fall far short in enforcing existing laws and policies. Social values and public opinions supportive of S&T are weak and not well integrated into public policy debates. Modern infrastructure to support implementation of TAs is limited in reach and quality. These seven countries also suffer from low investment in R&D and education, as well as poor governance. Table 3.14 shows barriers to implementing TAs in these seven countries.

The cost and financing of TAs, from development to acquisition, implementation, and maintenance, present a considerable challenge. Absence of or weak laws and policies serve as another significant barrier. The ability to reconcile domestic laws and policies with demands from external sources will be another challenge. For example, if Turkey is to gain entry to the European Union, its national laws and policies covering the full spectrum from immigration to employment, education, and personal data protection must be consistent with EU directives.[241] This will likely require Turkey to pass new laws and policies and modify existing ones.

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[241] Turkey and the EU were scheduled to begin membership talks in October 2005, and science and culture are expected as lead areas in the screening talks. See "Turkey Wants Parallel Start of EU Screening Process, Accession Talks" (2005).

Table 3.14
Barriers for Brazil, Chile, Colombia, Indonesia, Mexico, South Africa, and Turkey

Barriers	Brazil	Chile	Colombia	Indonesia	Mexico	South Africa	Turkey
a. Cost and financing	*	*	*	*	*	*	*
b. Laws and policies	X	X	*	*	X	X	X
c. Social values, public opinions, and politics	X	X	*	*	X	*	X
d. Infrastructure	*	*	*	*	*	*	*
e. Privacy concerns							
f. Resource use and environmental health							
g. Investment in R&D	*	*	*	*	*	*	*
h. Education and literacy	*	*	*	*	*	*	*
i. Population and demographics							
j. Governance and stability	*	*	*	*	*	*	*
Total number of barriers	**7**	**7**	**7**	**7**	**7**	**7**	**7**

NOTE: X denotes those barriers that are also drivers.

Although public support for S&T is present in Brazil, Chile, Mexico, and Turkey, it is largely confined to urban populations. A large portion of the populations in these seven countries belongs to the rural economy, and opposition to implementing TAs might stem from these populations' ignorance and fears. How the national leadership will respond to these sentiments through education, political dialogues, and innovative solutions will significantly determine whether these countries will acquire certain TAs, how they will be used, the problems they will address, and who will benefit from them.

The lack of infrastructure is another important barrier for these countries. Even TAs that require a low level of S&T capacity demand some basic infrastructure and institutional capacity to enable their implementation. Again, modern infrastructure is largely limited to urban centers in these countries. Institutional and human capacity in S&T, as well as in management, finance, and business, concentrate in capitals and major cities. In this connection, public investment in R&D is also limited to a few national universities and laboratories, and private-sector investment is quite restricted. Although world-class excellence in research exists in a few areas, much of that knowledge and expertise is confined to a few top researchers. Their departure from research as a result of retirement, emigration, or other reasons could mean the end of important research programs in these countries.

As for education and literacy, although adult literacy is quite high in these countries, national budget constraints do not allow a widespread penetration of modern teaching tools, including up-to-date textbooks, libraries, and access to the Internet for teachers or students. Good private schools and top public schools in their capitals might have facilities and teachers on par with the best in the economically and scientifically advanced countries, but only a tiny fraction of their populations has access to them. This reality hinders technological learning that is critical to expanding human capacity to implement TAs and increasing public support for TAs. Consequently, these weaknesses in infrastructure, R&D, and education will make it more difficult for these countries to implement TAs.

Finally, corruption among officials is a major problem in all these countries. It takes valuable resources away from essential institutional, human, and physical capacity building activities and adds to the cost of all economic activities. In addition, armed militants continue to battle government forces in Colombia and Indonesia, and political tensions might again turn into open violence between the government and militant groups in Indonesia, Mexico, and Turkey. Such internal security problems can affect government priorities in spending, favoring expenditures on the armed services over investment in infrastructure, health, education, and R&D.

Countries with the Capacity to Acquire One to Five Technology Applications: Cameroon, Chad, the Dominican Republic, Egypt, Fiji, Georgia, Iran, Jordan, Kenya, Nepal, and Pakistan. These 11 countries have the least capacity—institutional, human, and physical—among our 29 selected countries.[242] Using the United Nations' HDI as an indicator, all these countries, except Fiji, rank in the bottom half, and several in the bottom quarter, of the 177 countries ranked.[243] On the RAND S&T Capacity Index, these countries all rank in the bottom half, and most in the bottom quarter of our representative countries.[244] On the World Bank's Knowledge Economy Index, these countries all rank in the bottom one-third of the 29 selected countries in terms of their innovation scores.[245]

Countries in this group have the capacity to acquire only the five TAs that require a minimum level of S&T capacity—cheap solar energy, rural wireless communications, GM crops, filters and catalysts, and cheap autonomous housing. Although these countries have the capacity to acquire only a small number of TAs, these TAs—if implemented on a broad scale and in a sustainable manner—have the potential to improve livelihood for the vast majority of their populations who live in poverty.

For example, the United Nations Development Programme (UNDP) estimates that more than 1 billion people worldwide lack access to water and that more than 2.4 billion people lack access to basic sanitation. Access to clean water is lowest in Africa, while Asia has the largest number of people with no access to basic sanitation.[246] Cheap solar

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[242] Although Pakistan and Iran have the capacity to build nuclear power generators and nuclear weapons, their use of S&T in education, government, transportation, health, commerce, agriculture, and other areas is very limited. See Institute for Science and International Security (undated) and Uranium Information Centre (2005). See also Appendix H (the RAND S&T Capacity Index) for S&T indicators for these two countries and how they compare with scientifically proficient and advanced countries.

[243] Of the 177 countries on the HDI 2002 index, Fiji ranks 80; Jordan, 90; Georgia, 97; the Dominican Republic, 98; Iran, 101; Egypt, 120; Nepal, 140; Cameroon, 141; Pakistan, 142; Kenya, 148; and Chad, 167.

[244] The Egyptian government recently announced a 12-year strategy, between 2005 and 2017, to bolster the country's S&T capacity. The plan will increase public funding for scientific research from 0.9 percent to 1.0 percent of the national budget. Under the strategy, Egypt will launch postgraduate and other training programs in biotechnology, renewable energy, agriculture, water, and information and communication technologies. However, declared goals and strategies do not always receive sustained and sufficient political and funding commitment in implementation in Egypt and elsewhere. So it remains to be seen whether this pronouncement will be implemented and promote S&T capacity in Egypt. See Sawahel (2005).

[245] See Appendix K for details.

[246] See the UNDP's global water-related data at UNDP (undated c); "Billions Without Clean Water" (2000); Millennium Ecosystem Assessment (2005). The assessment concluded that desertification is

energy and filters and catalysts can help these populations to improve access to clean water.[247] Cheap solar energy and cheap autonomous housing might help to reduce indoor air pollution generated by wood- and coal-burning cooking stoves that are used by hundreds of millions in developing countries. In sub-Saharan Africa, 80 percent of households depend on wood for cooking and warmth. Chemical compounds and minute particles produced by burning wood and deposited in lungs threaten the respiratory health of both the young and old. Women and children are most vulnerable, because they typically are responsible for cooking and spend more time inside the home. Without alternative clean energy, WHO estimates that at least 10 million women and children will die prematurely in the next 25 years from smoke produced by indoor cooking stoves.[248]

The two main drivers for implementing these TAs, as is the case for countries in the preceding groups, are reducing resource input to increase economic competitiveness and the need to respond to pressures from population growth and demographic trends.

Pressures associated with population growth and demographic trends are particularly intense in these countries in light of their poor economic performance. There is a desperate need for economic growth to provide jobs and improve standards of living. The population of Pakistan, which was 150 million in 2002, is projected to reach 205 million by 2015, more than one-third of which will be under the age of 15. Egypt will see its population rise from 70 million in 2002 to 90 million people by 2015. Iran's population will grow from 68 million in 2002 to 81 million in 2015. Population growth in other countries in this group, though less in actual and percentage terms, will also impose a heavy burden on these countries, given depleting resources such as water and land and compounded by the lack of economic growth.[249]

As for barriers to implementing TAs, the countries in this group share the same ones as the preceding groups. Particularly notable is that none of these 11 countries has barriers that are simultaneously drivers, as is the case for all the other representative countries. This difference suggests how much further these countries have to go to develop institutional, human, and physical capacity to implement TAs. For them, it is more about building capacity—because there is virtually none—rather than reconciling or modifying what is present with the demands of these TAs. Table 3.15 indicates the barriers for these countries.

The lack of money and financial mechanisms to enable implementation of TAs is a major barrier. Foreign assistance might help pay for a few demonstration projects or training and hardware for a number of users in the launch period; however, large-scale diffusion and sustainable implementation of these TAs will ultimately depend on finding ways to finance their use. At the individual level, income gain and creative financial arrangements (e.g., micro-lending) are necessary for individuals to purchase these TAs.

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threatening 2 billion people worldwide and that areas in sub-Saharan Africa and Central Asia are most vulnerable to further desertification.

[247] Water-related diseases kill and maim millions of people in the developing world each year. Clean water can prevent these deaths and injuries. See, for example, a list of water-related diseases (World Health Organization, undated) and a WHO study on emerging issues in water and infectious diseases (World Health Organization, 2003). The urgency and importance of clean water for Africa is emphasized in United Nations GEMS/Water Programme Office (2003).

[248] See Williams (2005).

[249] Only Georgia's population is projected to decline in real terms during the same period as a result of reduced birth rate and migration.

At the national level, policymakers have to see value in investing in these TAs and follow through with actions (e.g., budget allocations, laws, awareness campaigns, and enforcement efforts) to promote their implementation in a sustainable manner.

In addition to shortage of funds, laws and policies, as well as good governance and stability, are typically in short supply in these countries.[250] Many have autocratic regimes that are more interested in staying in power than fostering economic growth and development. TAs that might diminish government control and alter the balance of power are unlikely to be allowed widespread use without government control. Political instability and uncertainties in leadership succession are also common problems. Indeed, peaceful transfer of power and open and competitive political processes still appear elusive in most of these societies. Widespread corruption and abuse present another severe handicap for these countries. Money allocated to development activities frequently ends up in the pockets of corrupt officials and their families and friends, and rulers often treat the national treasury as their personal bank account. For example, Transparency International ranks Cameroon, Chad, Kenya, and Pakistan as among the most corrupt countries in the world. Iran, the Dominican Republic, Egypt, and Nepal rank slightly better.[251]

Poverty in corrupt societies marked by great disparities in wealth and power frequently breeds popular discontent. The political leadership might be able to suppress popular dissent, but underlying political and social problems will thwart efforts to build national capacity for long-term economic growth. Without fundamental and lasting changes to make politics competitive and increase government transparency and accountability, neither domestic funds nor international assistance will likely make a significant difference to reduce poverty or achieve other development goals in these countries. Ethnic, tribal, and religious rivalries in the absence of political leadership further complicate politics in these countries and hinder development. For example, ethnic tensions between native Fijians and the Indo-Fijian community (who make up nearly half of the total population) toppled an elected Indo-Fijian–led government and brought economic hardship to the entire population. Subsequently, many Indo-Fijians, who make up a large number of Fiji's entrepreneurs and professionals, have chosen to resettle elsewhere. Their departure from Fiji represents a loss of important business capital and professional knowledge and networks for the Fijian economy.[252]

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[250] See Kaufman, Kraay, and Mastruzzi (2005).

[251] In this group, Jordan is the least corrupt. In fact, Jordan is regarded as less corrupt than Brazil, China, Colombia, Mexico, Poland, South Africa, Korea, and Turkey. Among the 29 selected countries in this study, only Australia, Canada, Germany, the United States, Chile, Japan, and Israel are considered less corrupt than Jordan in Transparency International's Corruption Perception Index scores for 2004. See more details at Transparency International's Web site, http://www.transparency.org.

[252] See more in country report on Fiji in Freedom House (2004).

Table 3.15
Barriers for Cameroon, Chad, the Dominican Republic, Egypt, Fiji, Georgia, Iran, Jordan, Kenya, Nepal, and Pakistan

Barriers	Cameroon	Chad	D.R.	Egypt	Fiji	Georgia	Iran	Jordan	Kenya	Nepal	Pakistan
a. Cost and financing	*	*	*	*	*	*	*	*	*	*	*
b. Laws and policies	*	*	*	*	*	*	*	*	*	*	*
c. Social values, public opinions, and politics	*	*	*	*	*	*	*	*	*	*	*
d. Infrastructure	*	*	*	*	*	*	*	*	*	*	*
e. Privacy concerns											
f. Resource use and environmental health											
g. Investment in R&D	*	*	*	*	*	*	*	*	*	*	*
h. Education and literacy	*	*	*	*	*	*	*	*	*	*	*
i. Population and demographics											
j. Governance and stability	*	*	*	*	*	*	*	*	*	*	*
Total number of barriers	**7**	**7**	**7**	**7**	**7**	**7**	**7**	**7**	**7**	**7**	**7**

Because these are mainly low-income countries and corruption is rampant, there is very little infrastructure, low levels of literacy, and limited R&D investment. As a result, human capacity to acquire and apply S&T is low. There is also little popular demand for S&T. Caught up with daily survival, people in these societies do not necessarily see the value in building S&T capacity because the payoffs are not generally immediate. Indeed, the need to meet external debt servicing requirements and other urgent short-term priorities make it very difficult even for honest policymakers to allocate their meager national budgets to improve infrastructure, education, science, and health.

Therefore, for these low-income countries, the capacity to implement TAs will be severely constrained by these weaknesses. Although these TAs do not require a high level of S&T capacity, they do require a moderate level of institutional, human, and physical capacity, as well as political and social stability, for their implementation. Unfortunately, such requirements are generally lacking in these countries.

Determining Country Capacity to Implement Technology Applications Relevant to Problems and Issues

The previous section examined how drivers and barriers affect a country's capacity to implement TAs, clearly demonstrating that the capacity to acquire a TA does not necessarily imply the capacity to implement it. To analyze a country's capacity to implement TAs, we considered three factors: (1) capacity to acquire, defined as the percentage of the "top 16" TAs listed for that country in Figure 3.1; (2) the percentage of ten drivers for implementation applicable to that country, as listed in Figure 3.1; and (3) the percentage of ten barriers to implementation applicable to that country, also as listed in Figure 3.1.[253]

Figure 3.2 shows the position of each of the 29 representative countries on a plot for which the y-axis is the product of factors 1 and 2—that is, the capacity to acquire *scaled* by the percentage of drivers[254]—and the x-axis is factor 3. Both axes are shown as percentages, with the y-axis starting at zero (i.e., there is no capacity to acquire TAs and there are no drivers) and ending at 100 (i.e., the capacity to acquire all 16 TAs and all 10 drivers are applicable), and the x-axis starting at 100 (i.e., all 10 barriers are applicable) and ending at zero (i.e., no barriers are applicable).

In Figure 3.2, countries are represented in the colors and icons that we established for them in Figure 3.1. We note that Figure 3.2 provides a first-order assessment of the capacity to implement TAs, in that we applied equal weighting to all TAs, drivers, and barriers, although we recognize that specific TAs, drivers, and barriers might be more significant in particular countries.

The upper right-hand quadrant of Figure 3.2 (shaded in blue) represents countries for which implementation of TAs is strongly driven by a high level of S&T capacity and the presence of many drivers and few barriers. The upper left-hand quadrant (shaded in green) represents countries for which implementation of TAs is strongly driven by a high level of S&T capacity and the presence of many drivers, but for which many barriers are simultaneously present. The lower right-hand quadrant (shaded in yellow) represents countries for which implementation of TAs is not supported by a high level of S&T capacity and for which the number of both drivers and barriers is small. The lower left-hand quadrant (shaded in red) represents countries for which implementation of TAs is not supported by a high level of S&T capacity, and the number of barriers exceeds the number of drivers.

This approach is consistent with current research findings in international development, which shows that multiple factors must be present to sustain economic growth and development (e.g., infrastructure, good governance, a healthy population, literacy, political stability, sound banking and financial structure, and a dynamic innovation system). International development assistance in the 1950s and 1960s emphasized infrastructure building, such as roads and dams, without careful consideration of the impact on human communities or the environment. This oversight resulted in massive waste, corruption, and environmental destruction. More-recent emphasis on IT and rural health quickly gave way to improving governance when it became clear that official corruption and abuses could handicap a society's ability to build capacity and use any tool to attain ultimate goals in economic and social development.[255]

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[253] As noted previously, a detailed analysis of where on each driver-barrier continuum particular countries fall was beyond the scope of this study. However, we do identify which drivers and barriers are present in specific countries, so that the percentage of drivers and percentage of barriers that apply are the appropriate quantitative metrics for a country at this level of analysis.

[254] Multiplying capacity to acquire by the percentage of drivers is consistent with the view that the absence of drivers reduces the probability that the TAs a country can acquire will be implemented.

[255] See Kaufman and Kray (2003). This study concluded that good governance is not a luxury that can only be afforded by the rich, developed countries and that rising income does not automatically promote good

Figure 3.2
Selected Countries' Capacity to Implement the Top 16 Technology Applications

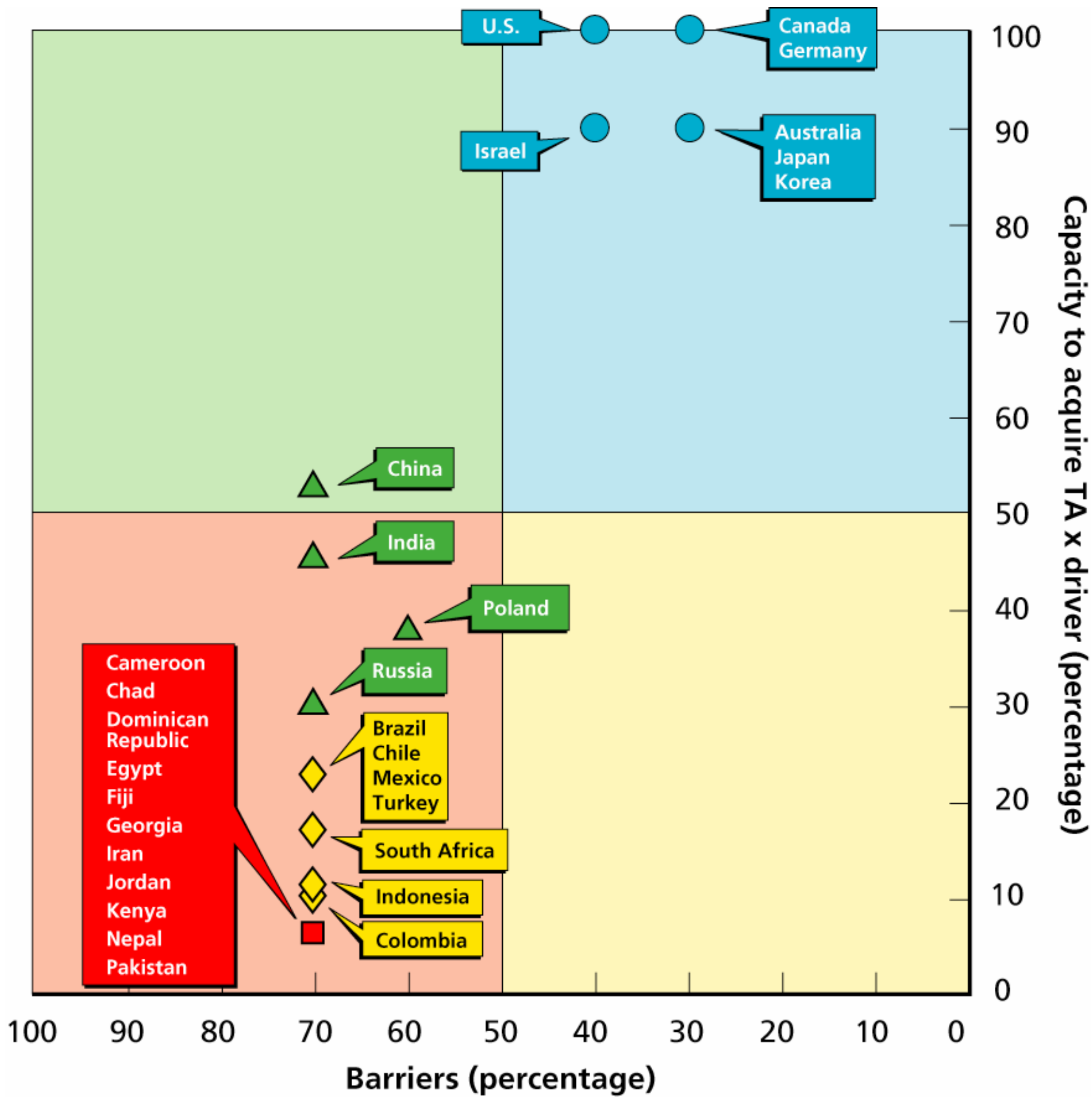

Figure 3.2 indicates that the blue countries of Figure 3.1 (e.g., the United States and Germany), which appear in the upper right-hand (blue) quadrant of Figure 3.2, are most capable of implementing the TAs that they have the capacity to acquire. By comparison, the red countries of Figure 3.1 (e.g., Cameroon and Fiji) have the least capacity to implement TAs that they have the capacity to acquire. It is interesting to note that the green and yellow countries of Figure 3.1, except for China, also appear in the lower left-hand (red) quadrant in Figure 3.2. Having a smaller "tool kit" than the blue countries, and possessing fewer drivers and more barriers, means that they encounter greater challenges in attempting to implement TAs beyond laboratory research,

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governance. However, improving governance is shown to have a positive impact on improving income equality, economic growth, and stability.

demonstrations, or limited diffusion. We also note that no country appears in the lower right-hand (yellow) quadrant. This results from the positive correlation between a country's capacity to acquire TAs and the number of barriers it faces, i.e., countries that have a high level of S&T capacity to acquire technology typically have fewer barriers, whereas countries with a low level of S&T capacity to acquire technology typically face many more barriers. The exact causal relationship requires a more in-depth and focused investigation, but what we see here is a linkage between S&T capacity and the drivers and barriers that define the context in which technology implementation occurs.[256]

Figure 3.3 summarizes the selected countries' capacity to acquire and implement TAs. The capacity of our selected countries to acquire TAs is represented, as in Figure 3.1, by colored boxes (and icons in the country line icons). The top 16 TAs that these selected countries have the capacity to acquire are indicated by numbers that correspond to the list in Table 3.3, and their applicable drivers and barriers are indicated by letters that correspond to those in the caption to Figure 3.1. The color frames around these boxes (and the additional white icon in the country lines) indicate the capacity of these selected countries to *implement* TAs. Those that have commensurate capacity in acquisition and implementation of TAs will have the same color frame (and the same white icon added to the country line). Those that have different capacity in acquisition and implementation of TAs will have a different color frame that indicates their capacity for implementation (and a different white icon that represents the capacity level).

Figure 3.3 shows the country boxes for Australia, Canada, Germany, Israel, Japan, South Korea, and the United States—blue group countries—having blue frames (and both black-and-white circles in the country lines), reflecting their positions in the upper right-hand (blue) quadrant of Figure 3.1. China, too, has the same color frame and identical icon as a Figure 3.1 green country in the green quadrant of Figure 3.2. The other green countries—India, Poland, and Russia—by comparison, are green countries in the lower left-hand (red) quadrant of Figure 3.2. Hence, the country boxes for India, Poland, and Russia are green, but they have red frames (and a black triangle inside a white square in the country line). We note, however, that the difference between India and China in Figure 3.2 is relatively small, and due to the assignment to China of one additional driver, education and literacy. So, while China is the only green country in the green quadrant of Figure 3.2, India is alone at the top of the red quadrant. Expansion of its educational system into less-developed areas and improvement in its overall literacy rate could bring India up into the green quadrant with China.

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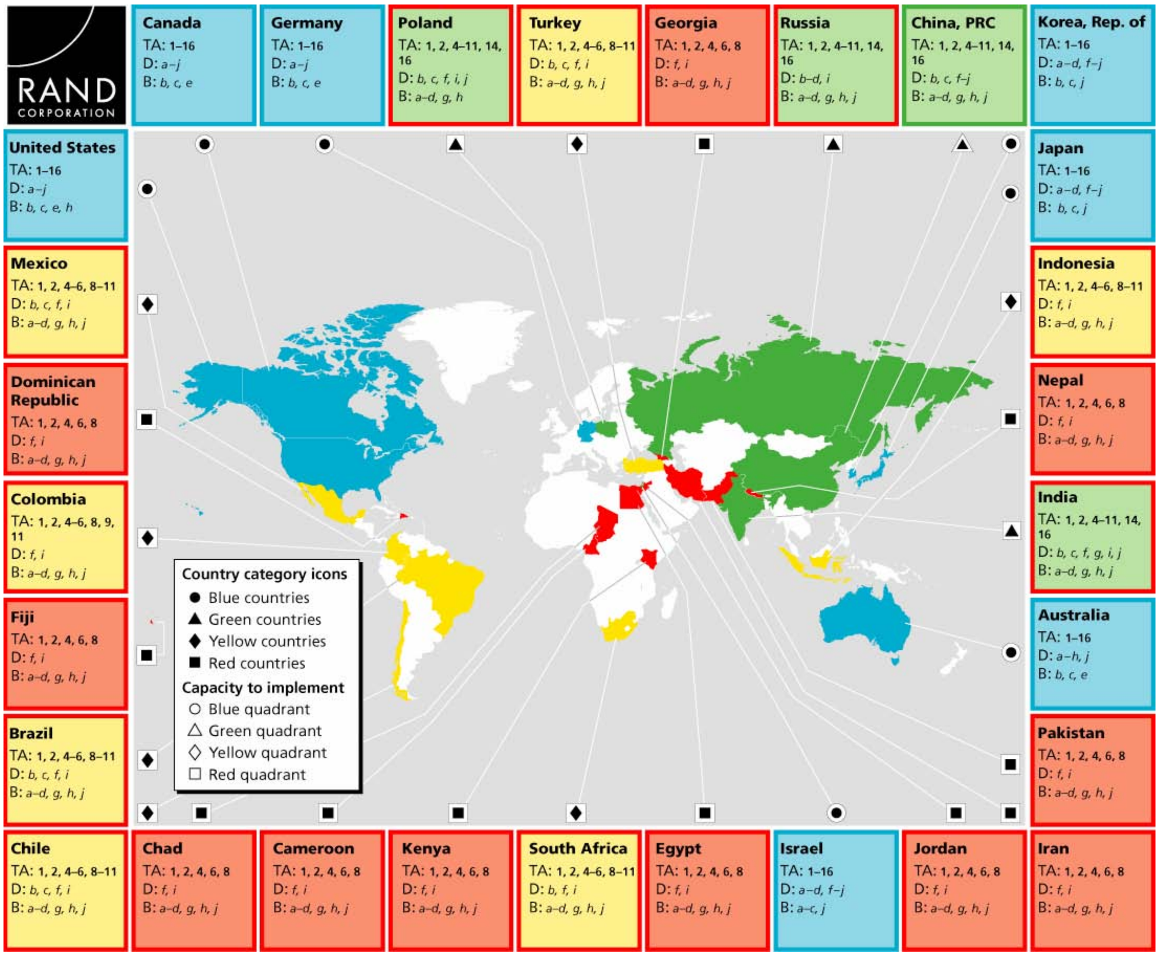
[256] For example, extensive case studies in Africa demonstrate that greater attention should be paid to building an enabling macroeconomic environment to promote implementation of technology. Attention should also be paid to the ways in which the environment interacts with an effective technology policy. See Ogbu, Oyeyinka, and Mlawa (1995). Another example is a speech by Antonio Vigilante, resident representative of UNDP, to the Pan-Arab Regional Conference on the World Summit on Information Society in Cairo, Egypt, on June 13, 2003, on the topic of a networked society. Vigilante underscored the importance of explicit policies backed by political and resource commitment, education, and other factors to the insertion of information and communication technologies into national development.

Figure 3.3
Summary of Selected Countries' Capacity to Acquire and Implement the Top 16 Technology Applications



As mentioned previously in this chapter, TAs are created in reaction to most established or perceived needs of society and are implemented to address specific problems and issues. In a previous section, we identified the following present-day needs, which we believe are likely to continue in the future to be fundamental to the well-being of societies across the globe:

- Promote rural economic development
- Promote economic growth and international commerce
- Improve public health
- Improve individual health
- Reduce resource use and improve environmental health
- Strengthen the military and warfighters of the future
- Strengthen homeland security and public safety
- Influence governance and social structure.

The following sections examine the selected countries' capacity to address these problems and issues with TAs that they have the capacity to acquire, taking into account the drivers and barriers applicable to each selected country.

For the purpose of this analysis, we assume that the drivers and barriers are invariant across the problems and issues, because they represent the broader environment and institutional, human, and physical capacity of these countries. As previously noted, we will focus on the top 16 TAs of our net assessment in Chapter Two as a representative and workable set of TAs with the potential for broad societal impact in the year 2020.

We recognize that our assessment is limited by what we know at this time and our foresight of capacities and conditions in these countries to the year 2020. To first order, we treat the different TAs and drivers and barriers as having equal impact on problems and issues, although we recognize that they might differ in reality. Nevertheless, we believe that equal weighing is sufficient to illustrate the principal result of this analysis—that capacity to *implement* TAs to address problems and issues is strongly determined by the capacity of a country to *acquire* TAs, and the *drivers and barriers* present.

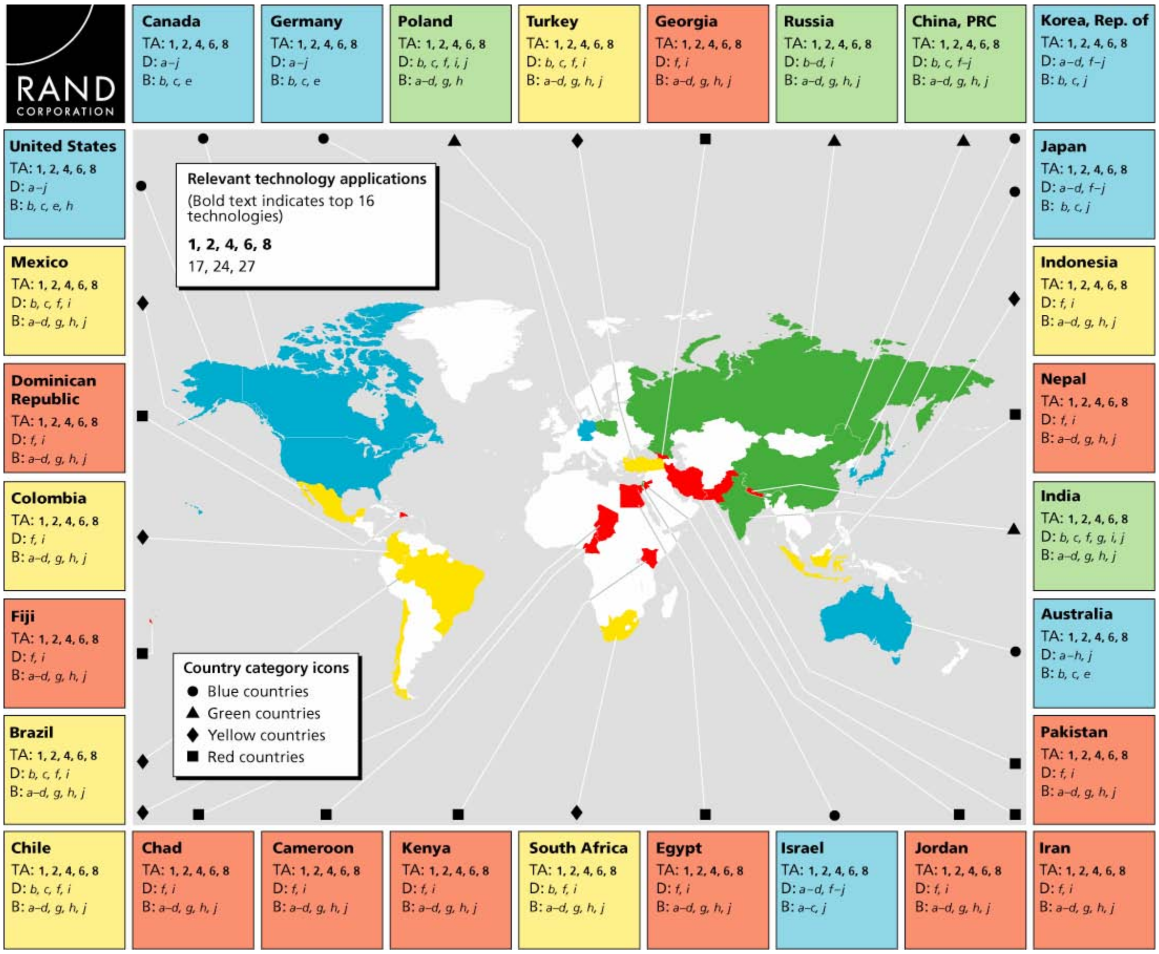
Table 3.3 of a previous section indicated the relevance of each of the 56 TAs in Table 2.2 of Chapter Two to the problems and issues listed above. The sections below use these data to construct equivalent figures to Figure 3.1 through 3.3 for each problem or issue area. These figures indicate the capacity of the 29 representative countries to acquire TAs relevant to each problem or issue area (denoted as RTAs); provide the data for analysis of the combined effect of RTAs, drivers, and barriers on implementation of RTAs; and summarize the capacity to acquire and implement TAs relevant to each problem and issue area.

Promote Rural Economic Development

Promoting economic growth in rural areas continues to challenge national governments, nongovernmental organizations, and multilateral development banks. The lack of infrastructure, weak institutions of governance, low level of knowledge and technical capacity, shortage of financial resources, and other difficulties have hindered efforts to spur economic growth in these communities.

Figure 3.4 shows the relevant technology applications (RTAs) for promoting rural economic development as defined in Table 3.3. Figure 3.4 also shows the selected countries' capacity to acquire RTAs, as well as the drivers for and barriers to implementation for each country, as discussed in previous sections and shown in Figures 3.1 and 3.3.

Figure 3.4
Selected Countries' Capacity to Acquire Relevant Technology Applications for Rural Economic Development



Five of the "top 16" TAs are RTAs for rural economic development: cheap solar energy (1), rural wireless communications (2), GM crops (4), filters and catalysts (6), and cheap autonomous housing (8). Of the remaining 40 TAs, only hands-free computer interface (17), unconventional transport (24), and monitoring and control of disease management (27) are RTAs for rural economic development.[257]

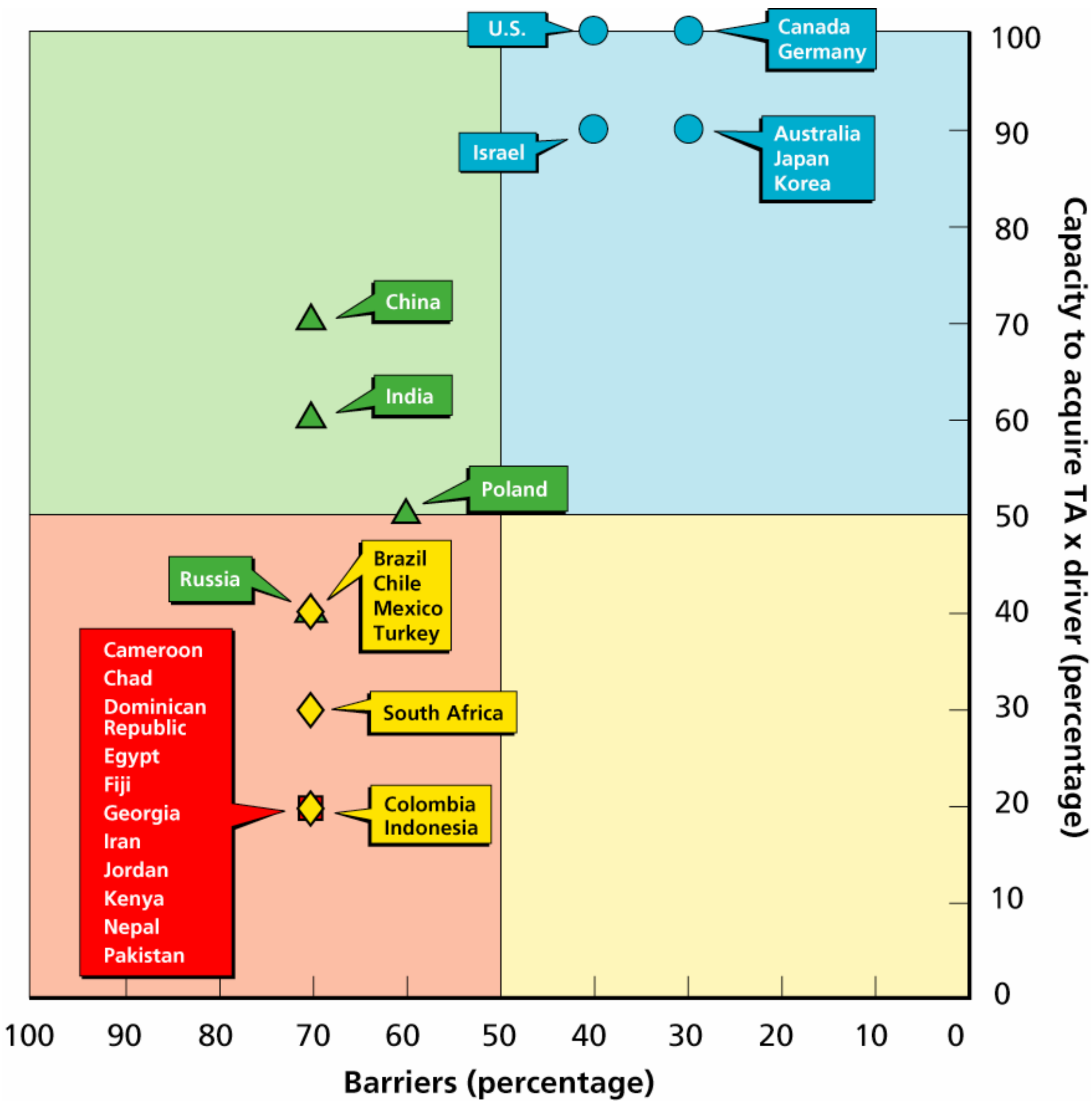
As in previous sections, we confine our analysis to the top 16 TAs. It is noteworthy that even the least economically developed and scientifically advanced countries have the capacity to acquire all five of the TAs that are RTAs for rural economic development. This bodes well for countries in the yellow and red groups, as well as for China and India, because reducing rural poverty is a top priority in all these societies. Population growth, the need for rural economic growth to slow massive urban migration and soothe rural discontent, depletion of essential resources such as arable land

[257] The numbers in parentheses correspond to those in Table 3.3.

and water, and increasing energy prices all provide governments of these countries with strong motivation to implement these RTAs.[258]

However, when we assess the ability of these countries to implement RTAs, we find a less sanguine picture, as shown in Figure 3.5, which is a quadrant chart similar to that of Figure 3.2, with the percentage of RTAs for rural economic development replacing the percentage of top 16 TAs.

Figure 3.5
Selected Countries' Capacity to Implement Relevant Technology Applications for Rural Economic Development



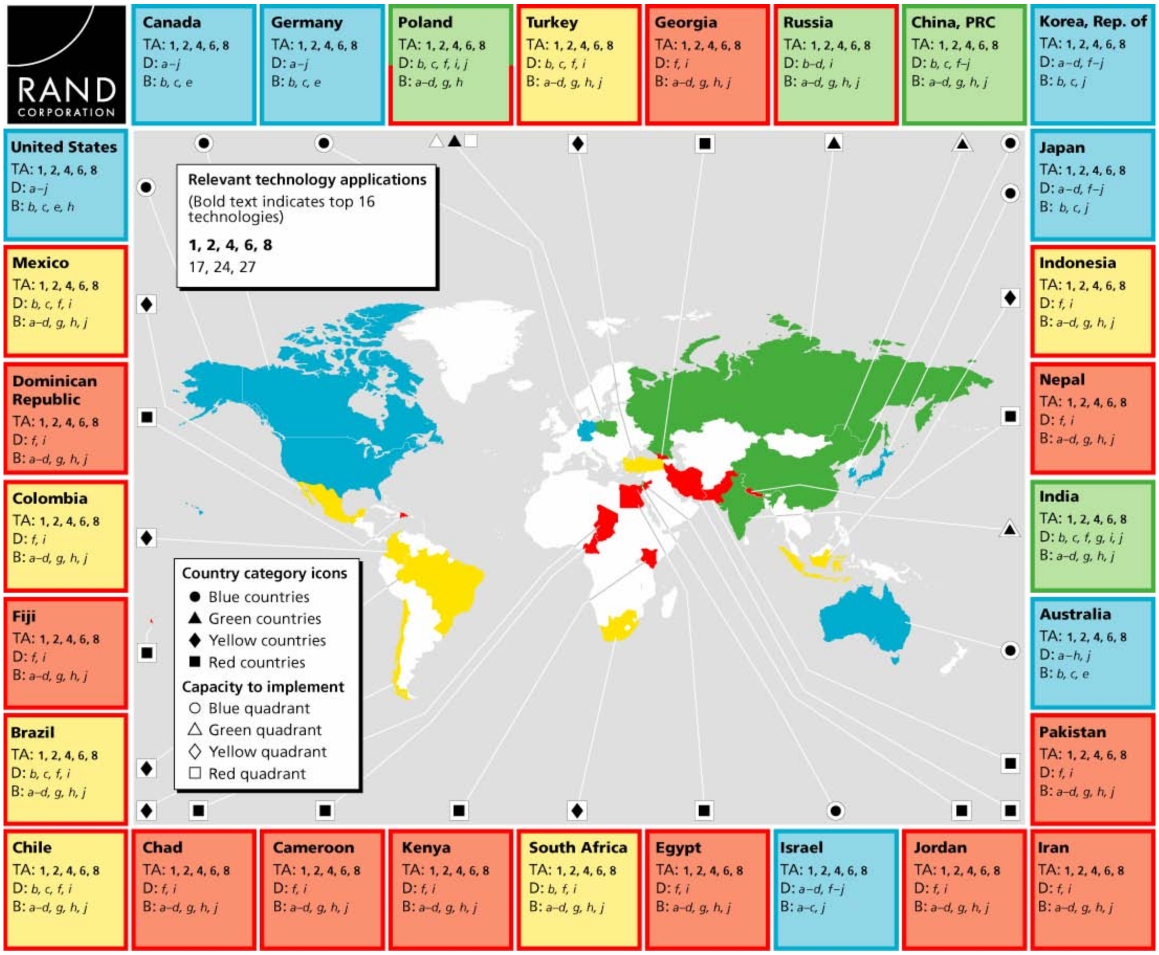
[258] See, for example, Jiangtao (2005). The Chinese government estimates that 400 million people from rural areas will move to urban centers by the year 2020, and nearly half of this number will flow into coastal cities where economic growth has been strongest in China.

Figure 3.5 shows that the blue countries should be able to implement all five RTAs with little difficulty. China, India, and Poland—three of the four green countries—also show a commensurate capacity to implement these RTAs. Russia, by comparison, is in the lower left-hand (red) quadrant because it has fewer drivers to push for implementation of these RTAs. Increasing rural development is an important matter on the national agendas of these green countries. Their governments are keenly aware of the political ramifications of rural discontent—for example, voting politicians out of office, or riots and public chaos that could scare off investors. Thus, these governments will be motivated to direct resources and build capacity to implement these RTAs.

However, countries (yellow and red) that are most in need of rural economic development have little capacity to implement these RTAs. The capacity to implement the RTAs varies among the yellow countries. Brazil, Chile, Mexico, and Turkey are equal to Russia, with South Africa next, and Colombia and Indonesia equal to all the red countries with very low capacity to implement these RTAs. Colombia and Indonesia and the red countries will experience great difficulty in implementing these RTAs. These countries command few drivers and are saddled with numerous barriers. They lack financial resources and are short on institutional, human, and physical capacity. Poor governance and stability presents another significant barrier. In these countries, corruption and abuses at lower levels of government frequently go all the way up to the national leadership. Foreign assistance, if not properly planned and monitored in its execution, can exacerbate corruption.

Figure 3.5 indicates that additional actions are necessary to sustain diffusion and implementation of these RTAs in all the red and several yellow countries. In addition to providing RTAs, multilateral development banks, national donor agencies, nonprofit foundations, and individual experts will need to work with public- and private-sector partners in these countries to shore up their capacity to mobilize available drivers and attend to barriers. At the same time, a national commitment to peace, clean government, and open markets is also essential. Foreign assistance cannot be the lead force in building capacity for long-term sustainable implementation of RTAs. Figure 3.6 summarizes country capacity to implement RTAs for rural economic development, using the same format as Figure 3.3, in which capacity to implement is shown by the color frame around the country box and the white icon in the country lines.

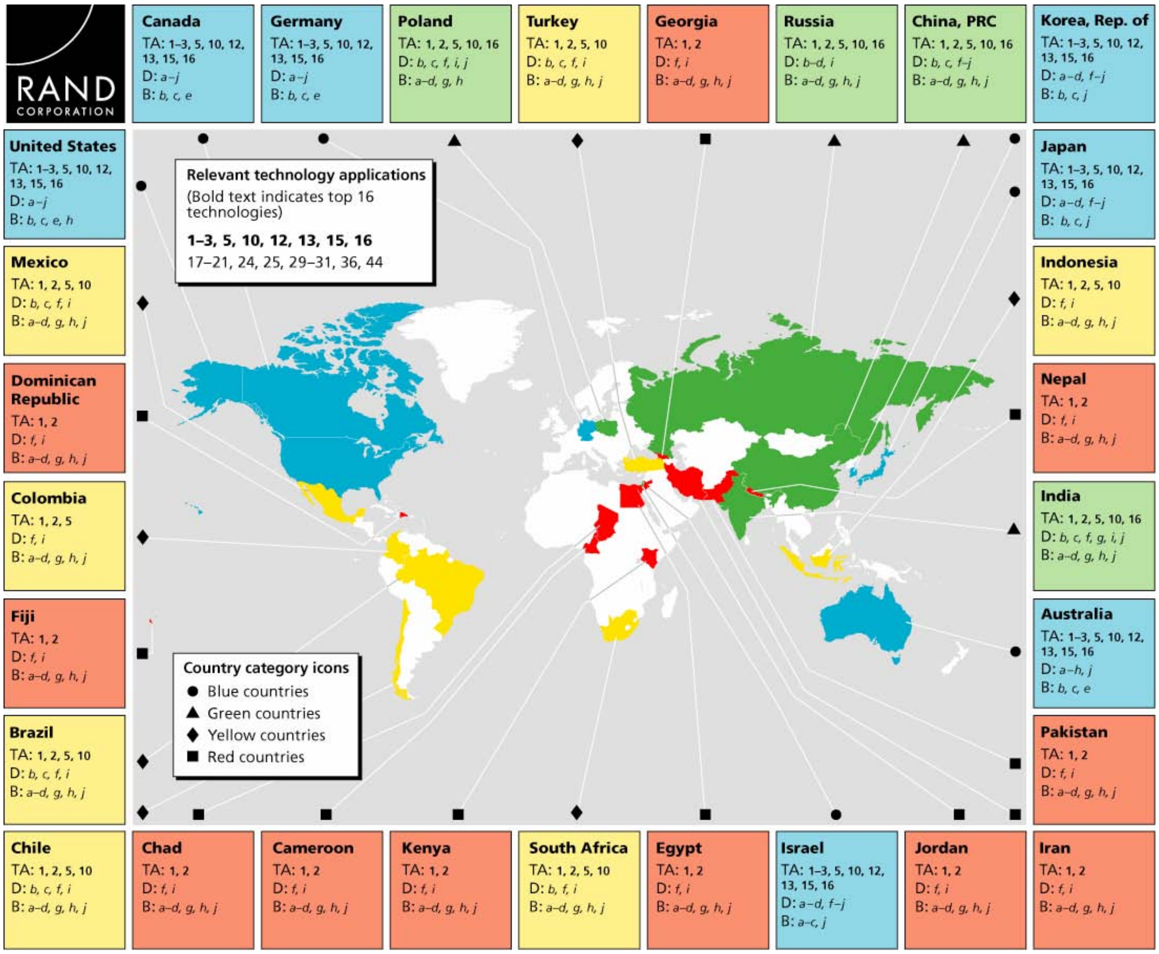
Figure 3.6
Comparing Selected Countries' Capacity to Acquire and Implement Relevant Technology Applications for Rural Economic Development



Promote Economic Growth and International Commerce

Economies have comparative advantages in their ability to produce goods and services. However, lower production cost is not enough for a seller to sell and profit. Economic competitiveness depends on being able to get goods and services to buyers at the right time and delivering the right quality and quantity. For example, not having paved roads, refrigerated trucks, and market information would undercut a farmer's ability to deliver his fresh vegetables in a timely manner, protect them from spoilage, and command the best prices from buyers. At another level, the advanced economies of North America, Western Europe and East Asia look for just-in-time delivery, secure electronic transfer, and other ways to ensure rapid, smooth, and safe transactions. Figure 3.7 shows the RTAs for promoting economic growth and international commerce, as defined in Table 3.3. Figure 3.7 also shows the selected countries' capacity to acquire RTAs, as well as the drivers for and barriers to implementation, as discussed in previous sections and shown in Figures 3.1 and 3.3.

Figure 3.7
Selected Countries' Capacity to Acquire Relevant Technology Applications for Promoting Economic Growth and International Commerce



The "top 16" TAs most relevant to promoting economic growth and international commerce are cheap solar energy (1), rural wireless communications (2), ubiquitous information access (3), rapid bioassays (5), ubiquitous RFID tagging (10), pervasive sensors (12), tissue engineering (13), wearable computers (15), and quantum cryptography (16). These are shown in bold in the inset box in Figure 3.7, while the RTAs from the remaining 40 TAs are shown in plain type.[259]

Again, the blue countries have the capacity to acquire all nine top 16 RTAs for this issue, while the green countries have the capacity to acquire five RTAs—specifically, cheap solar energy, rural wireless communications, rapid bioassays, ubiquitous RFID tagging, and quantum cryptography. Those in the yellow group have the capacity to acquire three to four RTAs—specifically, cheap solar energy, rural wireless communications, rapid bioassays, and ubiquitous RFID tagging. The red group countries,

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[259] The numbers in parentheses correspond to those in Table 3.3.

having the least S&T capacity, can acquire only two RTAs—namely, cheap solar energy and rapid wireless communications.

For the less-developed economies, having cheap solar energy and rural wireless communications will better enable their rural economies to contribute to the national economy and boost their competitiveness in international commerce. For the economically advanced economies (e.g., Japan and the United States), pervasive sensors and quantum cryptography will support new ways to manage logistics, determine market demand, and make electronic transactions more secure.

For this issue, the blue countries have a clear advantage over all other selected countries. Only they have the high level of S&T capacity, the extensive networked infrastructure, and the advanced trained personnel demanded by these RTAs. Figure 3.8 shows the selected countries' capacity to implement the RTAs, in a quadrant chart similar to that of Figure 3.2, with the percentage of RTAs for promoting economic growth and international commerce replacing the percentage of the top 16 RTAs.

Australia, Canada, Germany, Israel, Japan, South Korea, and the United States all sit solidly in the blue section.[260] For the green, yellow, and red countries, the picture is less promising. China, India, and Poland will have some distance to go in building capacity to implement these RTAs. If current trends in economic growth, S&T capacity building, and other indicators of development continue, these countries should become more able to implement the RTAs. However, considering their physical size and low level of high-quality, networked infrastructure present today, and what improvements will demand in human and financial resources, implementation of the RTAs might be primarily limited to the major metropolitan areas. Russia, by comparison, needs to turn around current negative trends of a deteriorating R&D infrastructure and worsening corruption and crime if it is to not slip further in its capacity to implement these RTAs.

The yellow countries will face even more difficult challenges to implement the RTAs for this issue. Current positive trends in economic growth and other indicators of development hold promise for increasing capacity to implement these RTAs. Their use might be limited in scope, like in the green countries, because of the lack of quality infrastructure beyond metropolitan areas. The red countries rank the lowest in their capacity to implement these RTAs. For these countries, even using the RTAs on a limited scale in metropolitan areas will be very difficult. Infrastructure, human, and physical capacity is low in these countries, and current indicators and trends do not suggest significant positive changes in the coming years. Figure 3.9 summarizes our assessment of the capacity of the selected countries to acquire and implement RTAs, using the same format as Figure 3.3, in which capacity to implement is shown by the color frame around the country box and the white icon in the country line.

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[260] For example, a World Economic Forum poll with business leaders reported that the top ten nations in terms of business use of information and communication technologies are Japan, Germany, Sweden, Switzerland, Finland, Iceland, Denmark, Israel, Singapore, and the United States. Business leaders were asked to rate in terms of how extensively companies take advance of foreign technology licensing, how aggressively they adopt new technology, and how much original R&D they perform. See "America Out-Teched" (2005).

Figure 3.8
Selected Countries' Capacity to Implement Relevant Technology Applications for Promoting Economic Development and International Commerce

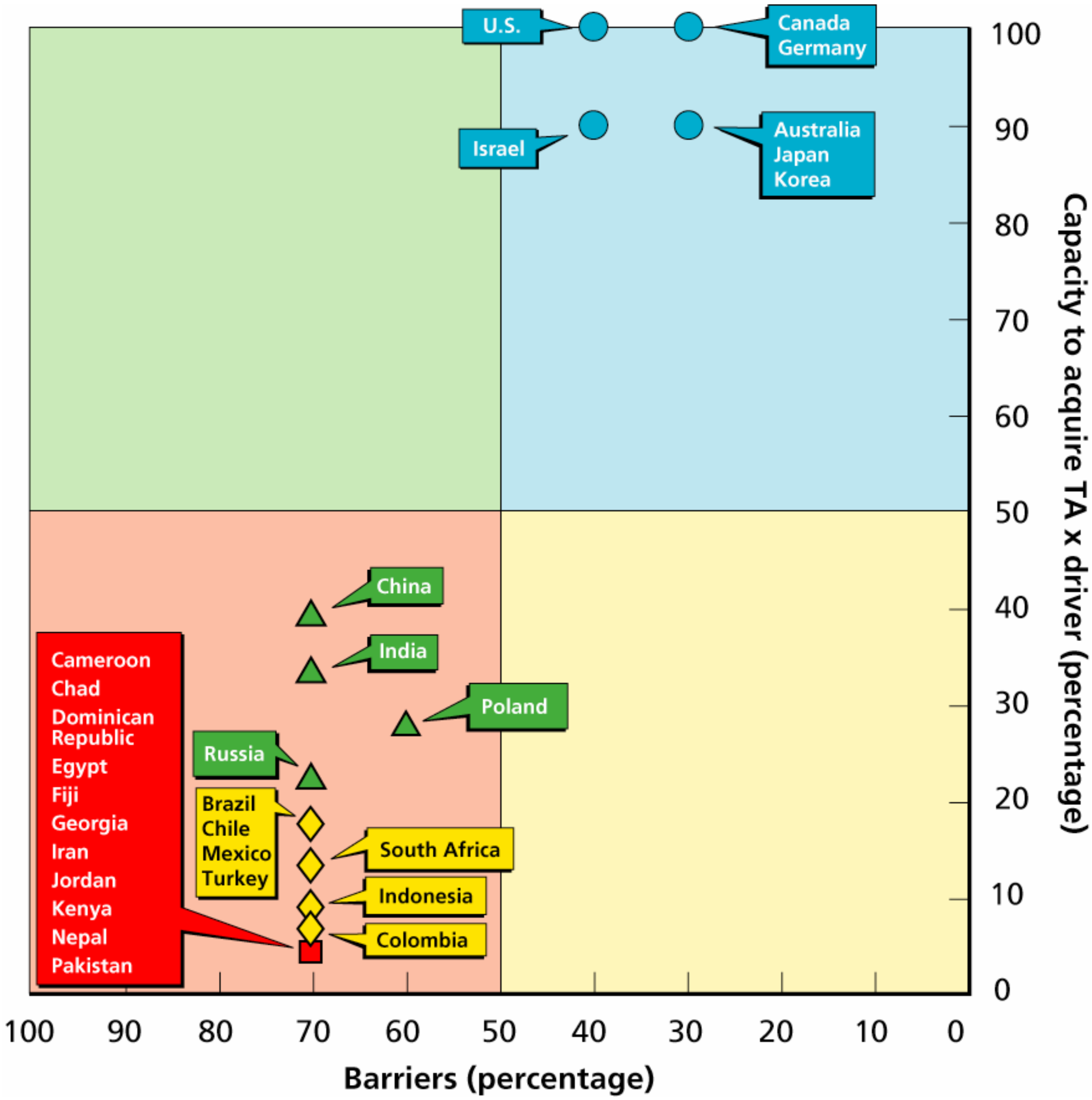
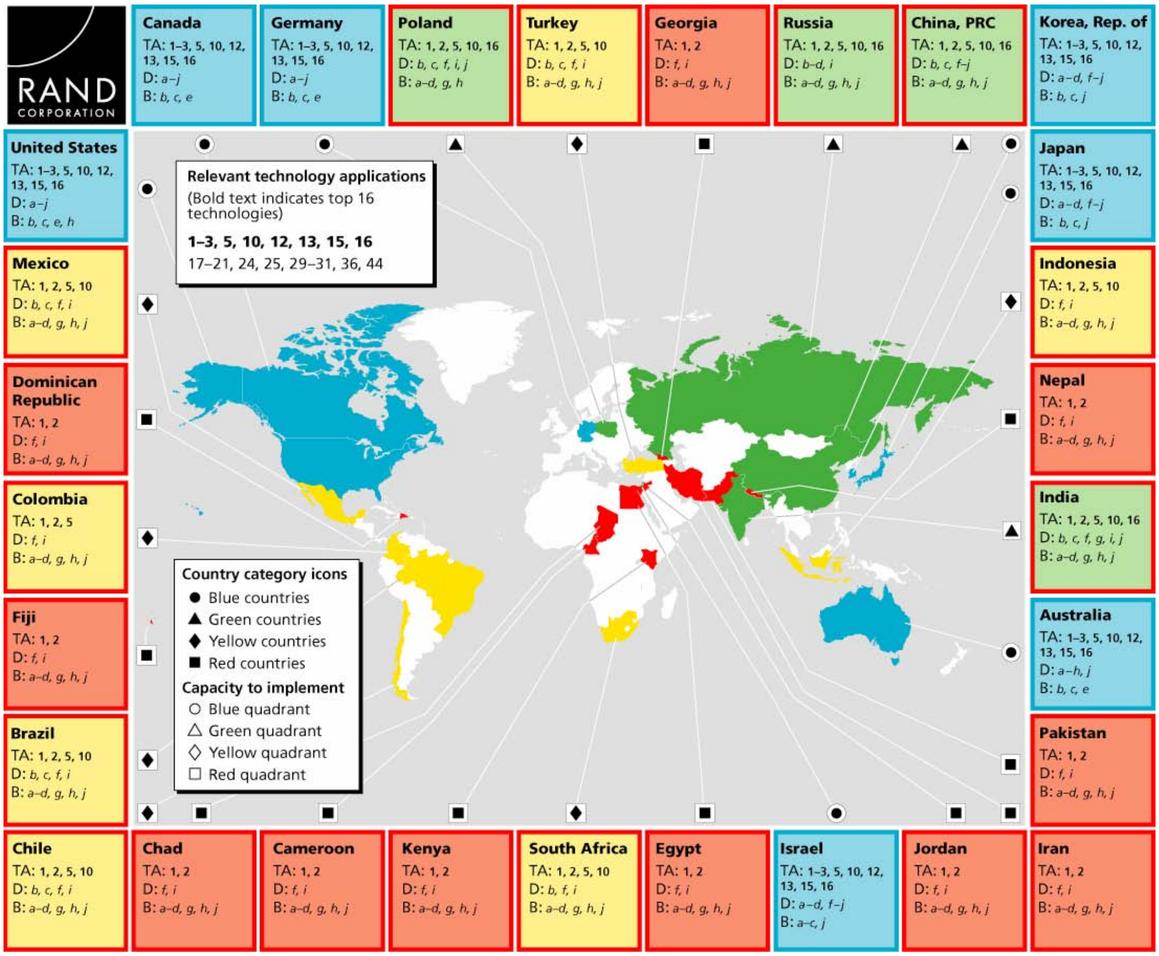


Figure 3.9
Comparing Selected Countries' Capacity to Acquire and Implement Relevant Technology Applications for Promoting Economic Growth and International Commerce



Improve Public Health

The outbreak of SARS and avian flu in Asia and other parts of the world in the past several years was a loud wake-up call for public health officials around the world. World health and agricultural experts are particularly worried by the situation in Southern China and Southeast Asia, where humans frequently live in close proximity to chickens, ducks, and other livestock that are often packed close together, creating conditions favorable for a bird flu pandemic that could kill millions of people.[261] Since the September 11, 2001 terrorist attacks on the United States, a great deal of attention and resources has been directed to threats posed by chemical, biological, and nuclear weapons. In addition, some diseases that international health organizations thought were wiped out following decades of vaccinations around the world (e.g., polio) remain firmly a part of our lives.[262]

[261] See, for example, World Health Organization (2005) and Sipress (2005b). WHO experts fear the number of deaths from a bird flu pandemic could reach as high as 100 million worldwide. See Sipress (2005a).
[262] See "Indonesia Polio Cases Reach 100" (2005) and Brown (2005).

Meningitis, tuberculosis, and other diseases are occurring in American cities and suburban neighborhoods, raising alarms among parents and health officials.[263]

Public health officials are eagerly seeking ways to protect communities and check the flow of diseases across borders in a world in which transboundary movement of people and goods is growing ever greater and faster. Figure 3.10 shows the RTAs for improving public health, as defined in Table 3.3. Figure 3.10 also shows the selected countries' capacity to acquire RTAs, as well as the drivers for and barriers to implementation, as discussed in previous sections and shown in Figures 3.1 and 3.3.

The "top 16" TAs relevant to improving public health are cheap solar energy (1), rural wireless communications (2), ubiquitous information access (3), GM crops (4), rapid bioassays (5), filters and catalysts (6), targeted drug delivery (7), cheap autonomous housing (8), and green manufacturing (9). These TAs are shown in bold in the inset box in Figure 3.10, while the RTAs from the remaining 40 TAs are shown in plain type.[264]

For this issue, the blue countries will have the capacity to acquire all RTAs; the green countries, all except ubiquitous information access; the yellow countries, most RTAs; and the red countries, a majority of the RTAs. The RTAs for promoting public health do not demand the most advanced level of scientific capacity, world-class, high-quality, and networked infrastructure, or necessarily a great deal of capital investment and technical expertise. Therefore, even the red countries will have the capacity to acquire at least five of these RTAs—namely, cheap solar energy, rural wireless communications, GM crops, filters and catalysts, and cheap autonomous housing.

For the blue countries, where a higher quality of public health exists, the benefits to be derived from these RTAs will provide only marginal gains on the whole. The importance of these RTAs will be to respond to new public health threats (e.g., using rapid bioassays to determine the presence of infectious disease viruses) or to provide emergency relief (e.g., using cheap solar energy and filters and catalysts when natural or man-made disasters disrupt power and water supplies).

For all other selected countries, where the quality of public health is generally lower, the RTAs will provide significant benefits. Enabling greater access to clean water, clean indoor air, and better nutrition, and preventing epidemics are all public health priorities and basic development challenges in these societies. Because the majority of the RTAs do not demand a high level of infrastructure, human, and physical capacity among their users, most selected countries exhibit a stronger capacity to implement them.

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[263] A UN report identified infectious disease as a major threat to the world in the years to come (United Nations, 2004). A number of U.S. and international experts also stress the dangers of infectious diseases as a result of global climate change and other factors. Some of these major studies are (Board on Global Health and Institute of Medicine, 2003); the U.S. Centers for Disease Control and Prevention's "Emerging Infectious Diseases" Web site (U.S. Centers for Disease Control and Prevention, 2003); WHO's 2000 report on epidemic-prone infectious diseases (World Health Organization, 2000); the U.S. Global Change Research Panel's 2000 report on how global warming will affect health issues in the United States (National Assessment Synthesis Team, 2000); and the Intergovernmental Panel on Climate Change's 2001 report on global warming impacts, particularly its chapter on human health effects (Intergovernmental Panel on Climate Change, 2001); the article "Infectious History" by Nobel Prize–winning scientist Joshua Lederberg (2000).

[264] The numbers in parentheses correspond to those in Table 3.3.

Figure 3.10
Selected Countries' Capacity to Acquire Relevant Technology Applications for Improving Public Health

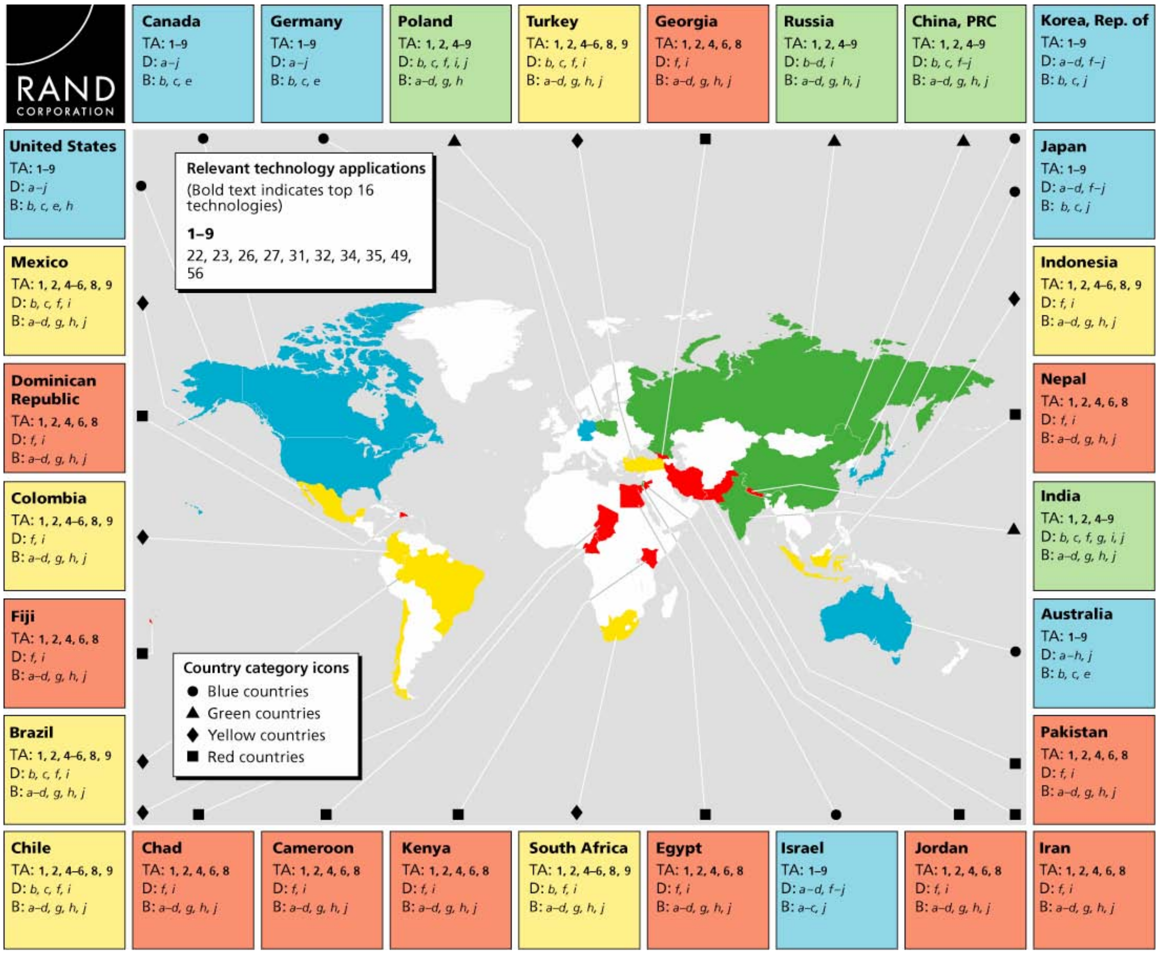


Figure 3.11 shows the selected countries' capacity to implement the RTAs, in a quadrant chart similar to that of Figure 3.2, with the percentage of RTAs for improving public health replacing the percentage of the top 16 TAs.

Figure 3.11
Selected Countries' Capacity to Implement Relevant Technology Applications for Improving Public Health

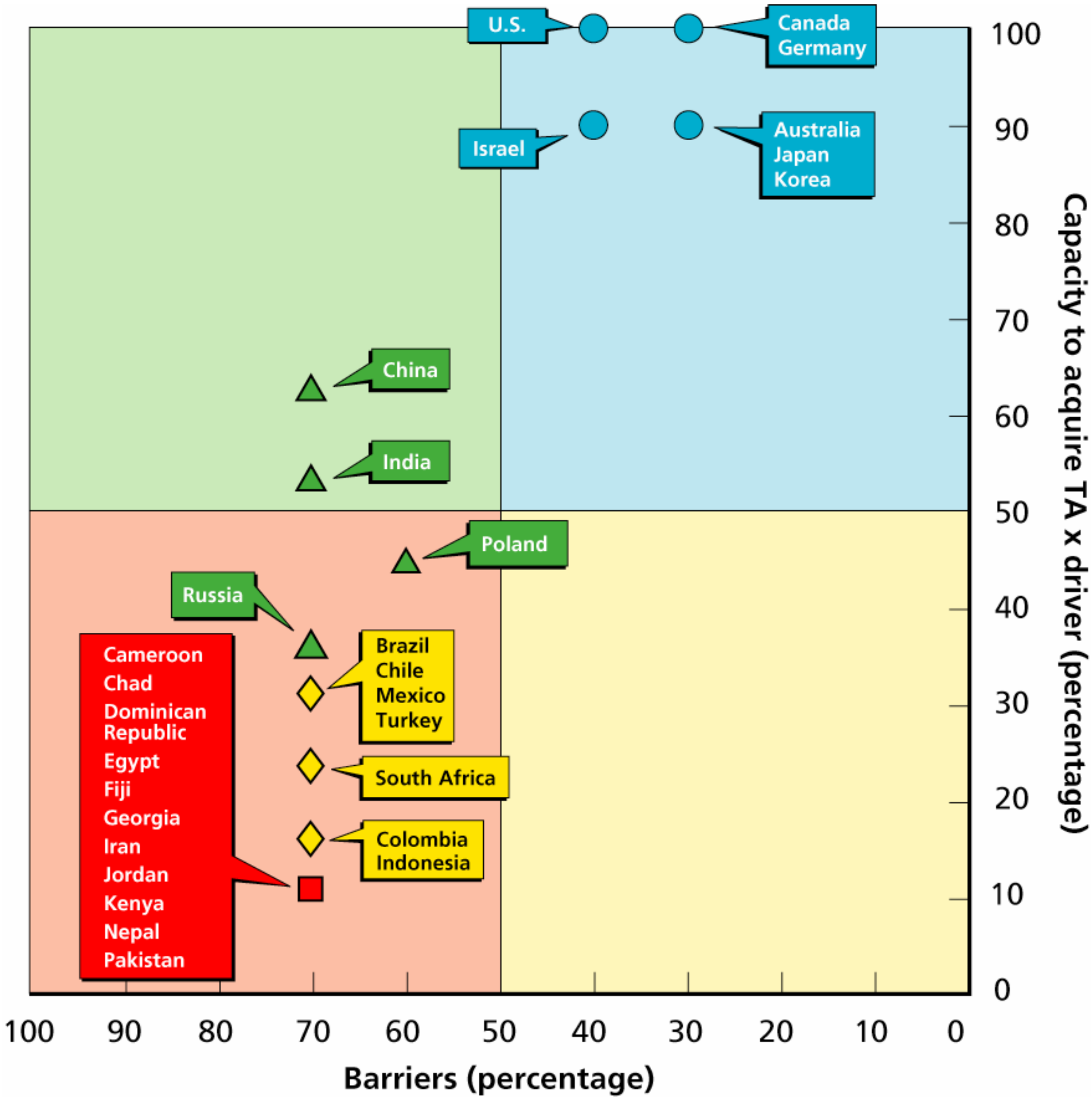
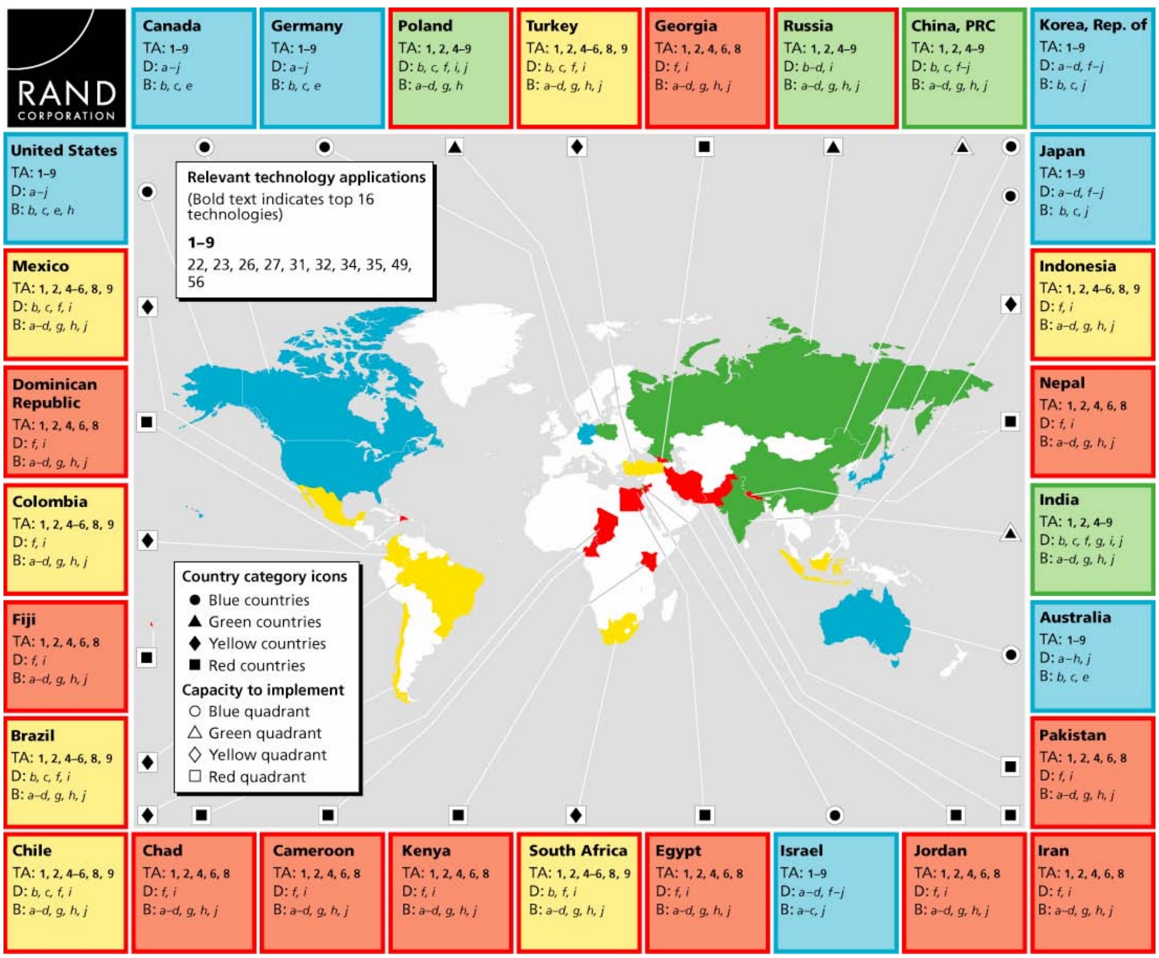


Figure 3.11 shows the blue countries in the upper right-hand (blue) quadrant with a high level of capacity to implement the RTAs. But more importantly, some of the green countries exhibit substantial capacity to implement these RTAs. China and India are squarely in the upper left-hand (green) quadrant, while Poland is just below its border. Russia, however, ranks lower, closer to the rising yellow countries: Brazil, Chile, Mexico, and Turkey.

Unfortunately, this is not the complete picture. South Africa is near the midpoint, and Colombia, Indonesia, and all the red countries are near the bottom of the lower left-hand (red) quadrant, reflecting their low capacity to implement these RTAs. These societies, especially the red ones, stand to gain most from the implementation of the RTAs. Although the red countries, as well as Colombia, Indonesia, and South Africa, have the capacity to acquire a majority of the RTAs, their capacity to implement them is severely constrained by the many barriers they face. They also have low levels of institutional, human, and physical capacity available to help them overcome these barriers.

Figure 3.12 summarizes our assessment of the capacity of the selected countries to acquire and implement RTAs for improving public health, using the same format as Figure 3.3, in which capacity to implement is shown by the color frame around the country box and the white icon in the country line.

Figure 3.12
Comparing Selected Countries' Capacity to Acquire and Implement Relevant Technology Applications for Improving Public Health



Improve Individual Health

Although actions to improve public health will benefit the health of individuals, improving individual health imposes a different set of demands on science, technology, and society. Cleaner air, safer workplaces, and improved nutrition benefit society at large. By comparison, improving individual health emphasizes medical detection and treatment to meet the needs of individuals. This can range from treating genetic diseases that affect an extremely small minority of the population, to advanced open-heart operations for infants with congenital heart problems, or drug treatment for various types of cancers.

For economically developing countries, improving public health is the greater concern for governments and development experts. Success is measured, for example, in terms of reduction in infant mortality rate and increased average life expectancy. Improving public health is a national objective in economically advanced countries, but individual health issues, by comparison, have greater prominence. These countries have established, modern, and functioning public health systems, and their high standard of living allows individuals to demand more in individual health services.

Figure 3.13 shows the RTAs for improving individual health, as defined in Table 3.3. Figure 3.13 also shows the selected countries' capacity to acquire RTAs, as well as the drivers for and barriers to implementation, as discussed in previous sections and shown in Figures 3.1 and 3.3.

Many RTAs that hold potential to improve public health will also create benefits for individual health. The "top 16" TAs relevant to improving individual health are cheap solar energy (1), rural wireless communications (2), ubiquitous information access (3), GM crops (4), rapid bioassays (5), filters and catalysts (6), targeted drug delivery (7), cheap autonomous housing (8), green manufacturing (9), tissue engineering (13), improved diagnostic and surgical methods (14), and wearable computers (15). These TAs are shown in bold in the inset box in Figure 3.13, while the RTAs from the remaining 40 TAs are shown in plain type.[265]

The overlap between RTAs for public health and individual health means that all selected countries will have the capacity to acquire several RTAs for individual health. The blue countries will have the capacity to acquire all RTAs for individual health. Green and yellow countries will have the capacity to acquire a majority of the 12 RTAs. However, red countries will have the capacity to acquire only those RTAs that have a lower level of capacity demands—cheap solar energy, rural wireless communications, GM crops, filters and catalysts, and cheap autonomous housing—the same five TAs relevant to improving public health.

[265] The numbers in parentheses correspond to those in Table 3.3.

Figure 3.13
Selected Countries' Capacity to Acquire Relevant Technology Applications for Improving Individual Health

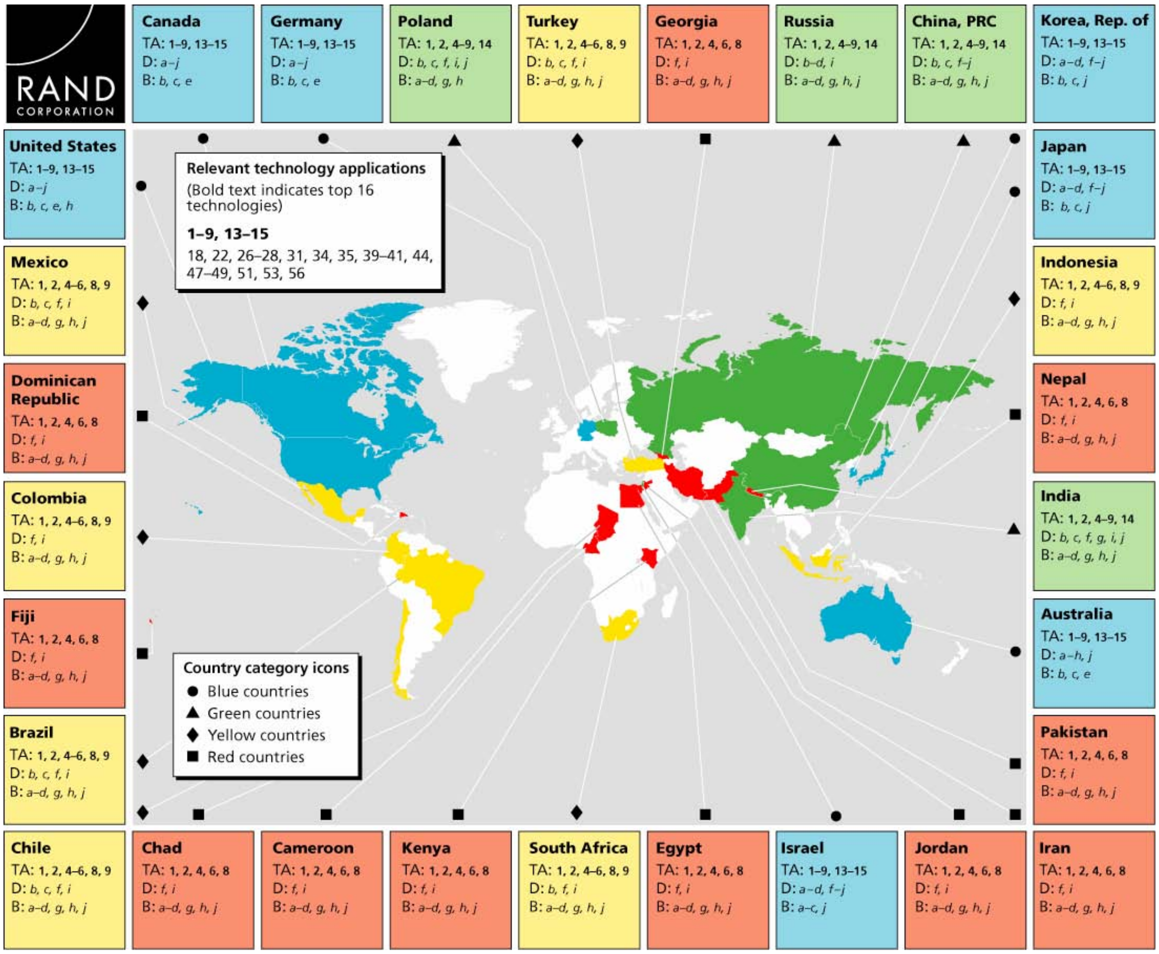
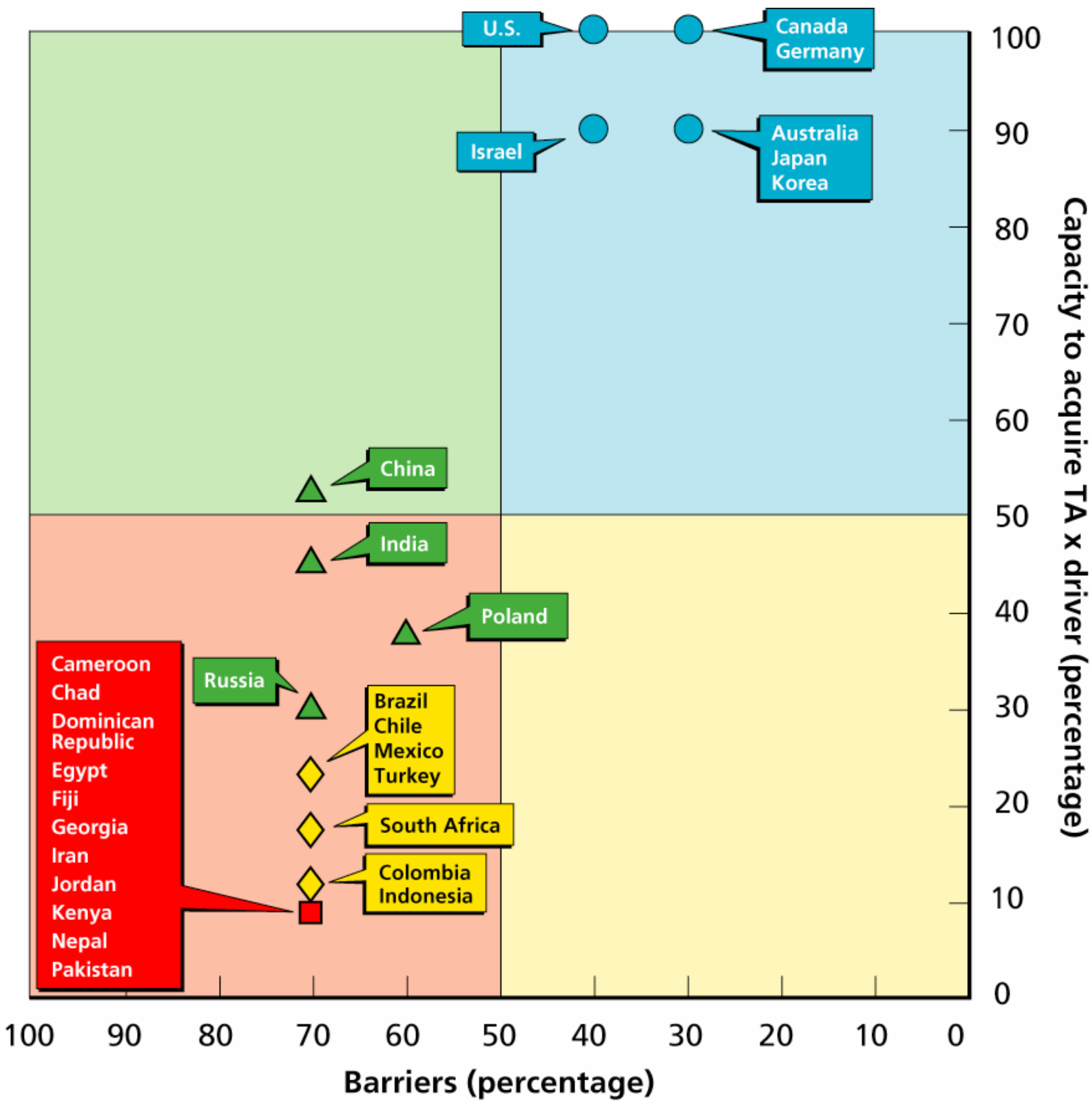


Figure 3.14 shows the selected countries' capacity to implement the RTAs, in a quadrant chart similar to those of Figure 3.2, with the percentage of RTAs for improving individual health replacing the percentage of the top 16 TAs.

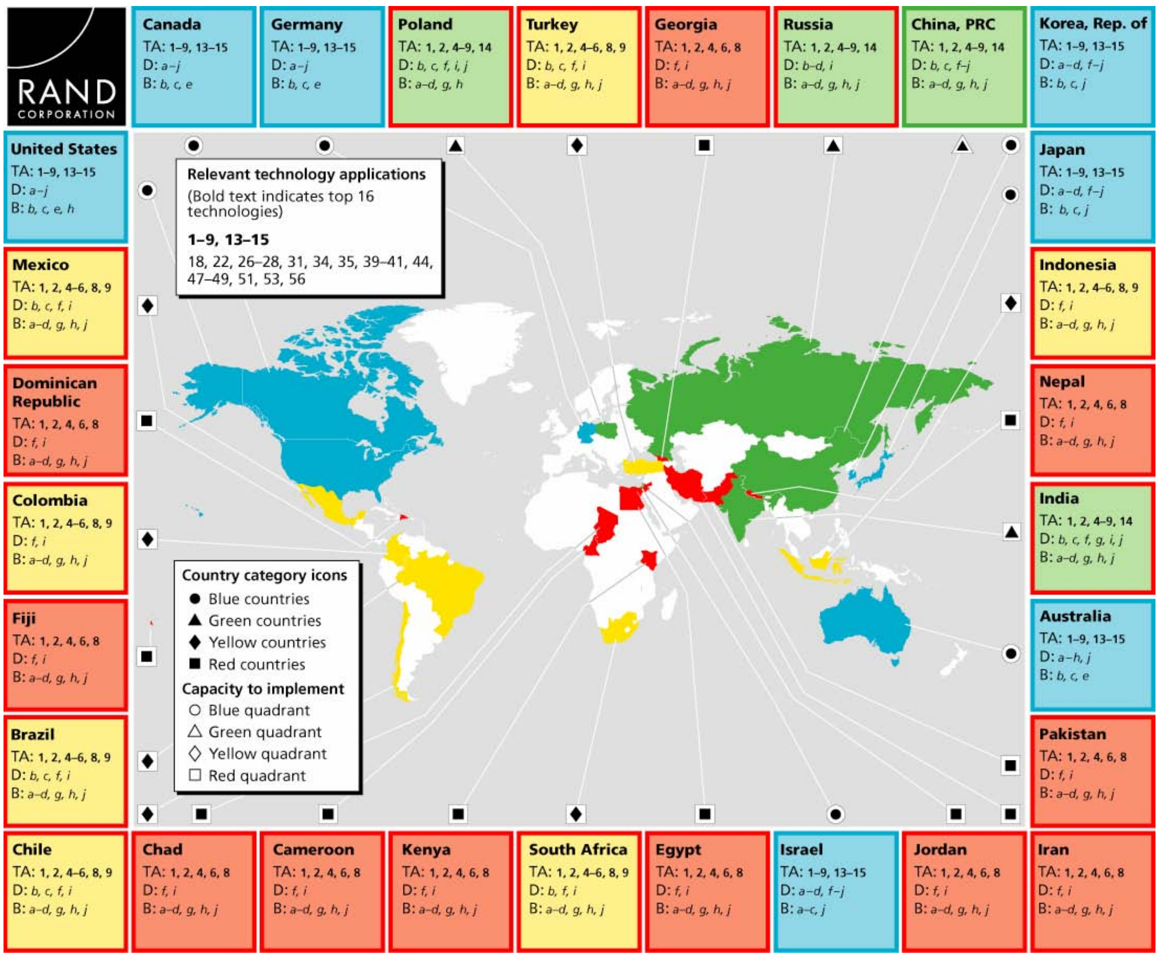
Figure 3.14
Selected Countries' Capacity to Implement Relevant Technology Applications for Improving Individual Health



The blue countries remain in the upper right-hand (blue) quadrant, reflecting a high level of capacity to implement the RTAs. However, the capacity of green and yellow countries is considerably less than their capacity to implement RTAs for public health. For these countries, improving public health has greater priority than improving individual health. For the red countries, successful implementation of RTAs for public health will have some individual health benefits. However, these countries cannot afford to devote their limited resources to medical technologies and treatments that will deliver cutting-edge care to individual patients. The shortage of institutional, human, and physical capacity in these countries also makes highly unlikely the acquisition and implementation—even on a very limited scale—of such TAs as improved diagnostic and surgical procedures that most of the green countries might be able to acquire and implement, and rapid bioassays that the yellow countries might be able to acquire and implement.

Figure 3.15 summarizes our assessment of the capacity of the selected countries to acquire and implement RTAs, using the same format as Figure 3.3, in which capacity to implement is shown by the color frame around the country box and white icon in the country line.

Figure 3.15
Selected Countries' Capacity to Acquire and Implement Relevant Technology Applications for Improving Individual Health



Reduce Resource Use and Improve Environmental Health

People around the world have a much greater environmental awareness today than in years past, because connections between economic activities and the environment are more widely publicized and, in some cases, better understood. Commercial enterprises are also motivated to reduce resource input and emissions as a way to cut costs. Many

TAs can help reduce the pressure of human activities on the environment, and they can help communities cope with increasing resource needs. However, for many developing countries, the interface between economic activities and the environment creates a vicious cycle. Forests are cut down for firewood because people do not have access to grid electricity. Farmers practice slash-and-burn agriculture because they cannot afford fertilizers. Human waste and chemicals are dumped into open waters that communities rely on for drinking, washing, farming, and fishing because no sewage drains and treatment facilities exist. All this can make communities more vulnerable to natural disasters (e.g., mudslides and droughts), health problems (e.g., dysentery from unclean water and respiratory infections from indoor air pollution), and even violent conflicts (e.g., when communities fight over the last stands of trees and scarce sources of clean water).

Figure 3.16 shows the RTAs for reducing resource use and improving environmental health, as defined in Table 3.3. Figure 3.16 also shows the selected countries' capacity to acquire RTAs, as well as the drivers for and barriers to implementation, as discussed in previous sections and shown in Figures 3.1 and 3.3.

The "top 16" TAs relevant to reducing resource use and improving environmental health are cheap solar energy (1), rural wireless communications (2), GM crops (4), filters and catalysts (6), green manufacturing (9), and hybrid vehicles (11). These TAs are shown in bold in the inset box in Figure 3.16, while the RTAs from the remaining 40 TAs are shown in plain type.[266]

Figure 3.17 shows the selected countries' capacity to implement the RTAs, in a quadrant chart similar to that of Figure 3.2, with the percentage of RTAs for reducing resource use and improving environmental health replacing the percentage of the top 16 TAs.

The blue, green, and yellow countries have the capacity to acquire all six RTAs. Even the red countries have the capacity to acquire the four RTAs that are in their "tool kits"—namely, cheap solar energy, rural wireless communications, GM crops, and filters and catalysts. Yet once again, only countries with better infrastructure, human, and physical capacity appear capable of implementing the RTAs, as shown by their relative positions in Figure 3.17, with China and India in the upper left-hand (green) quadrant, Poland on its border, and Russia, Brazil, Chile, Mexico, and Turkey in the upper parts of the lower left-hand (red) quadrant. South Africa is near the middle of the red quadrant, while Colombia, Indonesia, and all the red countries are in the lower portion of the red quadrant, showing little capacity to implement RTAs.

[266] The numbers in parentheses correspond to those in Table 3.3.

Figure 3.16
Selected Countries' Capacity to Acquire Relevant Technology Applications for Reducing Resource Use and Improving Environmental Health

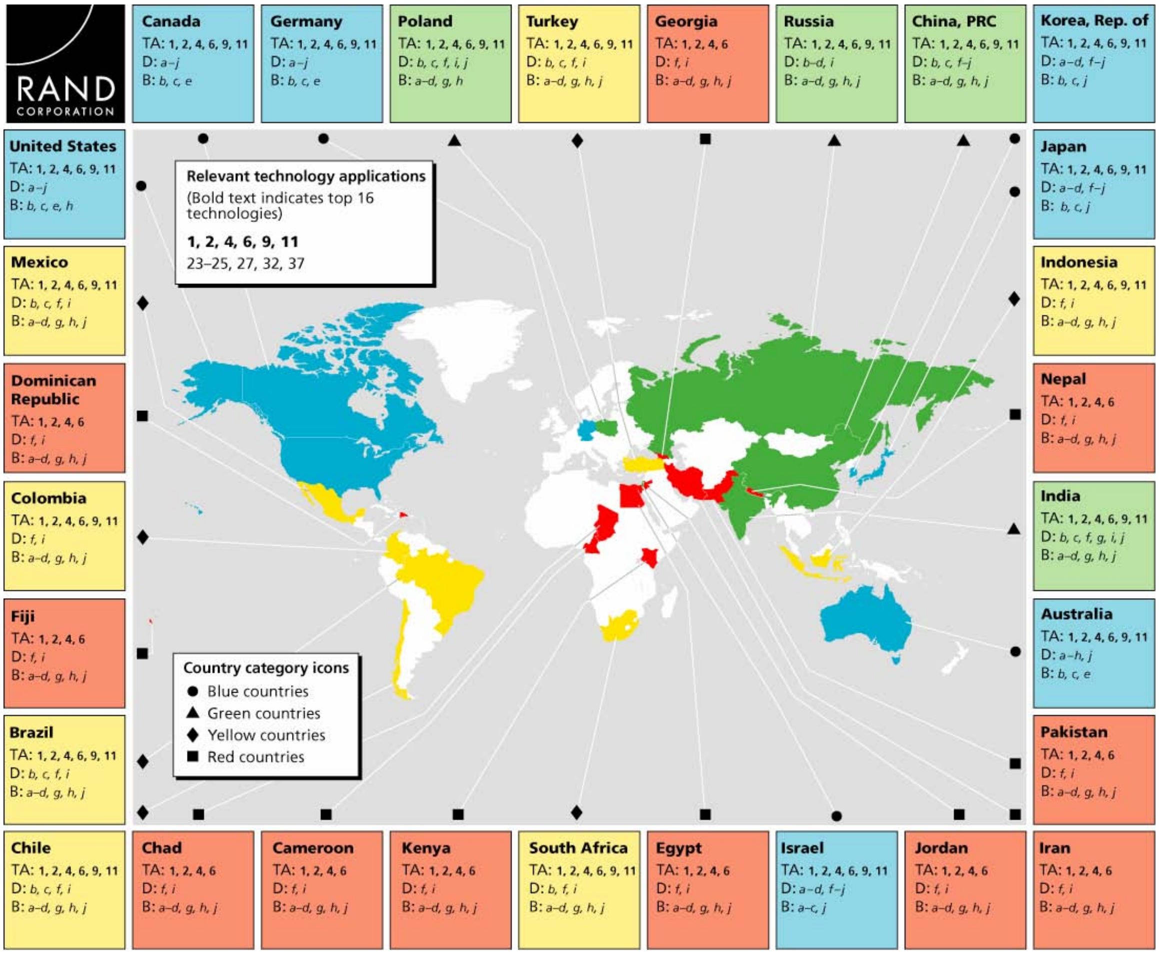
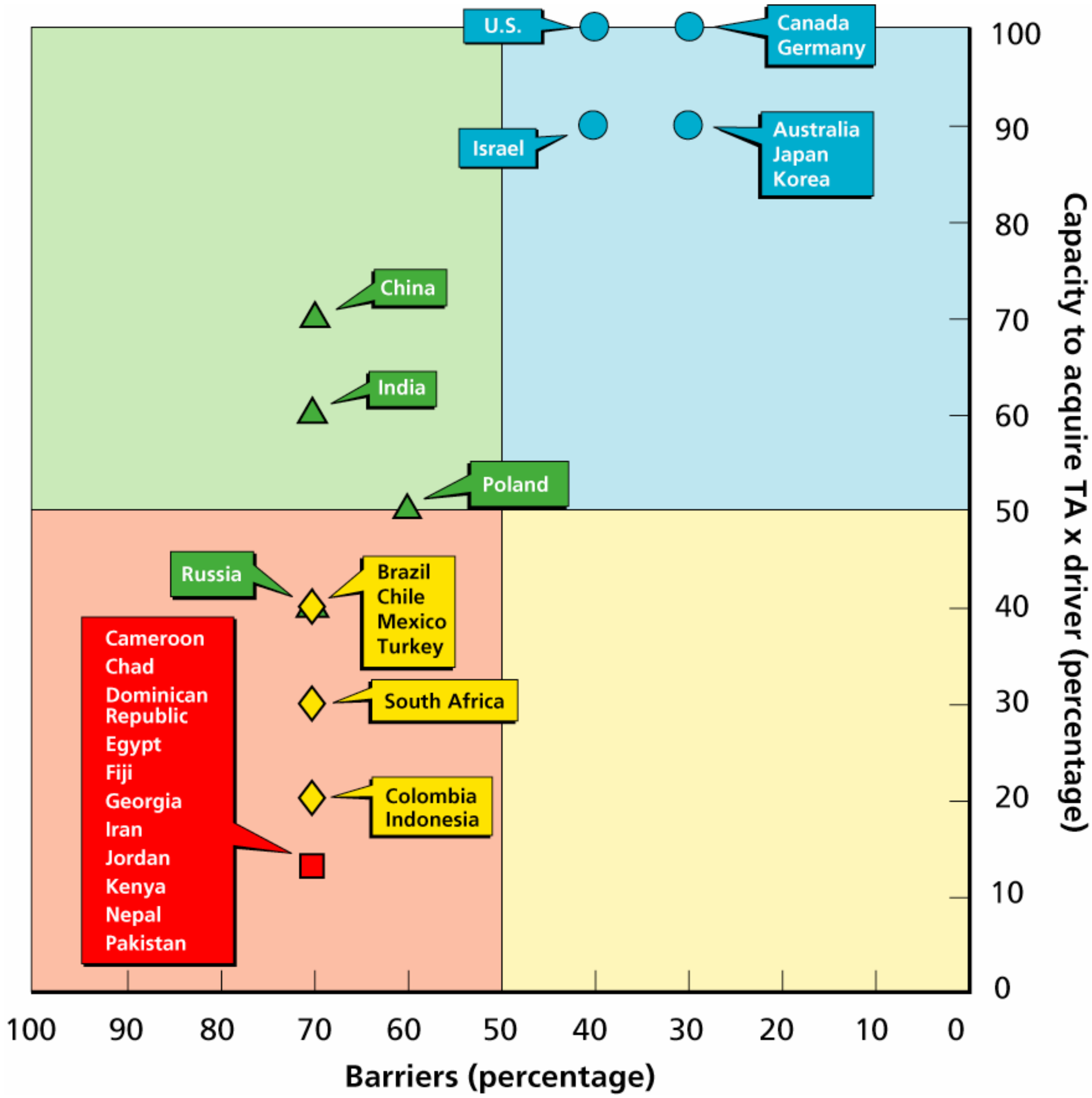


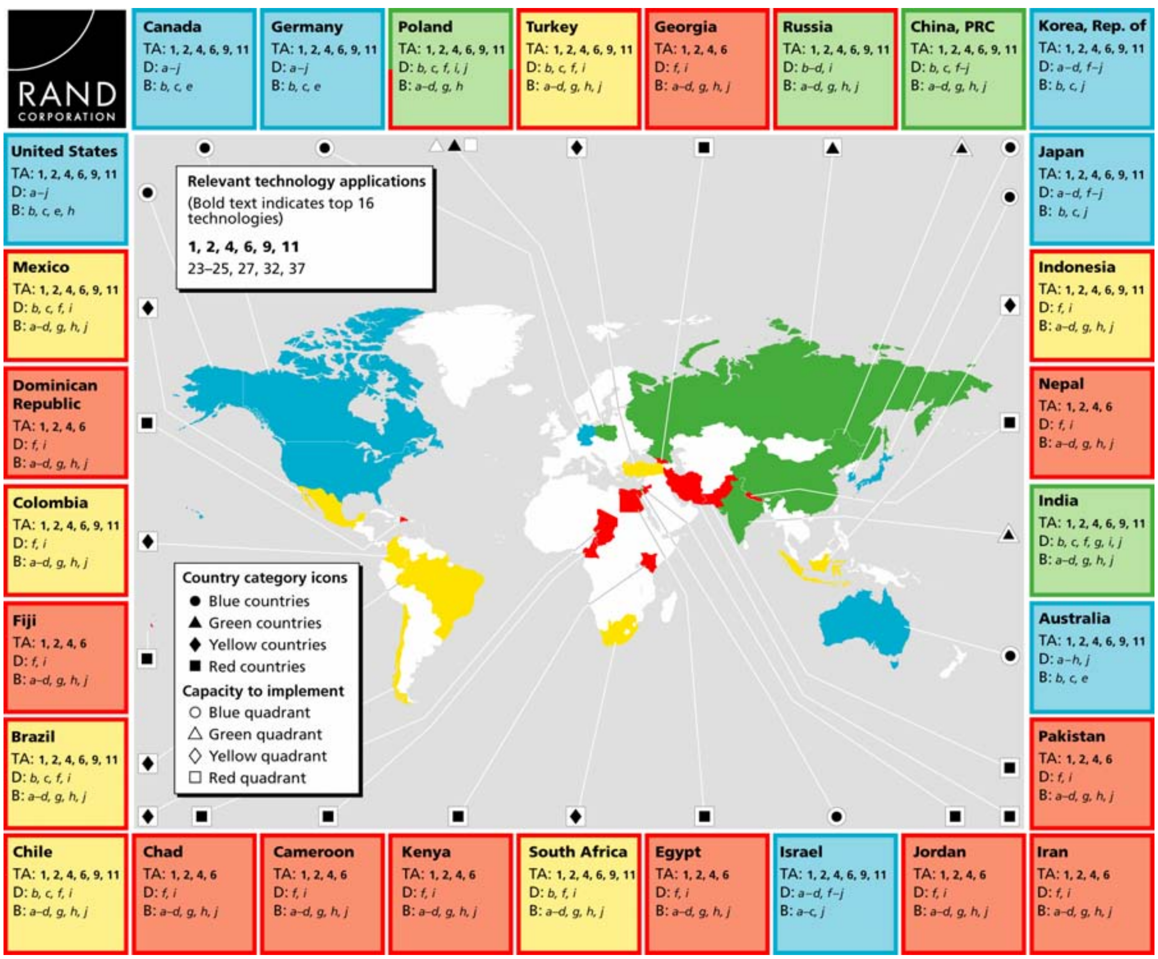
Figure 3.17
Selected Countries' Capacity to Implement Relevant Technology Applications for Reducing Resource Use and Improving Environmental Health



For the blue and green countries, rising energy costs will be a major motivation to use these RTAs. In most countries worldwide, there is appreciation of the cost of pollution and environmental destruction on human health and economic development. For the blue countries, and several green and yellow countries, public demand for a cleaner environment will drive their use of RTAs. Laws and policies that penalize industrial processes that have harmful impacts on human health and the environment will compel businesses to adopt more environmentally friendly practices. However, in most less-developed countries, environmental conservation will likely be overshadowed by other urgencies, and capturing environmental benefits from the RTAs might more likely be a secondary goal or a spillover effect. Consequently, stressing the broader economic benefits that might result from implementing the RTAs might better motivate their use in these countries. For example, women need not spend hours each day foraging for firewood if cheap solar energy is available to cook food and boil water. They can apply the time gained to farming or other income-generating activities. In the longer term, reducing reliance on firewood will reduce pressure on forests. Healthy forests can help control soil erosion, improve underground water quality, reduce sediment flows into rivers, and provide food, medicine, and construction materials.

Figure 3.18 summarizes our assessment of the capacity of the selected countries to acquire and implement RTAs, using the same format as Figure 3.3, in which capacity to implement is shown by the color frames around the country box and the white icon in the country line.

Figure 3.18
Comparing Selected Countries' Capacity to Acquire and Implement Relevant Technology Applications for Reducing Resource Use and Improving Environmental Health

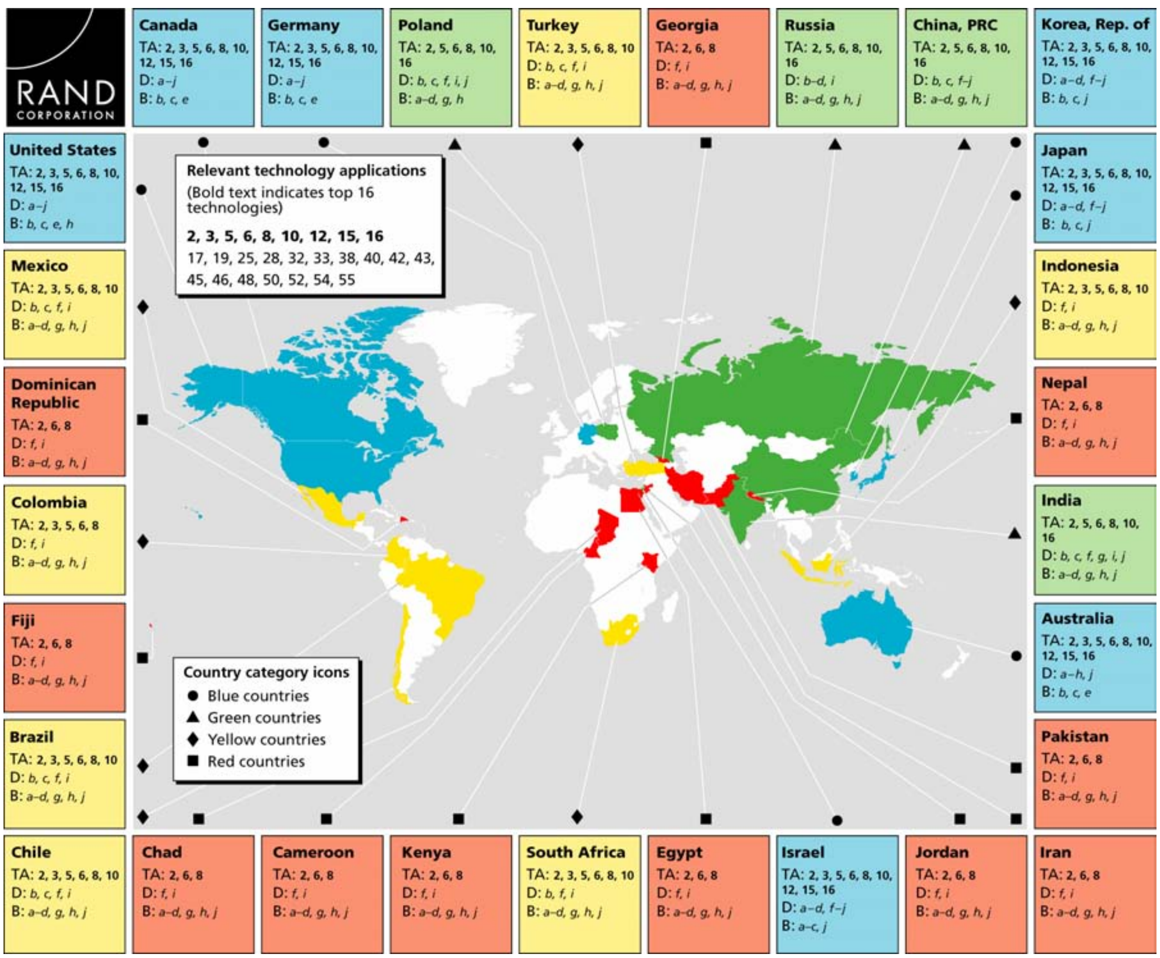


Strengthen the Military and Warfighters of the Future

The end of the Cold War and the emergence of new threats to national security have changed military perspectives on battlefields and warfare. The battlefields of the future are envisioned as more dispersed. Warfighters will have to cover larger and more-diverse terrains. Mission objectives will also range from winning the war to restoring stability and providing humanitarian relief, each imposing different skill and materiel demands on the warfighters.

Figure 3.19 shows the RTAs as defined in Table 3.3. Figure 3.19 also shows the selected countries' capacity to acquire RTAs, as well as the drivers for and barriers to implementation, as discussed in previous sections and shown in Figures 3.1 and 3.3.

Figure 3.19
Selected Countries' Capacity to Acquire Relevant Technology Applications for Strengthening the Military and Warfighters of the Future



The "top 16" TAs relevant to strengthening the military and warfighters of the future are rural wireless communications (2), ubiquitous information access (3), rapid bioassays (5), filters and catalysts (6), cheap autonomous housing (8), ubiquitous RFID tagging (10), pervasive sensors (12), wearable computers (15), and quantum cryptography (16). These TAs are shown in bold type in the inset box in Figure 3.19, while the RTAs from the remaining 40 TAs are shown in plain type.[267]

Although only the leading military powers have the capacity to acquire the full range of TAs relevant to the military, other countries will be able to acquire some RTAs to boost their regional influence or to develop niche capabilities to meet their particular military objectives. For example, acquisition of rural wireless communications, filters and catalysts, and cheap autonomous housing do not demand a great deal of institutional, human, and physical capacity. Our analysis indicates that even the least-developed countries in our selected group have potential capacity to acquire these TAs.

Figure 3.20 shows the selected countries' capacity to implement the RTAs, in a quadrant chart similar to that of Figure 3.2, with the percentage of RTAs for strengthening the military and warfighters of the future replacing the percentage of the top 16 TAs.

Figure 3.20 shows that the blue countries have the strongest capacity to implement the full range of RTAs to strengthen the military and warfighters of the future. They will be able to derive benefits for warfighting from the increased communication capabilities that enable rural wireless communications. They will be able to exploit pervasive sensors and ubiquitous information access to monitor the movement of friendly and enemy forces, improve battlefield awareness for their own soldiers, and support command, control, communication, and logistics management (which will also be enhanced by the capabilities that enable ubiquitous RFID tagging). They will be able to use wearable computers to scrutinize the psychological and physical profiles of warfighters and apply timely and appropriate medical interventions and treatments. They will be able to use quantum cryptography to protect tactical communication. All this will be possible because they have a much higher level of institutional, human, and physical capacity than the other selected countries have.

Green countries might be able to use the more capacity-demanding RTAs on a more limited scale. China and India, in particular, appear in the upper part of the lower left-hand (red) quadrant in Figure 3.20, with China near its border with the upper left-hand (green) quadrant, reflecting the growth of these countries' capabilities in dual use and military technologies. For yellow and red countries, however, putting rifles in the hands of soldiers is much cheaper and simpler than building digital networks to track the physical location and conditions. These countries might most likely acquire rural wireless communications to improve military command, control, and communication.

[267] The numbers in parentheses correspond to those in Table 3.3.

Figure 3.20
Selected Countries' Capacity to Implement Relevant Technology Applications for Strengthening the Military and Warfighters of the Future

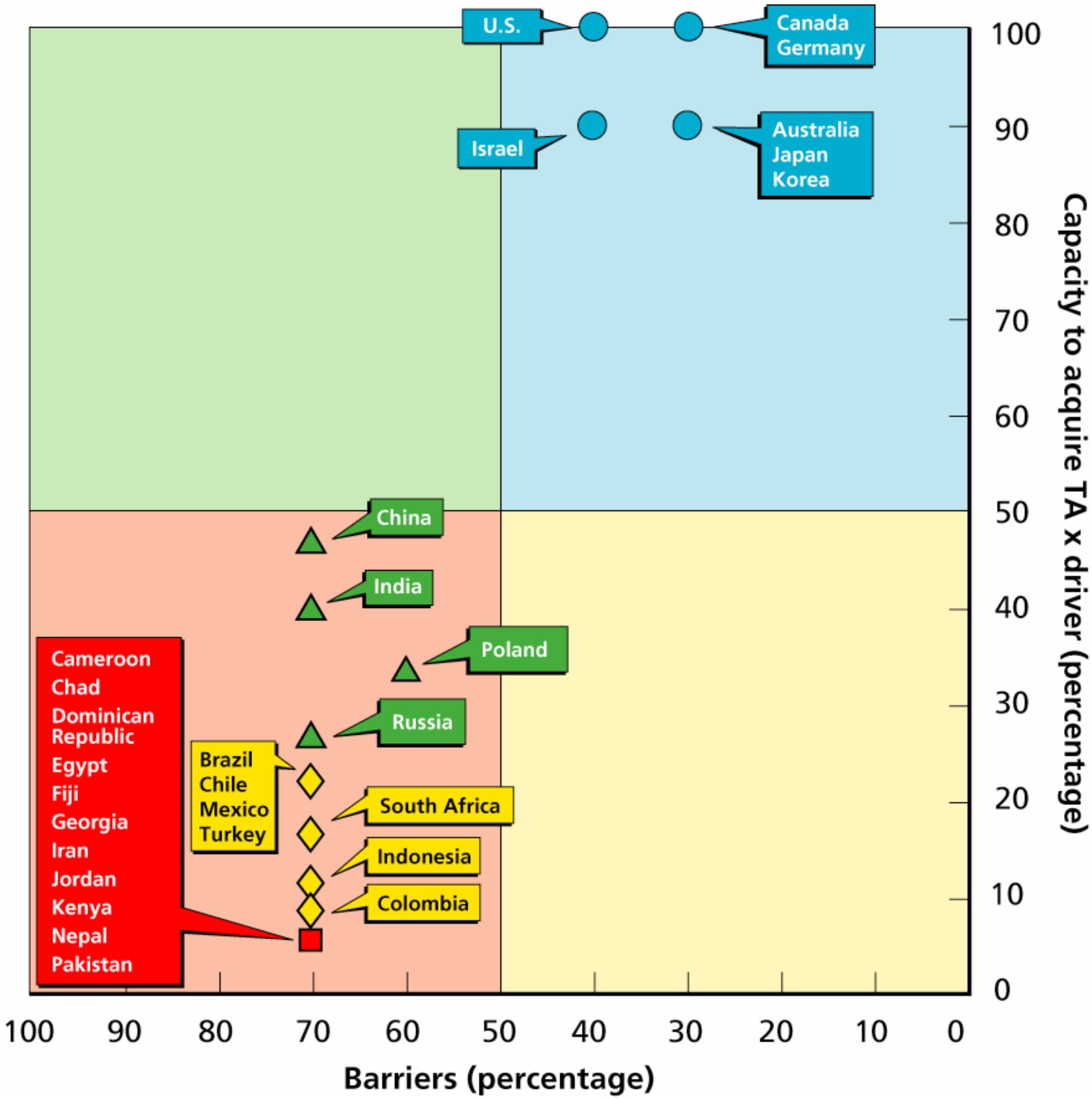
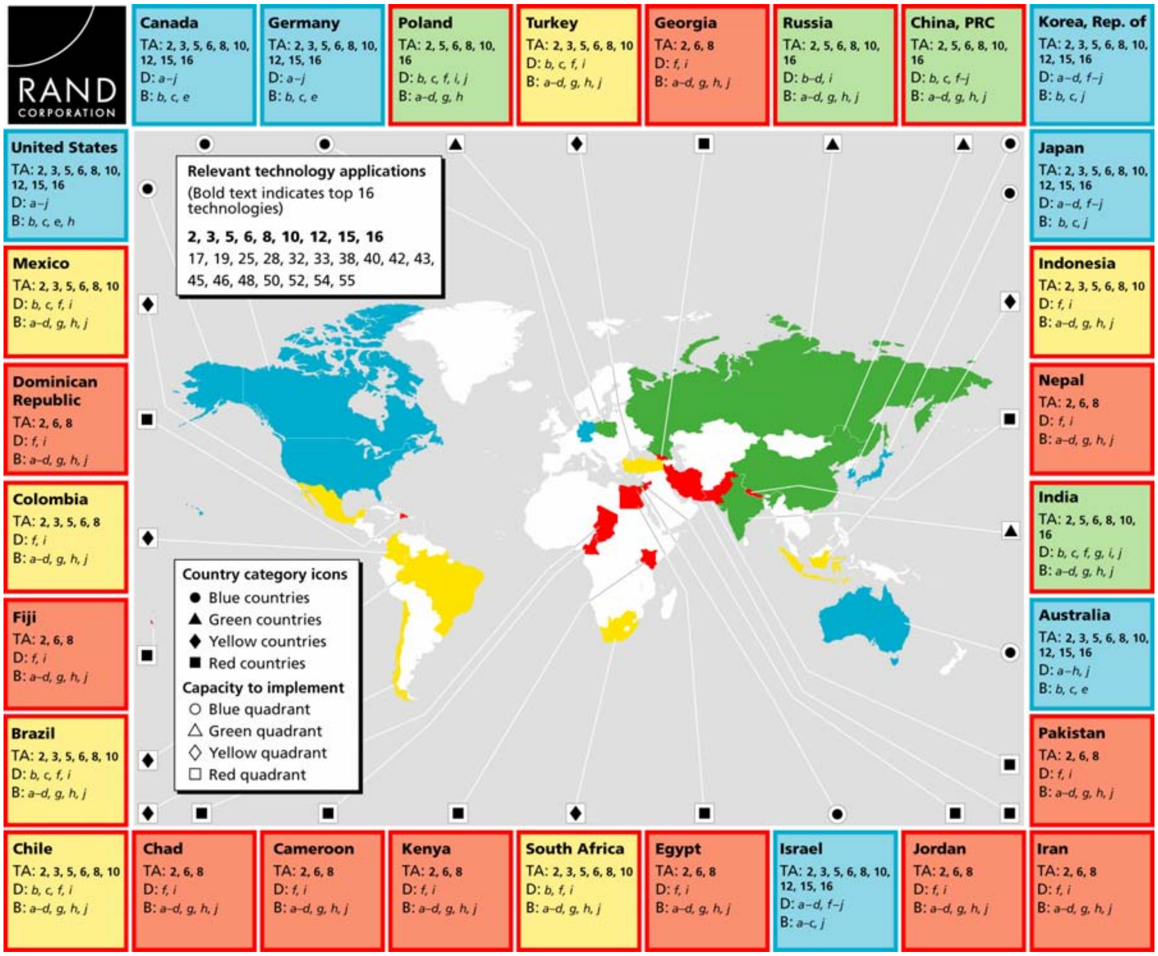


Figure 3.21 summarizes our assessment of the capacity of the selected countries to acquire and implement RTAs, using the same format as Figure 3.3, in which capacity to implement is shown by the color frame around the country box and the white icon in the country line.

Figure 3.21
Selected Countries' Capacity to Acquire and Implement Relevant Technology Applications for Strengthening the Military and Warfighters of the Future



Strengthen Homeland Security and Improve Public Safety

The changing nature of security threats compels policymakers and law enforcement to look for new ways to protect people. The terror attacks on September 11, 2001 sent a clear message that terrorists are no longer targeting just specific high-value personalities like politicians and corporate leaders. Every common man, woman, and child is now a target of terrorists. Terrorists also aim to spread fear and seek mass casualties.[268]

Whether dealing with the threat of dirty (i.e., radiological) bombs, biological or chemical weapons, contagious diseases, or hazardous material spills on highways, it is essential to have effective tools to detect, prevent, treat, clean up and recover.[269] For

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[268] See, for example, Enemark (2004). The author discusses the dangers of biological weapons and natural infectious diseases, with a focus on Northeast Asia, utilizing historical case studies and present-day responses to these dangers.

[269] The Public Health Security and Bioterrorism Preparedness and Response Act of 2002 (Bioterrorism Act of 2002) was signed into law on June 12, 2002, to bolster the nation's ability to respond effectively to bioterrorist threats and other public health emergencies (U.S. Congress, 2002).

example, emergency response workers need protective equipment, sensors to detect trace amounts of harmful agents, and computers to help organize data and assist law enforcement officers in tracking and arresting criminals before they do harm.

Figure 3.22 shows the RTAs for strengthening homeland security and improving public safety, as defined in Table 3.3. Figure 3.22 also shows the selected countries' capacity to acquire RTAs, as well as the drivers for and barriers to implementation, as discussed in previous sections and shown in Figures 3.1 and 3.3. The "top 16" TAs relevant to strengthening homeland security and improving public safety are rural wireless communications (2), ubiquitous information access (3), rapid bioassays (5), filters and catalysts (6), targeted drug delivery (7), cheap autonomous housing (8), pervasive sensors (12), wearable computers (15), and quantum cryptography (16). These TAs are shown in bold in the inset box in Figure 3.22, while the RTAs from the remaining 40 TAs are shown in plain type.[270]

Rural wireless communications will allow law enforcement and emergency response personnel to collect information from remote locations, such as farms, to protect crops from natural pests or electrical power plants to prevent terror attacks. This TA can also help to enable rapid transfer of incident response information to local authorities. Rapid bioassays will help experts to determine types of infections and appropriate response measures to stop the spread of disease. Filters and catalysts will help to provide safe, potable water when water supplies cannot be trusted or are disrupted by natural disasters or attacks. Targeted drug delivery can help communities to quickly respond to security and safety threats, such as chemical and biological attacks, and minimize the loss of lives. Cheap autonomous housing can provide temporary living quarters for individuals whose homes are destroyed or unavailable, as well as for relief workers. Pervasive sensors can help to detect intruders, as well as chemical, biological, nuclear, and other hazards. Backed by high-speed computing and communication systems and ubiquitous information access, law enforcement and emergency response personnel can establish real-time tracking and surveillance of persons and goods. Using wearable computers, their vital signs can be monitored from a safe distance. Wearable computers will also enable more rapid access to information necessary for timely incident response. Finally, quantum cryptography would ensure security and safety by protecting critical data and networks from hackers and attackers.

Clearly, the gap to acquire RTAs is significant between the more and less technologically and economically advanced countries. The gap in their capacity to implement them is even greater, as is shown in Figure 3.23. This figure shows the selected countries' capacity to implement the RTAs, in a quadrant chart similar to that of Figure 3.2, with the percentages of RTAs for strengthening the military and warfighters of the future replacing the percentage of the top 16 TAs.

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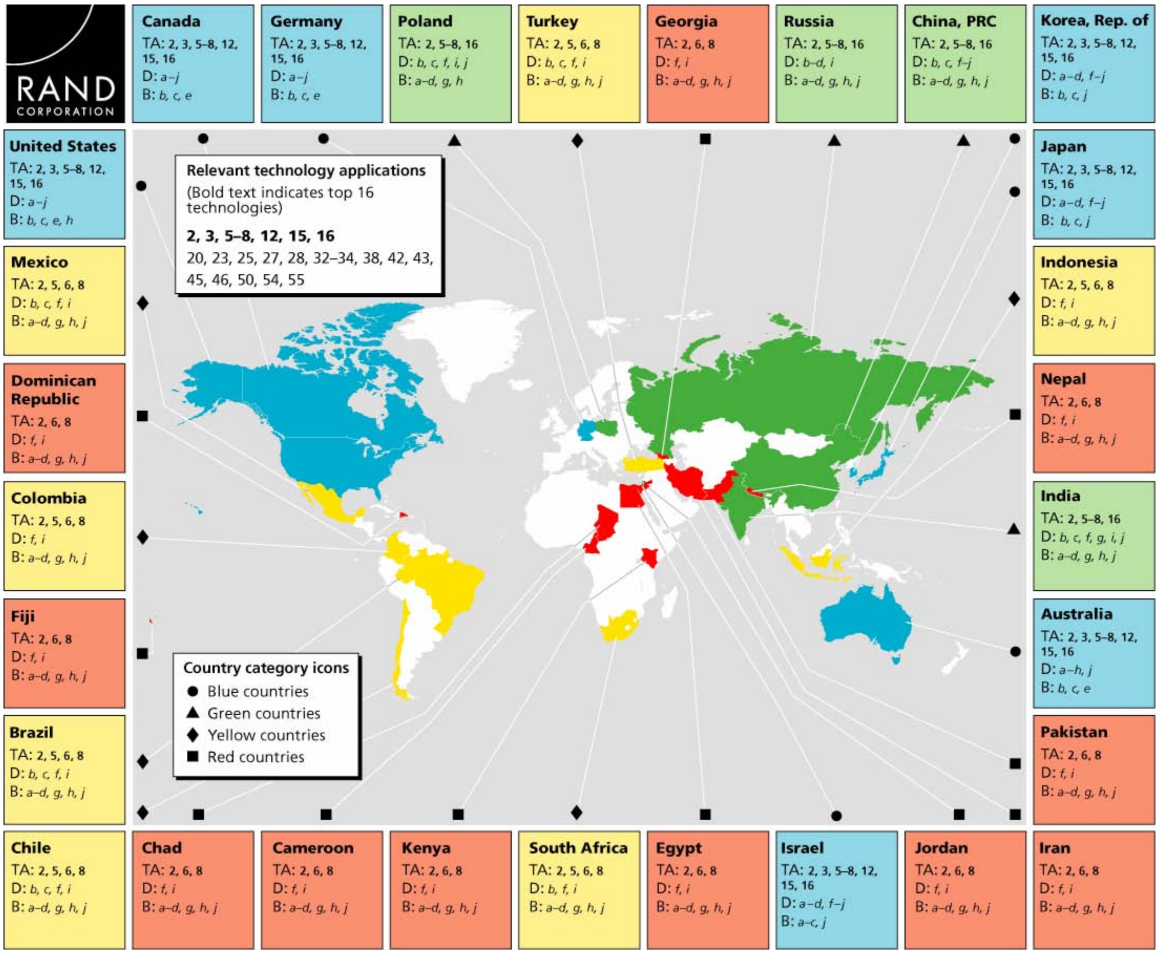
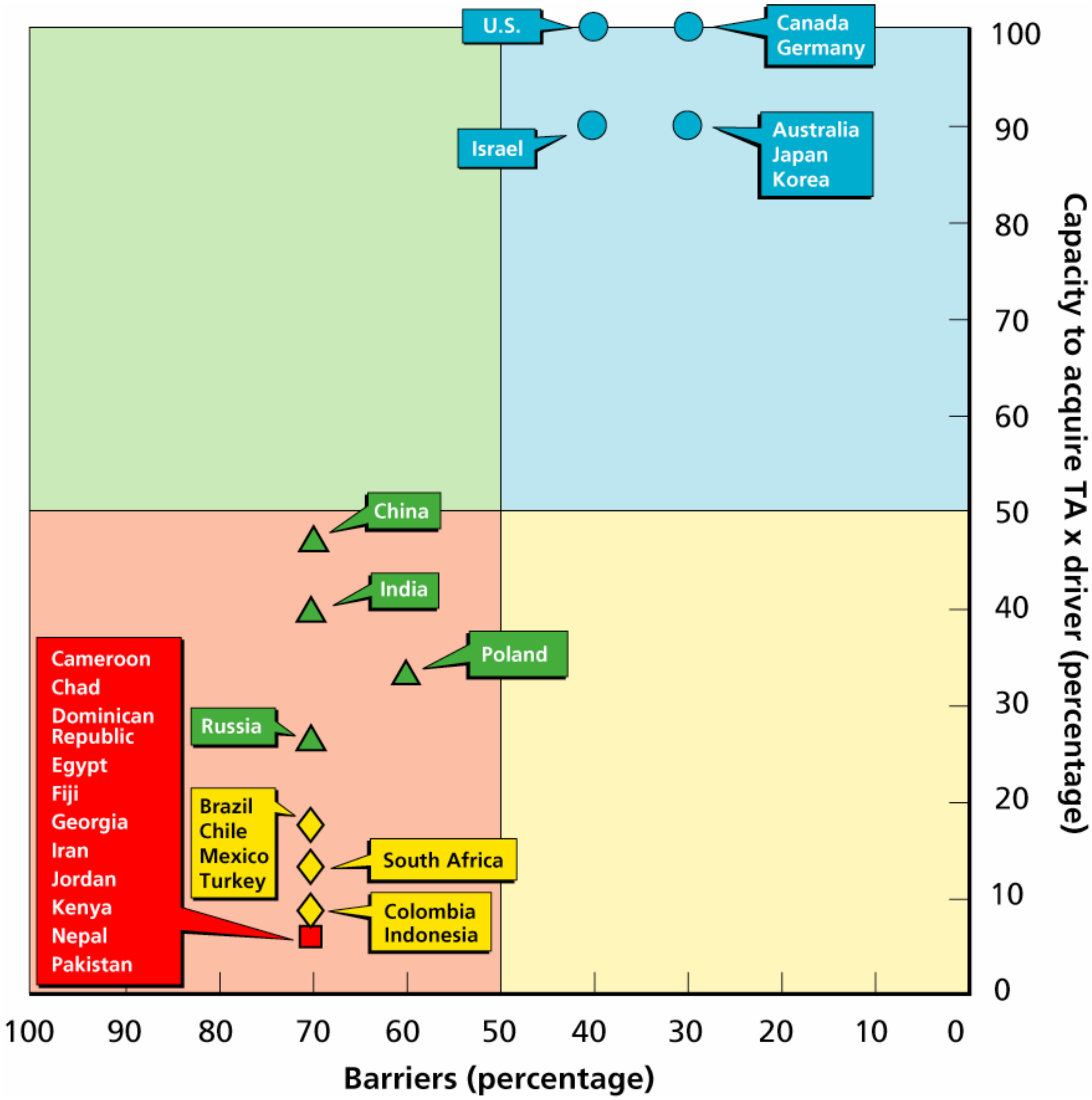
[270] The numbers in parentheses correspond to those in Table 3.3.

Figure 3.22
Selected Countries' Capacity to Acquire Relevant Technology Applications for Strengthening Homeland Security and Improving Public Safety



Because of the higher capacity requirements of some of these RTAs—specifically, ubiquitous information access, pervasive sensors, wearable computers, and quantum cryptography—only the blue countries have the capacity to acquire and implement all relevant TAs for strengthening homeland security and public safety. The green countries will be able to acquire most of these RTAs. In this group, China again appears near the border of the upper left-hand (green) quadrant of Figure 3.23, with India not far behind. The lower level of S&T capacity will limit the capacity of the yellow countries to acquire and implement more than rural wireless communications, rapid bioassays, filters and catalysts, and cheap autonomous housing. Red countries will have the least capacity to acquire RTAs. Within their "tool kits," they will only have rural wireless communications, filters and catalysts, and cheap autonomous housing; thus, they remain near the bottom of the lower left-hand (red) quadrant of Figure 3.23.

Figure 3.23
Selected Countries' Capacity to Implement Relevant Technology Applications for Strengthening Homeland Security and Improving Public Safety

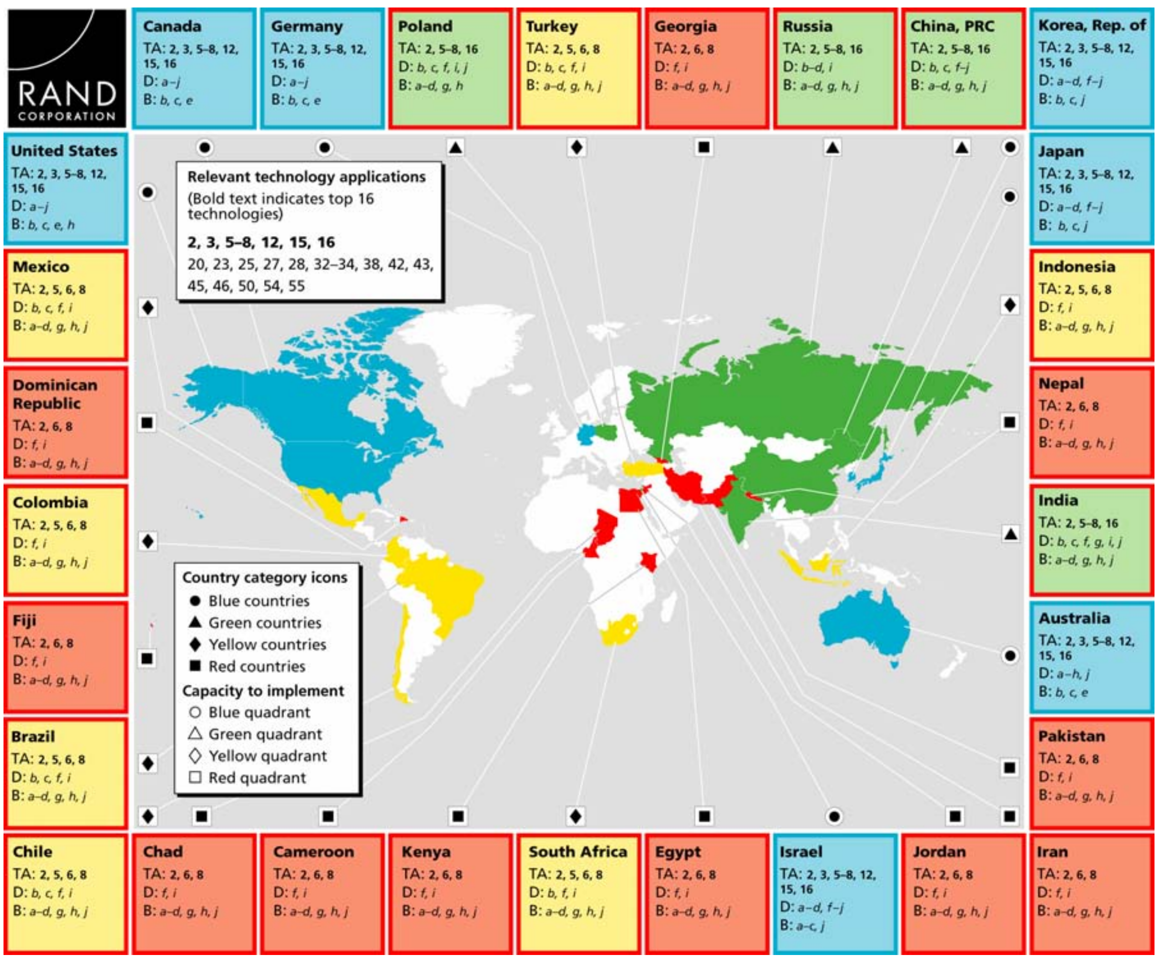


The terrorist attacks on September 11, 2001 and the continuing terror threat will provide strong motivation for the United States to use RTAs to strengthen homeland security and public safety. The use of pervasive sensors will likely be a priority. Most other blue countries will likely be motivated to implement RTAs because of their own history of terror attacks and concerns about public safety. Yet these blue countries are also open and democratic societies, so that RTAs with potential ramifications for individual rights, freedom, and privacy will likely spur public debates. Implementation might require policymakers to secure public trust and the adoption of legal protections. By comparison, in countries in which authoritarian governments rule, public debates about the ramifications for personal privacy and freedom of RTAs are unlikely to occur.

In these countries, RTAs implemented in the name of strengthening homeland security and public safety might become a convenient excuse to increase government power and control.

Figure 3.24 summarizes our assessment of the capacity of the selected countries to acquire and implement RTAs, using the same format as Figure 3.3, in which capacity to implement is shown by the color frame around the country box and the white icon in the country line.

Figure 3.24
Comparing Selected Countries' Capacity to Acquire and Implement Relevant Technology Applications for Strengthening Homeland Security and Improving Public Safety

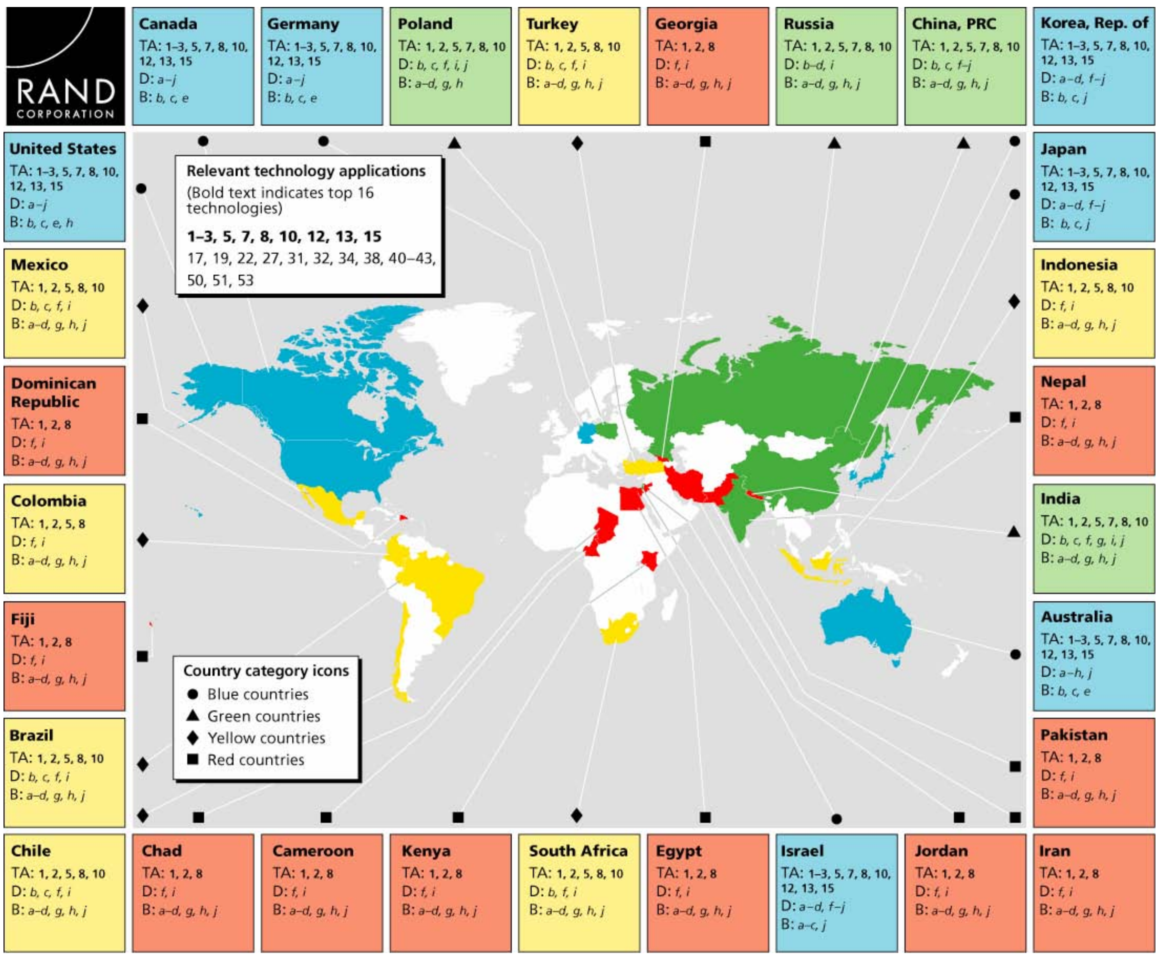


Influence Governance and Social Structure

Several TAs described in this study have the potential to change the balance of power between the government and the governed and alter existing social structures. Some may strengthen governments; others may give ordinary people more control over their lives and increase their ability to demand accountability from decisionmakers.

Figure 3.25 shows the RTAs that might influence governance and social structure, as defined in Table 3.3. Figure 3.25 also shows the selected countries' capacity to acquire RTAs, as well as the drivers for and barriers to implementation, as discussed in previous sections and shown in Figures 3.1 and 3.3.

Figure 3.25
Selected Countries' Capacity to Acquire Relevant Technology Applications That Might Affect Governance and Social Structure



The "top 16" TAs that might influence governance and social structure are cheap solar energy (1), rural wireless communications (2), ubiquitous information access (3), rapid bioassays (5), targeted drug delivery (7), cheap autonomous housing (8), ubiquitous RFID tagging (10), pervasive sensors (12), tissue engineering (13), and wearable computers (15). These TAs are shown in bold in the inset box in Figure 3.25, while the RTAs from the remaining 40 TAs are shown in plain type.[271]

[271] The numbers in parentheses correspond to those in Table 3.3.

Cheap solar energy will allow people to power television, satellite dishes, and other communication devices to obtain news, connect with communities beyond their local and national borders, and access information that might be suppressed by their own government. Rural wireless communications will expand public access to information and communication, which can empower communities to challenge local authorities. Ubiquitous information access will expand individual access to information but, together with ubiquitous RFID tagging, might make it easier for governments to monitor individual preferences and activities. The decision of authorities to use or withhold rapid bioassays, targeted drug delivery, cheap autonomous housing, and tissue engineering, particularly in times of emergency, to specific geographical, ethnic, racial, or religious communities could mean life or death to entire communities. The cost of access to these TAs will also determine who has access and to what extent. The same is true for pervasive sensors and wearable computers, which can significantly increase government ability to monitor individual behavior.

In nondemocratic societies, in particular, those in power might fear the impact these TAs might have on their authority and influence. Their anxiety might motivate them to restrict diffusion of TAs—as the Chinese government does in censoring the Internet. Such government intervention might reduce the salutary effects of TAs to alleviate rural poverty, improve human health and the environment, and protect public safety. Even in democratic societies, opposition from particular interest groups based on concerns about privacy, discrimination, or favoritism, or even based on ignorance, could also compel policymakers and individual end users to reject the implementation of TAs.

Consequently, prevailing political, economic, and social forces could promote or limit implementation of TAs that might influence governance and social structure.

Figure 3.26 shows the selected countries' capacity to implement the RTAs, in a quadrant chart similar to that of Figure 3.2, with the percentage of RTAs that might influence governance and social structure replacing the percentage of the top 16 TAs.

Figure 3.26 shows that the blue countries have the strongest capacity to implement these TAs. The green countries have substantially less capacity, and the yellow and red countries rank far lower. Unintended consequences may be mitigated somewhat in the blue countries by the presence of stronger institutions of governance and democratic, open systems in the blue countries to support public discussions about concerns, establish safeguards against abuse, and encourage public confidence in measures to regulate use of these TAs.

Figure 3.26
Selected Countries' Capacity to Implement Technology Applications That Might Affect Governance and Social Structure

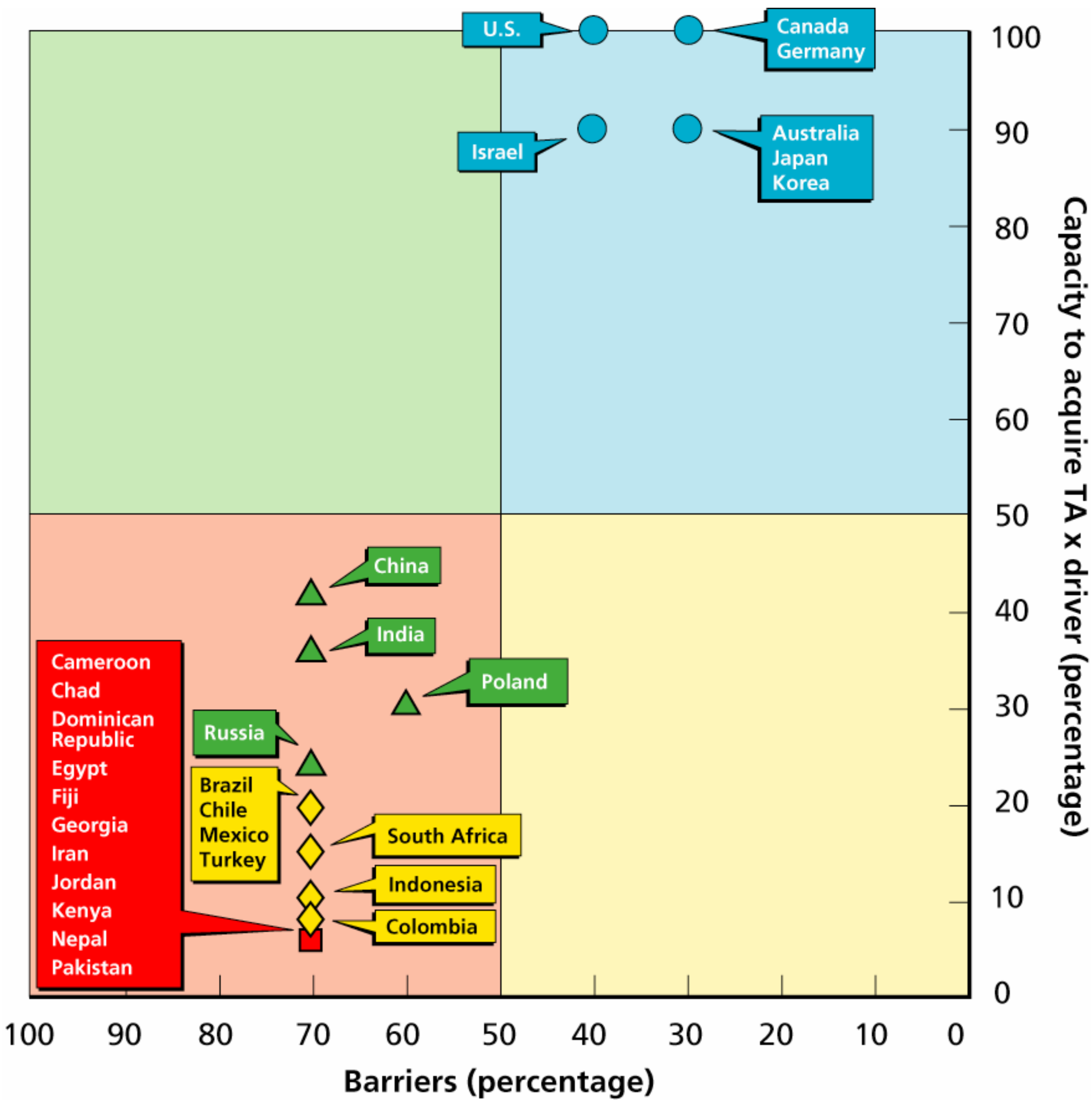
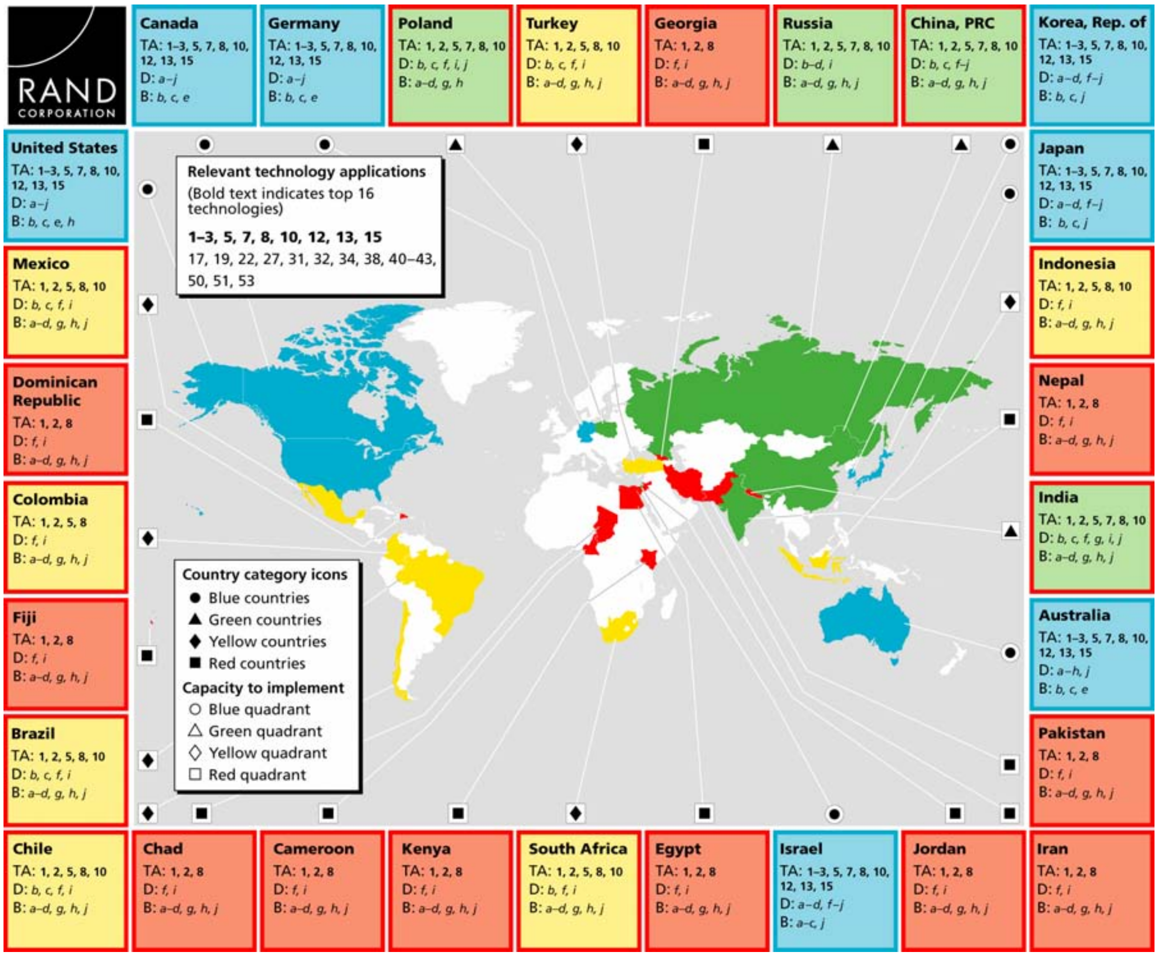


Figure 3.27 summarizes our assessment of the capacity of the selected countries to acquire and implement RTAs, using the same format as Figure 3.3, in which capacity to implement is shown by the color frame around the country box and the white icon in the country line.

Figure 3.27
Comparing Selected Countries' Capacity to Acquire and Implement Technology Applications That Might Affect Governance and Social Structure



Summary of Country Capacities for Technology Implementation

The previous sections demonstrate that technology implementation requires more than the existence of a TA, or even the presence of sufficient S&T capacity within a country to acquire that TA. Matching the TAs to important problems and issues is a first step in promoting their use.

Beyond this, however, many factors will drive or deter implementation. The cost to acquire, use, and maintain a TA can be a critical factor in determining whether it will be used, by whom, and to what extent. Politics, policies, and social values can also influence acceptance of a TA by end users and those with power to control its diffusion. The presence of institutional, human, and physical capacity to support the use of a TA is also critical. National investment in infrastructure, R&D activities, and education, as well as presence of good governance, can affect the capacity to acquire and implement TAs.

For the most economically and scientifically advanced countries, our assessment indicates a strong capacity to acquire and implement the full range of TAs to address a diversity of problems and issues. For the less economically and scientifically advanced nations, however, we observed substantial disparities between their capacity to acquire and implement TAs. For example, China, India, Poland, Brazil, and Chile are growing economically and scientifically; increasing S&T capacity and growth in their institutional, human, and physical capacities will help to narrow the gap in technology implementation between them and the scientifically advanced countries.

For those countries that have less-dynamic economies, less scientific growth, and also suffer from political and social instability, implementation of TAs will be very difficult, even when they have the capacity to acquire the relevant TAs. For example, our assessment indicates that even the least economically and scientifically advanced countries reviewed in this study have the capacity to acquire most TAs relevant to promoting rural economic development and improving public health. However, these countries lack the capacity to implement the relevant TAs. Our analysis suggests that outside assistance might help to introduce TAs to these societies and facilitate their use, but whether use can be sustained to produce benefits for those most in need will largely be determined by forces internal to these countries (e.g., quality of governance).

Review of Figures 3.1 through 3.27 reveals significant variations in the capacity of our selected countries to implement TAs. Most notably, there is a group of problems and issues for which all countries (except for the most scientifically advanced) show better capacity to implement RTAs. For example, compare Figure 3.5 for promoting rural economic development with Figure 3.2 for the “top 16” TAs. For these problem areas—promoting rural economic development, improving public health, and reducing resource use and improving environmental health—the scientifically proficient green countries China and India have moved squarely into the upper half of our quadrant charts (Figures 3.5, 3.11, 3.17, respectively), with Poland not far behind. Moreover, several of the scientifically developing yellow countries show increased capacity—most notably Brazil, Chile, Mexico, and Turkey—which have moved up to occupy the same position as the scientifically proficient green country, Russia, in Figures 3.5 and 3.17. South Africa has moved above the position occupied by Brazil, Chile, Mexico, and Turkey on the quadrant chart for overall technology implementation (Figure 3.2).

This suggests that the global technology revolution can be a major factor in addressing global issues of rural economic development, public and environmental health, and resource use. However, the barriers discussed in previous sections must be addressed, and as noted previously, these are most challenging in the scientifically lagging red countries, which have the greatest needs.

With respect to improving individual health (compare Figure 3.14 with Figure 3.2), the situation is not as promising, with all countries showing the same capacity to implement the relevant TAs as for the top 16. This reflects the fact that technologies that are more relevant to individual rather than public health, such as improved diagnostic and surgical methods and tissue engineering, will not be widely available, except in the scientifically advanced blue countries. Improvements in individual health in other countries resulting from technological advances will likely reach only the rich or well connected.

The overall capacity to implement TAs, as indicated by Figure 3.2, illustrates the following widely recognized trends:

- The technological preeminence of the scientifically advanced countries of North America, Western Europe, and Asia
- The emergence of China and India as rising technological powers, with the scientifically proficient countries of Eastern Europe, as represented by Poland, not far behind
- The wide variation in technological capability among the scientifically developing countries of Southeast Asia and Latin America
- The large scientific and technological gap between most of the countries of Africa, the Middle East, and Oceania and the rest of the world.[272]

The capacity to implement the TAs relevant to strengthening homeland security, public safety, and the military and warfighters of the future does not differ greatly from overall capacity for technology implementation (compare Figures 3.2, 3.20, and 3.23). This implies that the global technology revolution is likely to support the emergence of China and India as military, as well as economic, powers.

For the remaining problem areas—promoting economic growth and international commerce and influencing governance and social structure—all countries (except the most scientifically advanced) show less capacity to implement relevant TAs than their overall technology implementation capacity (compare Figures 3.2, 3.8, and 3.26). This reflects the fact that TAs such as ubiquitous information access, pervasive sensors, tissue engineering, and wearable computers, which require a high level of infrastructure and institutional, physical, and human capacity, are unlikely to be widely adopted outside the most scientifically advanced countries. Thus, the greatest economic benefits stemming from such advanced technologies will likely be gained by these countries, although countries such as China and India may benefit via increased opportunities for manufacturing and services, respectively. As China and India improve their drivers, however, they will reap the benefits seen by the scientifically advanced countries.

With respect to the impact of TAs on governance and social structure, it appears that the combination of many barriers, few drivers, and capacity to acquire only a small number of the RTAs will moderate the impact of the global technology revolution in most of the developing world. However, individual TAs, such as cheap solar energy, rural wireless communications, and cheap autonomous housing, could have significant impact—for example, by simplifying household tasks and providing a gateway to the outside world, thus empowering women and changing their role in society; by providing opportunities for education and commerce in poor rural areas; and by strengthening the hand of civil society groups and the general public in influencing government decisions and actions.

We note that our analysis provides an assessment of the average capacity of each country to implement the full range of TAs relevant to each problem and issue. This represents a floor on which individual countries will have the ability to focus their capacity development to create spikes in their capacity to acquire and implement specific TAs relevant to specific problems and issues of national priority. Countries with a greater level of S&T capacity (i.e., the countries in the green group and those leading the yellow group) will have the best opportunity to use their developing institutional, human, and

[272] Notable exceptions to these regional trends among our selected countries are Israel, Turkey, and South Africa.

physical capacity to exceed their assessed capacity to implement TAs in selected areas, both civilian and military.

CHAPTER 4
CONCLUSIONS

In previous chapters, we identified and described integrated technology trends to 2020 in bio/nano/materials/information technology. We then assessed technology applications likely to result from these trends and identified several that appear poised to influence multiple sectors of society. In addition to assessing the technical and implementation feasibility of these TAs, we examined their potential regional and international ramifications. In this chapter, we present conclusions based on our technology foresights and the analysis of capacity to acquire and implement TAs of the 29 representative countries selected for our analysis.

Accelerated Technology Development Will Continue

Based on our technical foresights (e.g., see Appendices A through E and related references), we see no indication that the accelerated pace of technology development described in GTR2015 is abating, and neither is the trend toward multidisciplinarity nor the increasingly integrated nature of TAs. Indeed, most of the "top 16" TAs of Table 2.2 involve at least three of the technology areas addressed in this study, and many involve all four, as illustrated in Table 4.1. The continued integration of these technology developments will benefit from the continuing trend toward globally integrated publications media, Internet connectivity, and scientific conferences, as well as the development and cross-fertilization of ever-more-sensitive and selective instrumentation.

Table 4.1
Involvement of Technology Areas in Top 16 Technology Applications

Technology Applications	Bio	Nano	Materials	Information
Cheap solar energy	x	x	x	
Rural wireless communications		x	x	x
Ubiquitous information access		x	x	x
GM crops	x	x		
Rapid bioassays	x	x	x	x
Filters and catalysts	x	x	x	
Targeted drug delivery	x	x	x	x
Cheap autonomous housing	x	x	x	x
Green manufacturing	x	x	x	x
Ubiquitous RFID tagging			x	x
Hybrid vehicles		x	x	x
Pervasive sensors	x	x	x	x
Tissue engineering	x	x	x	
Improved diagnostic and surgical methods	x	x	x	x
Wearable computers		x	x	x
Quantum cryptography		x	x	x

Capability and Need Differences Are Driving Global Technology Revolution Differences Around the World

Because of vast differences in countries' S&T capacity required to acquire TAs, as well as their institutional, human, and physical capacity required to develop drivers for, and overcome barriers to, implementing TAs, the impact of the global technology revolution will show substantial regional and international variation. In addition, regional differences in needs will affect the market pull on TAs.

The scientifically advanced countries of North America, Western Europe, and Asia (including Australia) are likely to gain the most, because they have the capacity to acquire and implement all of the top 16 TAs, as well as all those relevant to the problems and issues of Table 3.3.

If emerging economies (such as Asia's China and India, and Latin America's Brazil and Chile) can address the multiple barriers to technology implementation (e.g., governance and stability, laws, policies, infrastructure, investment in R&D, education and literacy), they will be able to use TAs to support continued economic growth and human development for their populations. China and India are emerging technological powers with the best opportunity to begin to approach the ability of the scientifically advanced countries to use TAs to achieve national goals. Eastern Europe (represented here by Poland), as a region, appears to be poised next in line behind China and India. Russia's capacity to implement TAs appears to be deteriorating, and the most advanced of the scientifically developing countries (represented in this report by Brazil, Chile, Mexico, and Turkey) appear to be almost overtaking the former superpower.

The scientifically lagging developing countries, because of the severity of problems such as disease, lack of clean water and sanitation, environmental degradation, and the lack of resources to address these problems, have the most to gain from implementing the 2020 TAs of Table 2.2, especially those relevant to strengthening rural economic development, improving public health, and reducing resource use and improving environmental conditions, most of which they have the capacity to acquire. However, implementation of these TAs by these countries will require substantial building of institutional, physical, and human capacity. This will no doubt be assisted by the efforts and sponsorship of international aid agencies and rich countries, but a necessary and enabling requirement will be improved governance and country stability. Corrupt governments will not be able to mobilize resources or harness social support and political commitment to implement TAs to address societal problems and assist development, and unstable countries will not be able to garner and sustain the necessary investment to build and maintain the necessary human capital and infrastructure. Indeed, international development assistance can only provide "assistance." National governments must provide the vision, leadership, and commitment to effectively utilize available resources from within and without to realize national goals in development and security.

Public Policy Issues May Strongly Influence Technology Implementation

The nature of a TA can determine the politics that surround it. Many of the most controversial TAs involve biotechnology (e.g., GM crops, GM insects, genetic screening, gene therapy, and genetic selection of offspring). Other TAs spark heated debate because of their potential implications for personal privacy and freedom. These include pervasive sensors, certain uses of RFID, implants for tracking and ID, chip implants for the brain, and biometrics on ID. Genetic screening also raises privacy concerns. For example, would individuals with certain genetic characteristics and established links to certain types of disease and illness be denied health insurance or jobs, or face other forms of discrimination?[273]

Maintaining Science and Technology Capacity Requires Consideration and Action

Because of the accelerating pace of technology development and the rapid improvement of capacity to acquire and implement TAs in emerging economies, maintaining country position in relative capacity to implement TAs will require continuing efforts to ensure that, for example, laws, public opinion, investment in R&D, and education and literacy are drivers for, and not barriers to, technology implementation. This, of course, is not a blanket advocacy for all TAs. Some ethical, safety, and public concerns require careful analysis and consideration. Just because we can do something does not always mean that we should. In addition, infrastructure needed for desired TAs must be built, supported, and maintained. While the scientifically advanced countries appear to have a sizable advantage, this could erode, much as has happened to Russia since the end of the Cold War (for example, see Figure 3.5).

Capacity Building Is an Essential Component of Development

As described in Chapter Three, the implementation of TAs to address the problems and issues developing countries face is not primarily about technology, or even S&T, capacity. The greater challenge is the development of institutional, human, and physical capacity, including effective and honest governance. International consensus is growing[274] that development will require much more than efforts to bolster growth in particular economic sectors. Development is the consequence of improvements in such areas as economic growth, social equity, health and the environment, public safety and security, and good governance and stability. Thus, countries that have the best performance in these indicators of development have the strongest institutional, human, and physical capacity to implement TAs. Comparison of data in Appendix H on S&T capacity with data in Appendix J on human development shows that the scientifically advanced countries also rank highest on the HDI. This suggests that less-developed countries hoping to benefit from implementation of TAs will have to improve their performance in many of the development indicators shown in Appendix J in order to build the requisite institutional, human, and physical capacity.

Public Policy Issues Relating to Technology Applications Will Engender Strong Public Debate

As we have seen in previous chapters, and as noted above, some important TAs raise significant public policy issues that engender strong and sometimes conflicting reactions

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[273] See, for example, "Human Genetic Research Databases" (2004).
[274] See, for example, Kaufman and Kray (2003); Ogbu, Oyeyinka, and Mlawa (1995); and Vigilante (2003).

and opinions within and between countries, regions, and various ethnic, religious, cultural, and other interest groups. When raised, these issues need to be resolved if the full benefits of a TA are to be realized. These issues need to be debated in an environment that seeks to resolve conflicts. Such public debates, in addition to being based on sound data, need to be inclusive and sensitive to the traditions, values, and cultures that exist in society. In some cases, issues will remain and will moderate or even halt technology implementation—sometimes for good reason (e.g., when safety concerns cannot be adequately addressed) and sometimes simply because collective decisionmaking will decide what a particular society wants or does not want. Market forces will also moderate and vector the course of the global technology revolution, its technology applications, and their implementation. Predicting the net effect of these forces is literally predicting the future—wrought with all the difficulties of future predictions. However, these technology trends and applications have substantial momentum behind them and will be the focus of continued research and development, consideration, market forces, and debate. Many of these technologies will be applied in some guise or other, and the effects will be significant and astonishing, changing lives across the globe.

APPENDIX A: BIOTECHNOLOGY, BIONANOTECHNOLOGY, AND BIOMEDICAL SCIENCE TRENDS TO 2020

Brian A. Jackson and Felicia Wu

Looking back at the state of biotechnology, bionanotechnology, and biomedical science[275], key goals these fields set 15 years ago then have since been achieved. In 1989, the sequencing of the human genome was in its early stages; today, it is complete. In other areas, such as the broad application of gene therapy to cure human disease, the field faces similar challenges today as it did a decade and a half ago. As was the case then, the potential of biologically based technologies opens up a vast array of avenues that may be developed over the next 15 years. Rapid technological change may lead us far along many of those avenues, bringing society new options in medical technologies, new and improved products, or even the ability to make changes to or augment human beings. However, as was the case 15 years ago, many factors may modulate the pace of that change. The costs involved in these technologies, difficulties in understanding complex biological systems sufficiently to make desired changes, and fundamental questions about the potential risks these technologies pose to human health or to the health of our ecosystem may reduce the attractiveness or entirely close off some avenues as inaccessible, undesirable, or both.

The use of technologies that utilize and modify life will always raise concerns about the potential for negative or unforeseen impacts. Each application of these technologies—ranging from changing bacteria to produce compounds of interest, to modifying plants to alter their traits, to making alterations in the human genome—has brought up significant issues when first explored. Questions have been posed about the risks versus the rewards of these technologies, about who benefits from them, and how their use might shift the balance in ecosystems or even what it means to be a human being. No advance in technology will cause those questions to go away. Indeed, they should not, because such questions are a part of the process of guiding technology policy in an attempt to benefit from new technologies while seeking to minimize their potential deleterious impacts.

The process of globalization—enabled by transport, commerce, and communications systems—complicates addressing the questions surrounding these technologies. In making assessments of technological risk and benefit, an activity frequently done in the face of considerable uncertainty, there seldom exists an obvious or unambiguously correct answer. There is, therefore, no reason why all people or nations

[275] The term *biotechnology* covers all the techniques that use living organisms or substances from organisms to produce or alter a product, cause changes in organisms, or develop microorganisms for specific purposes. In this discussion, we also include *bionanotechnology*, which covers technologies at the nanoscale incorporating biological functions or ingredients or technologies that seek to affect or modify biological systems. By *biomedical science*, we refer to broader efforts to incorporate technology into medical practice to improve human health and address disease.

must reach the same conclusions. The differences between the United States and Europe regarding the potential risks of genetically modified (GM) foods serve as a case in point. However, such differences exist within the United States as well, as shown by the continuing debate over the inclusion of GM ingredients in products and the dispute regarding whether such products should be labeled. Such barriers are problematic for companies that want to profit from their innovations in as large a market as possible. In some nations and parts of the United States, moves have been made to build technological restrictions into legislation[276] or even constitutional law.[277] Going forward, these technologies will likely continue to face these types of barriers that could potentially hinder change.

However, while individual nations or states may put controls in place within their borders, other elements of globalization weaken individual states' power to slow the overall pace of technological change. The interconnectedness of markets and the mobility of scientific and technological talent mean that controls in one area may lead progress to simply shift to another. When the United States limited federal funding of stem cell research, a high-profile researcher moved to Britain where such research was still supported and encouraged,[278] and some individual U.S. states[279] and institutions[280] began supporting such research with their own funds. With so many actors in the overall technological system, controls on research or technology deployment become more difficult.

The following sections discuss recent advances and potential future trajectories for biotechnology, bionanotechnology, and biomedical science.

Biological Information: Genomics, Proteomics, and Other Technologies

Recent technological advances have produced a range of tools that provide access to technological information at ever-faster rates. The fruits of some of those tools, such as the rapid sequencing technologies that made it possible to complete the sequencing of the human genome,[281] are already available. Others, such as the now-expanding efforts directed at proteomics or technologies to directly monitor multiple chemical reactions occurring inside a living organism,[282] are only at the beginning of what is likely to be a rapid and far-ranging development process. Developments in nucleic acid and many types of protein microarrays now make it possible to perform many different experiments on a sample at once, producing large amounts of data more quickly and cheaply than by using previous methods. Array sensors for enzymes, analytes, antigens, antibodies, receptors, and nucleic acid targets are available on chips containing not only the biocomponents but also the integrated circuitry to record analytical results.[283] Such functionality will likely be increasingly integrated into medical technologies, moving

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[276] Dalton (2004).
[277] Anonymous (2004).
[278] Roosevelt (2004).
[279] Roosevelt (2004).
[280] Lawler (2004).
[281] Venter et al. (2001).
[282] Lok (2004).
[283] Defense Technical Information Center (2004).

toward miniaturized and implantable sensors that could further reduce the effort required to obtain detailed biological information about individuals.

Advances in technologies not directly linked to biology have also contributed to the increasing availability of biological information. Improvement in the broad range of electronics and information technologies underlying the medical imaging technology is one example. Medical imaging technologies allow physicians to view diseases and injuries directly, without the need for invasive surgeries. Also, improved information display and control, such as three-dimensional audio-visual displays of bodily organs or drug interactions, enable improvements in diagnosis, decisionmaking, and treatment.[284]

Application of Biological Information

As these technologies evolve into the future, already ongoing changes will make increasingly personalized medicine possible, matching specific therapies to the disease states that particular individuals face.[285] Continuing advances in rapid and parallel sequencing methods will make gene sequence information for individuals available at increasingly lower cost. Sequence data and technology have also begun to bear fruit in understanding differences in the responses to drugs among different patients, such as why some lung cancers respond to a particular chemotherapy drug while others do not.[286] Genetic differences among different cancers have also been used to predict the spread of the disease.[287] Medical imaging, such as tomography, has also been used to show why some drugs affecting the brain work better in some patients than in others.[288] Such findings can be directly applied to benefit individual patients in drug targeting and other therapeutic choices.

Improvements in the development of specific biomarkers—used in toxicological and epidemiological studies to detect whether a human or animal has been exposed to a potentially harmful agent—improve the ability to detect individuals' genetic susceptibility to toxicants, disease, and stress.[289] Biotechnologies are also being applied to the development of highly specific tests for individual substances or organisms, such as unconventional weapons[290] or naturally evolving disease threats,[291] that allow testing for particular hazards more rapidly than was previously possible.

It has been projected that, over time and beyond 2020, sequencing will become cheap enough so that all individuals will have access to their own genomic information.[292] With such information, individuals could make health decisions early in life based on their susceptibility to diseases that would not appear until much later. Analogous advances in imaging technologies could make it possible to more effectively diagnose and treat disorders that could otherwise only be detected via invasive procedures.

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[284] Fischetti (2004).
[285] Kallioniemi (2004).
[286] Marx (2004).
[287] Garber (2004).
[288] Ezzell (2003).
[289] Defense Technical Information Center (2004).
[290] Rider et al. (2003).
[291] Nelson (2004).
[292] "Future Visions" (2003).

The increasing availability of biological information is also paying dividends in research and medical laboratories that address a broad range of health and other problems. The speed of current sequencing technologies is already enabling quicker understanding of environmental threats, such as new diseases outbreaks. For example, in early 2004, approximately one year from the recognized outbreak of SARS (severe acute respiratory syndrome) in China, analyses based on genomic information on the virus were already being published.[293] More rapid methods for elucidation of the structures of biological molecules are providing an ever-increasing stock of detailed knowledge to understand living systems and to serve as the basis for efforts to intervene.

The broadened availability of information about biological systems is also contributing to drug discovery efforts.[294] Sequencing efforts aimed at other organisms can also contribute to research focused on human disorders. Completed in 2002, the mapping of the genome of the mouse, an animal frequently utilized in laboratory studies, is one such example.[295] Understanding the genomic basis of other animals' biological systems might also suggest novel treatment strategies for human disease. For example, as a result of heart attacks or other heart diseases, human hearts can scar in irreparable ways. Recent discoveries have shown that, unlike humans, the zebra fish can naturally regenerate its heart tissues. Future exploration of the fish's regeneration-promoting genes could lead to strategies for the scar-free repair of human hearts.[296]

In addition to revealing that subtle differences among individuals can have significant effects on the efficacy of particular pharmaceuticals, the growing body of biological knowledge and understanding has also demonstrated the exquisite complexity of biological systems and processes. Biological systems are not simply genetic information translated into the materials needed to build and support life. They involve regulatory functions that control gene expression, systems that modify gene products after they are produced, and so on. The fact that the complete draft of the human genome appears to contain many fewer genes than was predicted, based on the complexity of human anatomy and physiology, underscores the importance and role of these other layers of complexity. Research over the past decade has shown that components of human DNA (deoxyribonucleic acid) thought to have no function—introns, or "junk DNA"—actually may play a key role in regulating gene function. For example, "hidden genes" that work through RNA (ribonucleic acid) rather than protein seem to play a role in issues of inheritance, development, and disease.[297] The many interactions among the complex networks within living systems often make seemingly simple attempts at designing therapies for conditions or strategies for modification much more difficult than expected.[298]

All indications are that, over the next 15 years, tools for gaining more and more biological information will become more and more available. Some of those tools may be restricted to the clinic—diagnostics used to guide specific therapies that are responsive to the individual characteristics of patients and their diseases. Others will be broadly

[293] Chinese SARS Molecular Epidemiology Consortium (2004).
[294] Szuromi, Vinson, and Marshall (2004).
[295] Gregory et al. (2002).
[296] Simpson (2003).
[297] Gibbs (2003).
[298] For example, see Turgeon et al. (2004) and Raser and O'Shea (2004).

deployed, whether they are biotechnology-based sensor systems designed to monitor the environment for specific changes or substances or identification systems used to substantiate individuals' identity for specific commercial transactions or life events. As a result, the availability of biological information—the gene sequence of an individual, the molecular markers for a particular disease, the presence of a specific bacterium at a given place and time—will become easier to measure and determine. As discussed above, this availability has significant privacy implications. However, it will have other impacts as well.

Impacts of Increasing Information Availability

The increasing availability of information will create new needs. Many of the advances that have occurred to date, including rapid genome sequencing, have been enabled by companion advances in information technology and bioinformatics. Increasing volumes of information will drive continued needs for tools in these areas to put these data to effective use. Already, large data sets have enabled sophisticated efforts to model genetic[299] and metabolic networks[300] within organisms, both providing new insights and suggesting further avenues for research. Integration of artificial intelligence into such systems has already made possible the development of a "robot scientist" that carries out hypothesis-testing experiments on such large data sets.[301] Advances in bioinformatics will further enable such efforts, both delivering on many of the potential benefits of growing information availability and providing an approach to address and understand the biological complexity that current experiments are demonstrating.

Our ability to gather information will need to be matched with a companion understanding of how to interpret it. Because of the power of biotechnology-based information-gathering mechanisms, the ability to collect data often outstrips the understanding needed to interpret it. One example can be found in the literature on biomonitoring, techniques through which levels of pollutants within individuals can be measured even though the health effects of the materials are not clear.[302] Another is the recent observation that airborne particles can cause heritable mutations in mice.[303] The increasing rate of information collection could produce technical information overload, where measurements that are the most important are not clear. Depending on how the results of testing are applied—by individuals making personal health decisions, in the regulatory process, by opposing parties in litigation—the fact that we have access to the information may or may not be prove to be beneficial overall.

The impact of the proliferation of information-gathering capability over the next 15 years will also be significantly affected by how decisions are made about which of the growing number of tools are applied and when it is appropriate to use them. Although far cheaper today than even five years ago, gathering information using biotechnological methods is not free. Those costs, whether for environmental monitoring assays or medical diagnostics, will be a significant contributor to their net impact on society. If a specific medical diagnostic remains costly, access may be restricted to countries or individuals who can pay for its use; if the diagnostic's application becomes an accepted and expected

[299] Covert et al. (2004).
[300] Almaas et al. (2004).
[301] King et al. (2004)
[302] Stokstad (2004).
[303] Samet, DeMarini, and Malling (2004).

component of medical care for all, it could significantly increase national health care costs. On the one hand, if costs restrict the use of these technologies, their benefit in producing cross-cutting population-level data will be reduced; on the other hand, overusing these technologies could cost society resources that would be better used elsewhere. Developing consensus on when and where to use emerging information-gathering technologies will therefore be an important determiner of their impact over the next decade and a half.

The social and ethical impacts of increasingly available biological information are also not entirely clear. For example, one of the benefits cited of broader availability of information on individual patients and disease states is that it could enable scientific and medical advances based on broader analysis of large data sets.[304] Bringing individual patient data together into common data sets poses serious privacy concerns. For example, questions have been raised about whether genomic data at high enough specificity to be useful to researchers can be effectively anonymized,[305] especially as techniques for getting sequence information cheaply become more readily available. Concerns already exist about how to weigh the clear need to protect individuals and their privacy with the compelling benefits that can come from such medical research. There is also concern about researchers having access to medical records and about human subjects' protection requirements for activities such as disease surveillance.[306]

If technology reaches the point at which such biomedical data, including genomic sequence data, are used for purposes such as identification, concerns about individual privacy will increase. Early in 2004, such concerns led to proposal of a law in Britain that prohibited the taking of DNA from anyone without the individual's consent. Intended to prevent theft of samples to be used in activities such as "bogus insurance claims," the bill was interpreted as preventing all research on stored human tissue samples.[307] Broader potential social impacts of these technologies are even more difficult to predict. At the same time that higher-resolution data about how particular genes determine traits and characteristics will contribute to many activities that are significantly beneficial, they could also lead to more fundamental questions about the nature—and implications—of similarities and differences among individuals and peoples within the human race.

Genetically Modified Organisms

Growing understanding of genetic information and strategies for inserting or modifying genetic material have made possible a range of technologies based on genetically modified organisms (GMOs). Agricultural plants have been engineered to resist herbicides and increase the ease of weed management and to resist the attack of certain insects or other pests.[308] Bacteria, plants, and animals have been engineered to produce proteins and small molecules. Although the power of modern molecular biology techniques have opened up many new options and possibilities in this area, genetic modification of organisms by humans is not new. As recently discovered[309] through

[304] Normile (2004); Anonymous (2004).
[305] Lin, Owen, and Altman (2004).
[306] Fairchild and Bayer (2004).
[307] Anonymous (2004).
[308] Wu and Butz (2004).
[309] Jaenicke-Despres et al. (2003).

analysis of archeological samples, humans have been genetically modifying the crop known today as maize as far back as 6,300 years via traditional plant breeding and selection techniques.

GMOs—particularly food crops—have generated considerable public debate about the benefits and potential risks of the technologies and how those risks and benefits are distributed. Current GMOs have most significantly benefited the industrial world where farmers can afford to buy such premium seeds, which are frequently protected by the companies producing them with both technological and intellectual property protections. In the developing world, where such benefits as the increased production potential of some GMOs might accrue the greatest human benefit, modified seeds are still prohibitively expensive and out of reach for most farmers.[310] The public has shown considerable concern about the potential risks of GMOs and their release into the environment. These concerns include the potential risks of the inserted genes spreading to other plants, potential health risks from the modified plants, and the risk of cross-contamination of unmodified food products with GMOs.

Beyond genetic modification of plant crops, application of biotechnology to animal agriculture also represents a dynamic technology area that will likely continue to advance rapidly over the next 15 years. Animal agriculture in the United States is an important domestic industry, producing meat for both food consumption in the United States and export worldwide. Biotechnological research could enable animal breeders to breed GM animals that can grow at a more rapid pace for faster and increased food production. Other applications of GM animals include use of animal systems to produce pharmaceuticals, replacement organs for humans, and materials such as silk.[311] In the future, animal biotechnology may also be able to modify animals to improve their properties as food sources, such as producing more nutritious milk or milk that contains protein components useful for manufacturing other food products. Because of animals' mobility, these GMOs pose even greater concerns about the spread of modified organisms beyond areas where they are introduced.

Some potential applications of GM animals require broad release in the environment. Current efforts to develop GM insects, including boll worms designed to produce sterile offspring when they interbreed with other worms in the wild to help in pest control[312] or insects modified to help control vectors of human disease, such as mosquitoes,[313] will raise similar questions in the coming years. Such insect systems are specifically designed to do many of the things that have been concerns with respect to crop plants—travel freely and mix and interbreed with unmodified species.

How the deployment of GM organisms evolves over the next 15 years will be significantly affected by the public and regulatory environment. The current opposition to many of these organisms has been influenced by the fact that most GMO systems that have been produced are perceived as largely benefiting producers and biotechnology firms rather than consumers. Plants resistant to herbicides help the farmer, while the consumer is expected to accept the eventual product as equivalent to one produced without the technology. An example of this dynamic can be observed in a recent dispute

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[310] Wu and Butz (2004).
[311] Murray (1999).
[312] Jonietz (2004).
[313] Minkel (2004).

over labeling of milk products. Local farmers wanted to label their milk as produced "without hormones" and were sued by Monsanto over the claim based on the argument that milk produced using recombinant hormones should be viewed as indistinguishable from that produced without.[314] Although the use of biotechnology may lower prices to consumers, the perception that they do not substantially benefit from something they perceive as more risky than "natural" varieties influences their decisionmaking.

These issues have put pressures on a technology area and influenced the development and adoption of specific technologies that could have significant societal benefits. For example, success in modifying disease vectors such as mosquitoes in such a way that they are deemed sufficiently safe for environmental release would make available a method to control several serious global diseases at the source (rather than treating individual patients after they are affected by the diseases).[315] This approach could lead to significant social benefits in areas of the world where such diseases are rampant and where alternative solutions (e.g., the use of some insecticides) have been banned because of their negative effects. Success in modifying animals to provide organs suitable for human transplantation could help alleviate serious organ shortages worldwide, assuming the serious technical, ethical, and safety concerns surrounding xenotransplantation can be addressed.[316]

Changes could also occur that might shift the societal and market context in which these technologies are introduced over the next 15 years. Varieties of GMOs that consumers perceive to their benefit may be introduced, thereby changing the overall risk-benefit assessment among at least some of the technologies' current opponents (e.g., an increasing focus on GMOs that are appropriate to the developing world, in addition to agriculture in industrialized nations). Such shifts could be associated with significant changes in the production of these technologies—away from private-sector models and toward more public-sector or nonprofit involvement.[317] Similarly, assuming that no incidents occur from the use of GM organisms that result in confirmed harms, public acceptance of these technologies may increase as they become more commonplace.

Alternatively, continued controversy about GMOs could shape incentives for different portions of the biotechnology market. The presence of roadblocks to use of such technologies in settings open to the environment could increase focus on "industrial biotechnologies," synthesis of materials by bacteria or other processes "inside" in more isolated circumstances. Such technologies are being applied for a wide range of purposes, including the reduction of economic and social impacts of environmental remediation and natural resource recovery, the reduction of industrial pollution, and the facilitation of more-efficient, cost-effective manufacturing.[318] Industrial biotechnology researchers are seeking, for example, to replace products made from oil with products made by modified bacteria and plants. Among them are fibers to be woven into fabrics, bioplastics, and improving ethanol as a biofuel by genetically engineering enzymes to better process glucose.[319] Industrial biotechnology applications could make resources of materials that

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[314] Roosevelt (2003).
[315] Pew Initiative on Food and Biotechnology (2004).
[316] Kues and Niemann (2004); Cooper (2003).
[317] Wu and Butz (2004).
[318] U.S. Department of Commerce (2003).
[319] Carr (2003).

are now, quite literally, trash. Waste materials and sewage, which have high sugar levels, can be used in productive applications; researchers have found a way to efficiently turn sugars directly into electricity, which vastly increases the efficiency of microbial fuel cells.[320] Moreover, plants can be genetically engineered to more efficiently take up soil pollutants such as heavy metals, for applications such as soil remediation and decontamination.[321] Successful development and adoption of such technologies could result in significant shifts in production in some industries with beneficial effects, in both the industrialized and developing world.

Therapies and Drug Development

The promise of improved therapeutics as a result of advances in biotechnology is currently being realized.[322] Genomic and structural information are providing the basis for the design of new drugs. Similar information on specific disease states provides insights on why particular drugs function differently for particular individuals. For example, structural genomics research has led to better drug design for protein kinases, which are targets for treatment of a number of diseases.[323] Diseases such as cancer, diabetes, and various inflammations are all linked to perturbation of protein kinase-mediated cell signaling pathways; now finding inhibitors of these kinases is aided through a better understanding of genomics.

Although the availability of individual genomic and metabolic information raises the possibility for individualized medicine, the current structure of the pharmaceutical industry and regulatory apparatus may limit full realization of that potential. Development and approval of pharmaceuticals is expensive, and firms seek out "blockbuster" drugs, whose high demand and profit margins can provide returns to the companies. Multiple stakeholders in the drug discovery effort may have conflicting interests. Among them are public and private funders of basic research, academic scientists, multinational pharmaceutical firms, smaller biotech companies, and government regulatory agencies.[324] The regulatory structure in the United States requires significant proof of both safety and efficacy, with the understanding that the costs of the regulatory requirements can be recouped during a drug's patent-protected run of exclusivity. Tax policies, intellectual property rules, and multiple national and international policies further complicate the picture.

Market incentives are not always sufficient for private firms to produce treatments for all diseases. This has produced what have been labeled "orphan drugs"—known treatments for diseases that affect only a few patients but are not broadly manufactured. Additional incentives have been put in place through policy action to encourage companies to develop those pharmaceuticals. Truly individualized medicine would generate many more such "orphans," for which the specifics of individuals' genetic makeup would break down the potential market for a drug into many smaller segments. As a result, without other changes that reduce development costs for pharmaceuticals, truly individualized medicine may not be realized. Less-complete individualization,

[320] Chaudhuri and Lovley (2003).
[321] U.S. Department of Commerce (2003).
[322] Szuromi, Vinson, and Marshall (2004).
[323] Noble, Endicott, and Johnson (2004).
[324] Kennedy (2004).

where specific genetic or other information about a person's condition is used to guide therapy with a few treatment options, matching an ideal dosage or mixture of drugs for their disease, is more likely to occur. Such a model would diverge less from the current industry and regulatory structure.

Some technology trends do suggest ways that development costs for new pharmaceuticals may come down, however. As the body of available genomic and structural information expands, the ability to test and explore lead compounds "in silico" (through computer simulations rather than via more-expensive experiments) should continue to expand and to increase in value.[325] Combination of such techniques with combinatorial and selection-based synthesis strategies—where many compounds are made, tested, and improved simultaneously—could further reduce the time required to identify promising compounds. Other biotechnology-based technologies could provide new ways to test lead drugs for toxic side effects, including model cell-based systems[326] or metabolic pathways assembled on chips in the laboratory.[327] If such advances provide ways to circumvent expensive animal trials of new drugs, they could reduce the costs of bringing such drugs to market. Alternative strategies for modulating the activity of genes within cells, other than traditional small molecule therapeutics, could also change the structure of the industry. RNA interference, a technique that can be used to selectively "turn off" genes within cells, could be such an alternative strategy.[328]

Other trends that could affect the business model within the pharmaceutical industry include shifts in the enforceability and utility of biotechnology intellectual property for protecting exclusive rights to particular treatments or therapies. Considerable effort has been made thus far by firms to patent gene sequences to secure ownership of therapies targeting the gene's product or using that product as a drug itself. Such an approach mimics that taken in traditional pharmaceuticals where patent exclusivity is used to protect marketing of specific drug molecules.[329] To date, considerable controversy has surrounded the appropriateness of such gene patents. Setting that debate aside, however, there may be technological changes that reduce the utility of such patents to protect biotechnology products. As biotechnology expertise becomes more global and more individual firms across the globe gain the expertise needed to make biotech-based products, it is likely that considerable intellectual property piracy will occur, especially of profitable biotech patents. This is similar to the situation that arose for digital recorded media, in which the proliferation of ready copying mechanisms weakened intellectual property protection and continues to hurt the profits of the involved industries.

As the most individualized of medicine, treatment for diseases through gene therapy—the insertion or replacement of a gene in a patient to correct a disease state—was a high-profile initial target of biotechnology research. Fifteen years ago, early trials of gene therapy were starting, but the experience in the intervening period has revealed that the use of the technologies was more difficult than initially believed. Problems in clinical trials that resulted in patient deaths tragically demonstrated the potential risks of the technology, which has resulted in its developing much more slowly than initially

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[325] Jorgensen (2004).
[326] Freedman (2004).
[327] Jung and Stephanopoulos (2004).
[328] Stipp (2003).
[329] See Hemphill (2002); Jackson (2003); and Hilgartner (2002) and the references therein.

expected.[330] Current exploration of the use of stem cells for therapeutic purposes has shown considerable promise for some diseases, but significant technical, ethical, and other hurdles remain to broad utilization.[331] More-advanced and less-controversial technologies—such as immunotherapy, which draws on a patient's own immune cells to treat disease—show significant promise. For example, researchers have now found ways to replicate specific T-cells called tumor-infiltrating lymphocytes (TILs) to treat metastatic melanoma, a type of skin cancer. Advances in technology that allow specific TILs to be isolated, tested, and optimized before use in treatment have contributed to the increase in the technique's effectiveness.[332]

For targeting therapies to the organs or locations that need them, significant progress has been made in the development of drug delivery methods. Some of these methods also take advantage of the specificity of the human immune system. For example, monoclonal antibodies, with drugs or treatment functionalities tethered to them, utilize the specific recognition of the immune system to preferentially bind to a targeted organ or tumor within the body. As well, nanotechnologies have begun to provide new strategies to target therapies based on encasing them in liposomes or nanostructures for later release at the intended site of action.[333]

Increasingly detailed biological information has recently made it possible to identify genes associated with behavioral and emotional traits and with the creation and maintenance of memory. Genes have recently been identified, for example, that are associated with interpersonal relationships or social cohesion[334] and parent-child connections.[335] Other efforts are aimed at development of drugs to strengthen memory or aid in forgetting of painful or damaging memories.[336] Although such advances are encouraging for treating such mental health disorders as depression, understanding how to affect such behaviors may raise concerns about the societal and ethical implications of certain choices. Although development of treatments to address disease states or deficiencies in individuals is generally considered acceptable, there still remains difficulty in determining what constitutes a deficiency and whether use of such treatments for enhancement purposes is or is not acceptable.

Reproductive Biotechnologies

The application of biotechnology in human reproduction has been an area of intense technological activity and intense controversy. Although efforts focused on assisting in human reproduction were undertaken much earlier,[337] the birth of the first baby through in vitro fertilization (IVF) in 1978 is frequently cited as the first major milestone in this technology area. Since its introduction, the use of technology for assisting in human reproduction has gone from controversial to relatively commonplace—with estimates of more than 1 million IVF children alive today worldwide.[338]

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[330] Weiss (2005).
[331] President's Council on Bioethics (2004a); National Bioethics Advisory Commission (1999).
[332] Martindale (2003).
[333] Allen and Cullis (2004).
[334] Balaban (2004).
[335] Beckman (2004).
[336] Marshall (2004); Miller (2004).
[337] See, for example, Genetics and Public Policy Center (2003).
[338] Szabo (2004).

Over the last 15 years, significant advances in the application of other biotechnologies to human reproduction have been introduced. For example, in concert with other assisted reproduction technologies, preimplantation genetic diagnosis—clinically available since 1990—allows genetic testing of embryos for a variety of disorders before implantation.[339] Technologies are now available that allow selection of the sex of a child, with improving success rates.[340] As these technologies have advanced, additional concerns have arisen about the appropriateness of specific types of technological intervention.[341]

In the future, it is likely that continuing advances will bring new potential applications of biotechnologies in human reproduction as well as continue to pose difficult ethical, social, and other questions. Even currently available technologies raise serious questions, depending on the ways they are applied. For example, as increasing amounts of genetic information become available, preimplantation genetic diagnosis could be applied to traits and characteristics beyond identification and avoidance of heritable genetic diseases.[342] In the context of such applications, questions remain about how to draw the line between acceptable and unacceptable selection of offspring traits. While less controversy surrounds testing aimed at preventing the occurrence of genetic disease (compared with testing aimed at selecting other potentially desirable or enhanced traits), uncertainty remains about how exactly "disease" should be defined. Even in cases in which disease states can be clearly identified, use of prenatal diagnosis to identify genes tied to disease *susceptibility* is a more difficult case, particularly when susceptibility may be only part of what is responsible for occurrence of disease or when no treatments for diseases themselves are currently available.[343]

Beyond the reproductive technologies that are currently in use, emerging reproductive technologies raise even more serious questions. The potential use of human cloning—for either reproductive or other purposes—has generated significant debate about the appropriate boundaries of technological intervention in reproduction. Similar questions are clear in the recent debate over research into applications of stem cells for medical purposes and the use of human embryos or products derived from them in research or the clinic. Other potential applications of biotechnology to directly *modify* human traits—enabling parents to more significantly shape the genetic heritage they provide to their children—pose even more serious concerns.[344] Because of the influence of cultural and social context on the perceived benefits, costs, risks, and appropriateness of such technologies, the "answers" reached will likely differ across the world, therefore producing different development and adoption trajectories for these technologies in different nations.

Beyond the technologies themselves, over the next 15 years basic shifts in how reproductive biotechnologies are applied and the societal concerns surrounding them could also guide both their impact and development trajectory. These technologies are

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[339] Robertson (2003).
[340] Human Fertilisation & Embryology Authority (2003).
[341] Reproductive biotechnology issues have been major foci of both the National Bioethics Advisory Commission during the Clinton administration (see http://www.georgetown.edu/research/nrcbl/nbac/) and the current Bush administration's President's Council on Bioethics (see http://www.bioethics.gov).
[342] Robertson (2003).
[343] Holtzman et al. (1997).
[344] See, for example, Silver (1997).

currently expensive—for example, an average cost of $12,400 per cycle of IVF treatment—and, per cycle, have success rates ranging from 20 to 30 percent.[345] The costs of the treatment are frequently not covered by health insurance, therefore limiting access to these technologies to individuals with sufficient resources to pay for them. Significant reductions in costs, greater assumption of these costs by insurers, or increased chances of procedure success could result in shifts in demand for these technologies that would shape development of next-generation techniques. Concerns raised about the potential safety of reproductive technologies on the children conceived via the procedures[346]—should clear linkages between negative outcomes and the procedures be discovered—would presumably have a negative impact on the demand for the techniques.[347]

Because of the serious questions associated with many of the applications of reproductive biotechnologies, there will likely be significant barriers to the introduction and spread of many applications of reproductive biotechnology over the next 15 years. The nature of the pressures those concerns place on different sections of this technology area also make its likely trajectory difficult to project. The use of many technologies that pose fewer ethical and societal dilemmas—such as assisted reproductive technologies, many applications of prenatal diagnosis, and some techniques for gender selection of offspring—are likely to continue to spread as capabilities increase. Based on past experience, technologies whose primary purpose is framed in therapeutic or compensatory ways—preventing disease or providing children to the childless—will gradually be accepted and pass into the mainstream. Other technologies may not. The outcome of various efforts to ban or control some applications (e.g., reproductive cloning) could criminalize some technology applications in some countries.[348]

Biomedical Engineering

In treating human disease, technologies from outside the purely medical sciences have always made important contributions. Advances in imaging technologies described previously are a clear example. As these technological and engineering disciplines continue to advance, the range of their potential application in medicine will likely increase.

One example is the application of robotics within medical practice. Extending current applications in technologically assisted surgery and other techniques, robots and robotic instruments may be used in place of or alongside humans to increase efficiency or to aid in tasks that might otherwise put humans at risk of injury or death. Medical robotics has made significant advances over the past decade. Such robots could function to assist hospital staff, ranging from helping to perform basic functions—allowing staff to rest or, in some instances, completely replacing them—to directly assisting in performing medical procedures. As examples of the latter, robotic systems are being developed to track the tip of surgical instruments to enhance accuracy, as well as to train surgeons.[349] Handheld robots can also sense and compensate for physical tremors and other unwanted

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[345] American Society of Reproductive Medicine (undated).
[346] Similar issues are associated with measuring the success of assisted reproduction technologies more generally (see Braude, 2002).
[347] See, for example, the summary discussion in President's Council on Bioethics (2004b).
[348] See, for example, United Nations (2005).
[349] Hotraphinyo and Riviere (2001).

movement during various kinds of operations, such as eye surgery.[350] Over the next 15 years, continued progress in these technologies could increase use of robotics and robotic-assisted techniques in medicine. To the extent that machines can address some routine activities in medical care, staff workloads could be reduced and human activity devoted to higher payoff caregiving activities.

Significant advances have also been made in the integration of biomedical technologies within the human body—for example, to repair or augment the functioning of the internal systems. Artificial tissues and organs have been an attractive target of researchers to provide alternatives to all-too-scarce transplanted organs. Efforts are under way to develop a range of replacement organs, although the technological hurdles in developing them have proven higher than expected.[351]

Beyond replacement organs such as hearts, lungs, or kidneys, progress has been made on developing more-subtle implants aimed at restoring functions lost to accident or disease. Trials have been undertaken of artificial retinas that interface with retinal cells in damaged eyes[352] and chips directly linked into the brain to allow paralyzed or otherwise disabled patients to interact directly with a computer.[353] Other chips are in development that mimic the activity of parts of the brain that make memories, opening the possibility of implants to restore or augment the functioning of the mind.[354] Other types of implants have also been explored for nonmedical applications—for example, for tracking the location of convicted sex offenders,[355] for use as identification mechanisms,[356] and for parents to keep track of their children.[357] Individuals have also had implants installed in proof-of-concept experiments to demonstrate integration of human and machine functionalities.[358]

Although the majority of implants currently under development are aimed at repairing lost functionality, as their technologies improve they will almost certainly be applied to other purposes as well. A retinal implant originally designed to restore sight to the blind might be applied to allow individuals to monitor and record the events occurring around them. Chips designed to restore lost memory functioning might eventually be applied to augment memory functioning in otherwise normal individuals. As with genetic modification or drug-based modification of human thought, behavior, or capability, the use of such implants will likely raise questions about what exactly it means to be human—that is, understanding where the line falls between unproblematic "correction of deficiency" and where augmentation or modification begins to be considered unacceptable. As with other concerns of risks and benefits regarding these technologies, different conclusions may be reached in different areas.

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[350] Ang, Reviere, and Khosla (2000).
[351] Kirsner (2004).
[352] Ritter (2002).
[353] Pollack (2004); "Brain Chip Lets Monkey Use Mind to Move Cursor" (2002).
[354] Marrian and Tennant (2003).
[355] Bright (2002).
[356] Barkham (2004).
[357] Hopps (2002).
[358] Collins (2004).

Biomimetics and Applied Biological Science

In addition to their applications for informing work on living systems, information and technology developed through biotechnology is enabling applied biological engineering and biomimetic design. Biological ingredients have been used as starting materials for assembling structures and devices at the nanoscale, taking advantage of biological properties to drive the construction. For example, the recognition processes that drive assembly of the double helix of DNA have been used to build intricate DNA structures[359] or to act as templates for other constructions. Similarly, virus particles have been used as a scaffold to synthesize nanowires, taking advantage of biological properties to modify the viruses and control construction.[360]

Likewise, natural structures that have properties or carry out functions of interest have been drawn on as examples for engineering design. Spider dragline silk has long been held up as an example for advanced material development; functional components of natural systems, such as the efficient light-harvesting complexes in plants, have been similarly looked to for examples of how to build more-effective devices to carry out similar functions.

Coming full circle, research efforts in synthetic biology are aimed at taking the biological information and, rather than using it to modify organisms, applying it to the de novo design of novel organisms in the laboratory.[361] Some such design efforts are at the level of individual proteins, designing biologically active molecules to carry out particular reactions.[362] Others design gene circuits, treating biological components like electronic parts to be assembled, as they build up functions.

Although learning from nature and using biological molecules as building blocks within nanodevices raise few difficult questions, synthetic biology—which could eventually produce replicating bacteria that could live and proliferate on their own—does. Like the concerns over the release of GMOs into natural ecosystems, similar concerns will likely be raised over the potential impacts of such organisms if and when they are released. The evolution of this component of biotechnology will therefore be strongly affected by the decisions reached regarding the regulation of biotechnologies.

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[359] Shih, Quispe, and Joyce (2004).
[360] Mao et al. (2004).
[361] Ferber (2004).
[362] Dwyer, Looger, and Hellinga (2004).

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APPENDIX B: NANOTECHNOLOGY TRENDS TO 2020

Eric Landree

Norio Taniguchi introduced the term "nanotechnology" in 1974,[363] and Eric Drexler popularized it in his much-debated book, *Engines of Creation: The Coming Era of Nanotechnology*,[364] which charted a direction for the future of nanotechnology research and development. This publication focused largely on one aspect of nanotechnology, molecular assembly, which could in principle enable manufacturing and production through the bottom-up assembly of consumer goods and products, one atom at a time. This view expanded on the vision of Richard Feynman's famous 1959 lecture at California Institute of Technology, "There's Plenty of Room at the Bottom."[365]

Currently, the U.S. government's National Nanotechnology Initiative uses the following criteria for defining nanotechnology:

1. Research and technology development at the atomic, molecular or macro-molecular 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.[366]

Scientific advances in microscopy and related fields now allow us to routinely observe and manipulate materials on the atomic or molecular scale. Nanotechnology, broadly viewed, has had a profound impact in virtually every scientific discipline in the physical, chemical, and biological sciences. Given the rapid growth of the discipline and the impact nanotechnology has already had in both science and industry, it is difficult to chart exactly where advances in this technology may take us in the next 15 years. Nonetheless, it is possible to look at advances in nanotechnology and areas of scientific advancement and see general trends that may suggest where the future of nanotechnology may lead.

An increasing number of nanotechnology-enabled products have begun to appear in commercial goods. For example, sunscreens are using nanoscale particles to enhance protection from ultraviolet radiation, and nanoscale coatings for glass lenses and textiles are being used to improve wear resistance and in some cases provide added functionality. Other commercial sectors, such as computer-integrated circuits and catalysis for chemical processing, have been using nanotechnology for many years. However, many of the advances frequently discussed in the scientific and popular literature are still only practical in research laboratories or limited to very high-end technologies. It may be

[363] Taniguchi (1974).
[364] Drexler (1986).
[365] Feynman (1961).
[366] National Nanotechnology Initiative (undated).

years, if ever, before many of these scientific discoveries can be transferred into useful consumer goods or services. For example, *Science* published an article in December 1989 describing the design and testing of a nanoscale tunneling diode.[367] While this discovery has contributed to the development of tools (e.g., scanning tunneling microscopes) and electron field emission devices, it has not replaced the semiconductor diode in integrated circuits, as some had predicted.

The transition of new and emerging nano-enabled technologies from the laboratory to commercial products is dependent on numerous factors, including integrating the device into products with characterized and reproducible properties; cost; scaling up the manufacturing or fabrication for commercial production; development of related technologies; market forces; and consumer acceptance of nano-enabled technologies. All of these factors will determine whether nanotechnologies will be able to move from the laboratory to the commercial market.

Nanotechnology-Enabled Sensors

One area in which nanotechnology is uniquely positioned to enable new capabilities is sensor technology. Given that we are now able to construct devices on the size scale of individual molecules, new methods of sensing and detection have enabled unprecedented levels of sensitivity (minimum detection limit) and selectivity (ability to detect specific chemicals or processes), as well as the ability to detect processes or events that were previously undetectable.

Today

There are currently few nanotechnology-enabled sensor technologies in commercial use. One example is Smiths Detection's (formerly Cyrano Sciences Inc.) handheld, trainable detection system that utilizes arrays of nanostructured materials in a polymer-fiber matrix to detect various chemical agents of interest. However, an increasing number of laboratories around the world are beginning to exploit advances in nanotechnology to improve chemical and biological sensor technologies.

This growth has resulted in a family of emerging nanotechnology-enabled products that, while still at various stages of laboratory and field testing, have the potential to significantly reduce the device size, amount of test sample needed, and time required for chemical and biological analyses. These sensor devices are based on various emerging nano-enabled technologies—for example, functionalized metallic nano-particles, functionalized nanowires and nanotubes, macroscopic materials with nanoscale features or surface treatments, and nanostructured mechanical systems. All of these techniques rely on measurable changes in the fundamental properties of the material or material system as a result of interactions that are detectable by virtue of their nanoscale properties.

By 2020 (Potential Technology)

By 2020, several of the nanotechnologies that emerge in the early part of the 21st century will likely have been incorporated into commercial products and applications. New families of sensors that are lower cost and can be more easily integrated into building and infrastructure construction will materialize. Similarly to the use of video cameras for

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[367] Pool (1989).

physical surveillance, chemical and biological sensor technology will begin to be included with other surveillance and communication technologies to improve the detection of possible threats. In some cases, these new sensor systems may be integrated within existing surveillance or communication platforms (e.g., video cameras, motion sensors, telephones). For example, future buildings or structures considered particularly high risk may be built with enhanced surveillance systems that integrate video with chemical and biological detection systems that require limited human intervention. Many of these systems will be designed to monitor for a range of agents of interest and to provide results on the order of minutes. Other potential applications of nanotechnology-enabled sensors include the front end of building systems, vehicle control systems, and home safety equipment such as carbon monoxide and smoke detectors.

Future advances in long-lasting, unattended sensors and sensor platforms will require dramatic improvements in battery power management and capacity, as well as gas and liquid handling for micro-assay systems. For certain high-risk and national security–related functions (e.g., military operations, emergency response), wearable sensors will be commonly available and integrated into a networked communication platform that will be able to indicate whether an individual is being exposed to possible agents and to relay critical information such as location and level of exposure. The next 15 years will also see further incremental improvements in chemical and biological selectivity and sensitivity across all sensor platforms.

Societal Implications and Applications

In most cases, the use of nanotechnology-enabled sensing will be integrated into, or built on, existing surveillance or monitoring systems. Therefore, the scope of surveillance may not be influenced by nanotechnology-enabled sensors but the modalities (or depth) by which one is being scanned or monitored may be enhanced. Networked personal chemical and biological detectors will likely see widespread use only in homeland security and military applications, and particularly by emergency responders. Unless a very significant chemically- or biologically-related disaster occurs, it is unlikely that the general populace will have sufficient incentive to adopt the use of personal chemical and biological detectors. However, evidence suggests that future communications platforms (e.g., cell phones) may have an increasing number of integrated sensor devices.[368]

Nanotechnology-Enabled Power

Improvements in battery performance over the past several decades have not kept track with the rapid advances in electronic or digital technologies (e.g., processing power, data storage capacity). However, recent advances in nanotechnology suggest the potential for improvements not only in overall battery performance but also in an expanded range of materials that may be useful for battery and solar cell applications.

Scientists are actively pursuing nanotechnology and nanocomposites to improve the performance of battery electrodes. Much of the focus of this research is the integration of nanomaterials into conventional battery architectures. For example, scientists at universities such as Rutgers[369] and the Massachusetts Institute of

[368] Bell (2004).
[369] Amatucci et al. (2001).

Technology[370] have been working on nanocomposite electrodes that will improve the energy density and power density of conventional batteries. Industry is also actively participating in this area, trying to leverage new and emerging nanotechnologies to improve the performance of commercially available batteries.

In addition, over the past decade many microelectromechanical (MEMS) devices have been developed and commercialized into numerous applications (for example, airbag deployment systems,[371] sudden motion sensors for electronics that are dropped,[372] and near-infrared spectrometers[373]). MEMS are typically fabricated using semiconductor fabrication techniques (e.g., lithography, etching) that produce devices with individual features and components that are on the order of micrometers (e.g., one-millionth of a meter). More recently, a growing number of nanoelectromechanical systems (NEMS) have been envisioned and developed with the objective of further miniaturization. NEMS are electromechanical devices with features or components on the order of nanometers (e.g., one-billionth of a meter, or one-thousandth of a micron). One of the challenges associated with these emerging devices that have limited their usefulness has been the ability to power them. In many circumstances, the power sources used to enable these devices dwarf the MEMS/NEMS device itself. Consequently, researchers are actively pursuing ways to create nanostructured batteries that will allow on-device or on-chip power sources to enhance the range of applications for these minute devices. For example, university researchers are looking at ways to incorporate nanostructures into batteries to enable fabricating smaller, or three-dimensional, form factors. Many of these nano-enabled technologies are paving the way for battery architectures that were not possible using conventional two-dimensional thin-film battery designs or processes.

Advances in nanotechnology are also beginning to have a significant impact on solar cell technology. Companies such as Konarka Technologies Inc. have begun using dye-coated titanium dioxide nanoparticles to enable flexible, more-versatile solar cell form factors.[374] The nanoparticles allow the photovoltaic cells to be fabricated at lower temperatures that in turn have enabled Konarka to use flexible polymer substrates instead of conventional glass substrates. This has enabled the possibility of integrating solar cells into a wider range of materials (e.g., fabrics, building materials). Other researchers have looked at incorporating nanoparticles into solar cells with the goal of increasing the overall conversion efficiency. For example, researchers at the University of Toronto have used quantum dots (nanoscale semiconductor) particles, to achieve higher overall conversion efficiencies for solar cells with response in the infrared portion of the spectrum (greater than 800-nanometer wavelengths).[375] Konarka has recently formed a joint venture with Evident Technologies to replace organic dyes in its solar cells with quantum dots. The goal is to improve the sensitivity of the solar cells beyond the visible spectrum, thereby harvesting a larger portion of the available spectrum, resulting in greater efficiency.[376]

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[370] Chung, Bloking, and Chiang (2002).
[371] Forman (2005a).
[372] Forman (2005b).
[373] "Ocean Optics to Distribute Polychromix Spectrometers" (2005).
[374] Assisi (2004).
[375] McDonald et al. (2005).
[376] "Konarka and Evident to Develop Ultra High Performance Power Plastic" (2005).

Today

Currently, relatively few commercially available batteries or solar cells utilize nanotechnology-enabled advances. Much of the work on nanocomposite electrodes, nanostructured batteries, and nanomaterials for use in solar cells is done in university laboratories. However, an increasing number of companies are beginning to adopt some of the more recent advances and to release commercial products. For example, Konarka has several grants to produce nanotechnology-enabled flexible solar cells for the U.S. Army to reduce the total amount of weight soldiers must carry to power their equipment. In addition, several companies, including mPhase Technologies, Altair Nanotechnologies Inc., and Toshiba, are developing nanostructured electrodes with the objectives of improving shelf life and increasing battery discharge and recharge rates. Other companies are pursuing federal funding, such as Small Business Innovation Research grants, to work on nano-enabled electrodes and in other related areas.

With respect to power for MEMS/NEMS devices, the technology will require significant research and development before it becomes available for consumer products.

By 2020 (Potential Technology)

Within the next 15 years, many improvements in electrode design and battery architecture will likely have been integrated into commercial batteries. Technologies such as redesigned electrodes that utilize nanocomposites will probably have made significant market penetration, since the technology is compatible with conventional battery designs. It is also likely that three-dimensional battery designs utilizing nanostructures will make significant inroads in commercial products. Three-dimensional battery architectures are not likely to replace cell phone batteries or computer batteries in this time frame. However, there are important market drivers associated with MEMS and NEMS technology that stand to benefit a great deal from this emerging nano-enabled technology. Finally, advances in the use of nanomaterials and nanostructures in solar cell applications will likely provide improved, flexible form factors for solar cells. Recent work in the use of quantum-dot and other nanotechnology-enabled solar cells suggests that advances in nanotechnology may also increase conversion efficiency to the level of, or perhaps beyond, that seen in today’s commercial solar cells. Given improvements in processing solar cells, it is probable that solar cell technologies will be increasingly integrated into other consumer products such as building materials (e.g., roofing material), electronic devices (e.g., cell phone and computer cases), and perhaps even fabrics (e.g., tents and outerwear).

Societal Implications and Applications

Several emerging technology applications have been hampered by the challenges or lack of progress associated with battery and power technologies. Improvements in the area of nano-enabled power have the potential to significantly affect many aspects of how technology influences society. One of the driving forces for improvements in batteries is to enable and improve the performance of battery-powered automobiles and hybrid (gas-electric) automobiles.[377]

Another important potential societal impact involves the use of nanostructured batteries for applications in MEMS and NEMS devices. For many of these devices, the

[377] Altair Nanomaterials, Inc. (2003).

largest component is usually the power source, especially if the power is to be provided on-chip or on-device. In the next 15 years, significant advances in three-dimensional batteries are likely to enable smaller, autonomous sensors and communication devices. Improvements in NEMS and MEMS power sources could enable the potential widespread use of these technologies for smaller autonomous sensor platforms. Consequently, potential societal issues include enabling persistent or increased monitoring, managing the use of such sensors, and associated privacy issues.

Finally, advances enabled by the development of nano-enabled solar cell technology could potentially impact applications of distributed power. Cheaper, more rugged, and flexible solar cells that could be integrated into textiles or building materials could significantly affect the power distribution infrastructure. This technology could considerably benefit developing countries that lack sufficient power distribution capacity. It could also help enable further autonomous devices and applications that could in turn enable more pervasive sensing, raising possible further privacy issues.

Nanotechnology-Enabled Electronics (Integrated Circuits and Processing)

Like sensors, nanotechnology-enabled electronics seem to have the potential for many advances in the coming years. However, the path of integrating new nanoscience discoveries into commercial applications, particularly in the case of integrated circuit and chip design, is extremely challenging. Unlike many other areas in which nanotechnology is only just beginning to play a role, nanotechnology and nanotechnology-related processes have been enabling technologies within integrated processors since the 1990s. However, to continue Moore's Law,[378] new advances in both materials and processes are needed. Today's Pentium 4 processor produced by Intel Corporation already contains transistors that are on the order of 60 nanometers, with individual films that are 1.5 nanometers thick (or approximately the same thickness as 12 individual layers of silicon atoms).[379] Maintaining Moore's Law will require smaller features and even thinner films. However, as these features continue to shrink, fundamental physical and electrical properties change and no longer meet the requirements necessary for integrated circuits to function. The International Technology Roadmap for Semiconductors (ITRS), an annual report that outlines challenges associated with every aspect of the design and fabrication of integrated circuits, has outlined in detail the technological advances necessary to maintain Moore's Law.[380] Intel Corporation introduced the 90-nanometer technology node[381] in 2003. Integrated circuits using technologies developed for the 65-nanometer

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[378] Coined in 1965 by Gordon Moore, future chairman and chief executive of Intel, it stated at the time that the number of transistors packed into an integrated circuit had doubled every year since the technology's inception four years earlier. In 1975, he revised this to every two years, and most people quote 18 months. The trend cannot continue indefinitely with current lithographic techniques, and a limit is seen in 10 to 15 years. However, the baton could be passed to nanoelectronics to continue the trend. See "Nanotechnology Glossary M Through O" (undated).

[379] Thompson et al. (2002).

[380] International Roadmap Committee (2004).

[381] According to the ITRS 2004 edition, a *technology node* is used to define different stages along the road map and refers specifically to the tightest half-pitch metal feature used in dynamic random access memory (DRAM). For example, DRAM half-pitches of 180-, 130-, 90-, 65-, 45-, 32-, and 22-nanometer technology nodes have been used to define different stages along the ITRS.

technology node are scheduled to go into production in 2005.[382] According to the ITRS, there are several difficult challenges both for logic devices (e.g., processing) and memory devices associated with reaching the 45-nanometer technology node, which is expected to be introduced sometime around 2009. Scientists and engineers will need to discover strategies for introducing nonclassical complementary metal oxide semiconductor (CMOS) designs and new dielectric materials into existing manufacturing techniques, while at the same time not dramatically increasing the cost of production per chip. Possible candidate technologies include single-gate non-classical CMOS designs—for example, transport-enhanced field-effect transistors (FETs) that use strained semiconductor layers to enhance electron mobility, ultra-thin-body silicon-on-insulator FETs, and source/drain engineered FETs that are designed to maintain the source and drain resistances relative to the channel resistance. Other candidates include multiple-gate nonclassical CMOS designs. As the name implies, these deigns incorporate multiple gates to help provide better control of the current through the transistor channel. In multiple-gate designs, the electrical current may flow either horizontally, in the plane of the substrate, or vertically, out of the plane, depending on the specific architecture of the FET.

The ITRS report also predicts that beyond the 45-nanometer technology node, scientists and engineers will need to discover methods implementing non-CMOS devices and architectures into CMOS platform technologies. The ITRS suggests that the scaling of CMOS device and process technologies will probably end by the 16-nanometer technology node (7-nanometer channel length) sometime around 2019. Possible candidate technologies mentioned for this time frame include carbon nanotube FETs, one-dimensional semiconductor nanowire FETs, single electron transistor designs that transport current between the source and drain one electron at a time, resonant tunneling diodes, devices based on quantum effects observed in superconducting materials, and quantum cellular automata that process and transmit information through isolated, interacting cells or quantum dots.

However, all of these technologies are at the very early stages of development. Much research is still needed in producing these devices in large quantities and at the extremely tight tolerances required for the semiconductor industry. In addition, while there has been some progress in novel nanotechnologically-enabled innovations in individual devices that may take the semiconductor industry well past the next decade, very little research has been conducted on how to integrate the next-generation transistor (let alone 10^6 of them)[383] into a single computer chip. Furthermore, little research has been performed on architectures using nano-enabled technologies and the potential limitations that may exist for such densities.[384]

In addition, the costs associated with the design and construction of integrated chip fabrication plants (fabs) is extremely expensive. The approximate total building costs for a facility that produces computer chips using 200-millimeter wafers are between

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[382] Singer (2005).

[383] The Intel 8086 integrated chip introduced in 1978 had approximately 29,000 transistors. The Pentium 4 introduced in 2000 had approximately 42,000,000 transistors on one chip. See Altavilla (2002).

[384] Forshaw et al. (2004).

$1.2 and $1.5 billion.[385] The 300-millimeter fabs cost on the order of $3 billion.[386] The larger the wafer, the greater the number of individual chips that can be produced simultaneously. Therefore, by using larger wafers, the industry can reduce costs by taking advantage of economies of scale. However, the cost associated with introducing non-CMOS materials (e.g., carbon nanotubes) or additional fabrication steps, such as those associated with nonclassical CMOS designs, will likely increase overall cost for fabricating individual chips and may increase the total costs for individual fabs.

However, other advances in nanotechnology may allow conventional processors to be fabricated on a greater range of substrates and materials (i.e., polymers).[387] This would enable relatively simple computational devices to be integrated into a wider range of commercial goods, including fabrics for specialized applications and commercial packaging.[388]

In addition to processing power, discoveries in nanotechnology have also contributed to improvements in both memory and storage. Many of the constraints in integrated circuit design also influence the ability to increase memory density or data storage capacity. Scientists and engineers are using nano-enabled technologies to create smaller features, which in turn are enabling higher memory densities and larger overall memory capacity. Academia and industry are also looking to other advances in nanotechnology to enable new methods for data storage and retrieval. For example, IBM is using arrays of atomic force microscopy tips to physically deform a polymer film substrate as a new means of recording data, known as Millipede.[389] Nantero is also currently developing a nonvolatile, radiation-hardened, nano-enabled memory based on carbon nanotubes, called NRAM.[390]

Today

Today's computer processors allow unprecedented levels of computation, data manipulation, and storage. With the exception of a few specialized applications, the capabilities of today's computer systems meet most (if not all) of the needs of the average user. While this is true for individual users, businesses have increased their dependence on increasingly sophisticated computers for a range of applications, including business, finance, and analysis. However, while the number of "traditional" computers per user is not increasing as dramatically as it once was, the number of computing devices per individual is growing rapidly. Smaller specialized computing devices (including cell phones, personal digital assistants, household appliances) enabled by overall increases in computation power and memory are proliferating at a growing rate. As a result, specialized computer chips and processors are beginning to emerge in all manner of commercial products.

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[385] Han and Ong (2001).

[386] 200-millimeter wafers refer to the size of the initial wafer upon which multiple integrated circuits can be produced simultaneously. Using 300-millimeter wafers means that more individual chips can be produced on a single wafer, which improves efficiency and decreases fabrication costs per chip.

[387] Wagner et al. (2004).

[388] Duan et al. (2003).

[389] Lutwyche et al. (2000).

[390] See Nantero's Web site, http://www.nantero.com.

By 2020 (Potential Technology)

By 2020, integrated circuits will have reached the fundamental physical limits of conventional, scalable CMOS circuit design. Semiconductor materials (silicon, germanium, gallium-arsenide) will still be the primary material for almost all integrated circuits. Integrated circuit and device manufacturers will have adopted nonclassical CMOS designs and architectures to achieve the requirements for the 16-nanometer technology node. The economic constraints of designing and building integrated circuit fabrication plants will continue to be significant. Given the already high costs associated with building a fab, chip builders will continue to try to gain efficiencies by optimizing the processes and materials used today. Fabrication plants will look to nonplanar and other nonclassical CMOS designs to maintain Moore's Law out to about 2020. Integrated chips, and consequently computing devices, will likely become more specialized, allowing improved performance without necessarily requiring faster chips. Integrated chip designers will diversify and produce a wider range of specialized processors to maintain market share.

Non-CMOS materials systems and designs (carbon nanotubes, molecular switches, etc.) will appear only in very limited quantities and will likely not be cost-effective for widespread commercial use. Challenges associated with engineering new nanoelectronic chip architectures will also still be a factor, in terms of both cost and overall performance.

However, the ability to manufacture relatively low power and (computationally speaking) simple devices in a range of substrate materials including flexible systems, will mean that computational devices will be increasing embedded in commercial goods. Integrated circuits in items such as packaging materials, clothing, and medical devices will become simpler and more specialized and begin to see more widespread use. Improvements in nanotechnology-enabled power and nanotechnology-enabled advances in memory and data storage devices will also contribute to the proliferation of integrated circuits and electronic devices in all manner of consumer goods. Advances in nontraditional data storage media, such as IBM's Millipede, will allow for usage in a wider range of devices and a wider range of products.

Societal Implications and Applications

By 2020, nanotechnology will likely have enabled integrated devices to become incorporated into a wider range of commercial goods and products. Items such as clothing will incorporate simple computing devices, for example, for monitoring an individual's vitals for medical or other specialized applications. Integrated devices will allow increased functionality in current radio frequency identification (RFID) chips that will further improve logistics and supply chain management functions. However, the improved RFID[391] will still be a relatively simple device and, therefore, will not pose a significantly greater risk to personal privacy than is already posed by the increasing use of RFID technology. The expanding use of RFID technology may outpace the ability to collect and manage all of the potential information available beyond that of dedicated functions such as inventory monitoring. Nonetheless, it is likely that by 2020, individuals will have an increasing number of personalized automated devices (cell phones, digital

[391] *Improved RFID* refers to the concept of a conventional RFID chip with improved sensing and computational power enabled by nanotechnology.

cameras, personal authentication devices for accessing and managing financial or medical records or for personal identification, etc). In 2020, managing the information from these specialized integrated devices will resemble today's attempts to manage the glut of information on the Internet.

Advances in Nanobiotechnology

Advances in nanotechnology-enabled sensors will have a large impact in the area of nanobiotechnology. Many of the advances in sensing biological systems (e.g., proteins and micro-organisms) and biomolecular phenomena (e.g., DNA identification and biological process) are enabled by improvements in nanoscale sensing. The sensors we are beginning to construct are on the order of biological processes one is interested in investigating, enabling new tests and experiments that were previously difficult, time consuming, or nonexistent.

Research in nanobiotechnology not only has the potential to improve biological detection methods but also other aspects of biology, including drug discovery, drug delivery, surgical methods, biocompatibility, diagnosis, implants, and even prosthetics.

Other active areas of nanobiotechnology research include spectroscopic tools for characterizing biological processes, biomimetic artificial nanostructures, materials for biomolecular sorting and sensing, and functionalized nanostructures for controlled drug delivery.

Research into nanobiotechnology is also resulting in the emergence of a new field of computation, by contributing to the design of DNA and molecular-based computers. These computational devices, whose computational power is derived from the ability to explore a very large number of combinations of molecules in a relatively short time, are potentially a very powerful tool for investigating certain classes of mathematical problems.

Today

Currently, most DNA detection techniques, though highly automated, are wet chemistry techniques and require replication of the DNA strands for conventional detection methods via polymerase chain reaction or other genetic material amplification methods. This still requires a degree of human interaction for sample preparation. Other molecular biology detection methods are wet chemistry based, also requiring cultures or other methods of replicating the specimen or sample to achieve some minimum detection limit.

Many implants or other materials entered into the body are selected to minimize the chance of being rejected. Currently, nanobiotechnology research is discovering new ways to improve the way that foreign materials can be entered into the body without being rejected. For example, scientists have shown that helical rosette nanotube-coated titanium used for orthopedic implants demonstrates enhanced cell adhesion when compared with uncoated titanium. Helical rosette nanotubes are constructed from organic materials that stack up to form a nanotube with a hollow core about 1 nanometer in diameter.[392]

Currently, nanostructured materials and some biologically functionalized nanostructures are finding potential applications in chemical engineering. For example,

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[392] Chun et al. (2004).

scientists have developed biologically functionalized nanoparticles for use in DNA[393] and protein[394] detection. Nanomaterials and functionalized nanostructures are also enabling applications in such areas as microfluidics and "lab-on-a-chip" devices that integrate an entire chemistry lab on a small substrate and are beginning to migrate from the laboratory to commercial products.

By 2020 (Potential Technology)

By 2020, several advances will have been made that would allow for faster, more accurate testing and detection of biological specimens. Improvements in sensor technology will allow devices that are portable and would be able to do some types of biological detection in the field with minimal human interaction.

Research into nanostructured materials and coatings could result in improvements in prosthetics that provide increased surface area and biocompatibility for bone growth and that reduce rejection. In many ways, the body's ability to tolerate, or even accept, foreign materials and devices will be enhanced by improvements in nanobiotechnology. Scientists and doctors will be able to tailor the surface structure of medical devices at the nanoscale to improve acceptance and facilitate desirable biological processes (e.g., bone growth) while inhibiting undesirable processes (e.g., infection).

As mentioned above, improvements in nanotechnology-enabled sensing, nanotechnology-enabled integrated circuits and electronic devices, and nanotechnology-enabled power will enable improved passive and active biological surveillance and patient monitoring. Some of these nanobiotechnology devices will find applications for monitoring patients; others may find applications for monitoring the health and well-being of military personnel and emergency responders.

While improvements in the use of nanostructured materials in drug delivery will continue, some of this work, and the acceptance of these applications, will depend on other research on the interaction of nanomaterials with the body and the environment.

Societal Implications and Applications

As noted above, one possible breakout area for nanotechnology by 2020 involves nanobiotechnology-enabled sensing. Another emerging application is the constant monitoring of individuals. It is likely that, by 2020, segments of the population will undergo some degree of monitoring for health, safety, or security reasons.[395] It is likely that incremental advances in nanotechnology that affect sensors, computation devices, and biotechnology will allow this type of enhanced sensing. However, given concerns regarding privacy, it is likely that this type of technology will be self-limited to a rather small segment of the overall population.

A recent report by the Royal Society and the Royal Academy of Engineering of the United Kingdom suggests that it may become increasingly important to consider the life cycle assessment, also known as cradle-to-grave analysis, for products containing nanomaterials.[396] The use of nanotechnology and nanomaterials in commercial products is expected to grow for the foreseeable future. Consequently, humans and the environment will be increasingly exposed to manufactured nanostructured materials.

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[393] Park, Taton, and Mirkin (2002).
[394] Nam, Thaxton, and Mirkin (2003).
[395] "Mexico Attorney General Gets Microchip Implant" (2004).
[396] Royal Academy of Engineering (2004).

Compared with the number of scientific papers and patents that discuss new discoveries in the area of nanotechnology, a relatively few but a growing number of papers look at the potential health and environmental impacts associated with nanotechnology. One of the recommendations made by the Royal Society and the Royal Academy of Engineering's report is that life cycle assessment should be taken into account for existing and expected nanotechnology developments, so that the benefits of nanotechnology are not outweighed by increased resource consumption during manufacturing, recovery, or disposal. Concerns over possible health or environmental consequences associated with nanotechnology, or the lack of information about the possible life cycle costs, may hamper the adoption of nanotechnology-enabled products.

Other articles have also suggested that some aspects of society's adoption of new technology depend on whether the technology is an artificial device (e.g., implants) versus augmentation of the body's own biological processes (e.g., stem cell research). Cases in which implants may be considered acceptable are those in which the situation is considered life threatening or if there is no other option.[397] Consequently, the social acceptability of some nanobiotechnologies might depend on whether they are widely regarded as organic or artificial.

Nanotechnology Manufacturing (Molecular Assembly)

Scientists have long sought the ability to recreate the manufacturing power of nature in the laboratory—that is, the ability to create something from the "bottom-up," one atom at a time. Conventional manufacturing of many nanotechnology-enabled products (e.g., computer chips, MEMS devices) starts with a macroscopic amount of material from which small amounts of material are removed through cutting, etching, or grinding to produce nanoscale components, referred to as "top-down" manufacturing. "Bottom-up" manufacturing, also referred to as molecular manufacturing or molecular assembly, may be considered one of the "holy grails" of nanotechnology. In 1989, it was also perhaps one of the most frightening aspects of the emerging nanotechnology area. Eric Drexler coined the term "grey goo" to refer to self-replicating nanoscale machines that he claimed could potentially replicate uncontrollably. In the June 2004 issue of *Nature*, Drexler expressed his regret over using the term "grey goo" and has dismissed such concerns, suggesting that the current perception of the risk of such an outcome is actually beginning to interfere with the work of nanotechnology researchers.[398]

Nonetheless, molecular manufacturing and nanoscale self-assembly are active areas of academic research, including using DNA and other biological systems for organizing nanostructures and harnessing the inherent properties of materials to create desired three-dimensional structures. In addition, the pursuit of nano-enabled manufacturing is not limited to academia. Large corporations,[399] as well as a few small start-ups (e.g., Zyvex Corporation),[400] are actively pursuing or investing in molecular manufacturing methods for possible future commercial applications.

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[397] Cavuoto (2004).
[398] Giles (2004).
[399] "Getting Molecules to Do the Work" (2004).
[400] See Zyvex's Web site, http://www.zyvex.com.

Much of the research that does exist is at the preliminary stages. But researchers have successfully created biological motors and small molecular memories using molecular manufacturing techniques.

Today

Much of the work currently being done in the area of molecular manufacturing is still considered fundamental science. However, in the area of film deposition and growth, researchers have used materials properties to pattern periodic islands and other nanoscale structures.

The growth and manufacturing of raw nanostructured materials, such as carbon nanotubes, nanoparticles, and more complex nanostructures, is a growing area for both academia and industry. More companies are beginning to develop and market nanostructured materials. However, researchers and engineers are still trying to improve the reproducibility and quality of individual nanostructured materials while scaling up manufacturing to increase the overall yield.

By 2020 (Potential Technology)

By 2020, significant progress in the manufacturing of more-complex structures or components for devices via molecular manufacturing will begin to emerge from the laboratory. However, given the challenges associated with this field, it is highly unlikely that molecularly manufactured devices with complex functionality will become commercially available during this time frame.

Further incremental advances in other forms of nanostructure fabrication and functionalized nanostructures will continue throughout this period, as will the market for these materials as new properties are discovered. However, nanoscale devices with higher-level functionality constructed solely through the use of molecular manufacturing techniques will not have significant impact.

One area that may see growth in the 2020 time frame is combining molecular manufacturing with more conventional “top-down” manufacturing. Areas in which this may be significant would include integrating functionalized nanostructures into conventional devices such as semiconductor integrated circuits or the development of new composite materials and devices with improved functionality. Current examples of this include carbon nanotubes added to paint to reduce static charge buildup, as well as functionalized nanostructures as coatings to lenses or textiles to provide wear resistance or hydrophobic properties.

It is likely that nanostructured materials, as new properties emerge, will increasingly be added to macroscopic devices and components to enable increased functionality or improved properties.

Societal Implications and Applications

Within the next 15 years, it is unlikely that finished commercial products will be fabricated using molecular manufacturing methods. However, the marriage of “bottom-up” manufacturing with more-traditional “top-down” manufacturing will enable more nano-enabled products to enter the market. However, as was mentioned for nanobiotechnology, public concerns over possible health or environmental consequences of increasing exposure to nanomaterials may limit their acceptance by consumers. The lack of evidence regarding the possible effects may result in potential barriers (both regulatory and societal) to the use of nanostructured materials in manufacturing.

APPENDIX C: MATERIALS SCIENCE AND ENGINEERING TRENDS TO 2020

David R. Howell and Richard Silberglitt

Seventeen years ago, a landmark study of materials science and engineering documented the scientific breadth of this field, as well as its application to diverse industries such as energy, chemicals, telecommunications, aerospace, and biomedicine, and recommended an increased emphasis on materials synthesis and processing (and its effects on performance) and on computer-based analysis and modeling.[401] The intervening years have seen tremendous growth in the interdisciplinary nature of materials research, the sophistication with which modeling and simulation is applied to materials design and analysis, and the capability to control materials synthesis and processing. The emergence and development of tools to observe, characterize, and manipulate materials at the atomic and molecular levels have fueled a substantial portion of this growth and continue to enable new materials research and development options.[402]

Materials science and engineering today encompasses active research on nanomaterials (i.e., materials with a component or dimension approaching 100 nanometers[403]) and biomaterials, as well as combinations of the two. Examples of applications enabled by the integration of research in traditional materials fields (such as metallurgy, ceramics, polymers, and solid state physics and chemistry) with developments in nanomaterials and biomaterials, include nanoparticle metals for high-energy propellants and fuel cells,[404] tooth repair via in situ growth of nanocrystalline enamel,[405] degradable polymeric microchips for time-release drug delivery,[406] and highly selective and sensitive miniature chemical sensors.[407]

Over the next 15 years, one can reasonably expect that the trend will continue toward increasingly sophisticated materials designed at the atomic and molecular scale to function in diverse environments, even inside living organisms. Application needs will continue to drive materials developments, while fundamental materials research provides new options for multifunctionality (e.g., conducting polymers, nanostructured coatings and thin films, bio-based composites, structures with controlled pore sizes and interfaces). The following paragraphs briefly review current trends in several materials research areas of application interest and identify materials-enabled technology applications that may become feasible by 2020.

[401] National Research Council (1989).
[402] See, for example, reports of the National Nanotechnology Initiative at http://www.nano.gov and the discussion of the development and use of nanoscale materials in National Research Council (2002), Chapter 1, pp. 4–10.
[403] A nanometer is one-billionth of a meter, roughly ten times the atomic length scale.
[404] See, for example, QuantumSphere’s Web site, http://www.qsinano.com.
[405] Yamagishi et al. (2005).
[406] Grayson et al. (2003).
[407] Novak et al. (2003).

Smart Materials: Environmental Sensing and Responsive Actuation

Materials science has evolved from study of inert building materials to designing functional materials with a specific suite of properties. Smart materials are materials with the ability to sense characteristics of their ambient environment and respond to cues from those characteristics. The need for materials that can sense and respond to environmental stimuli inspired the development of a wide variety of smart materials. Here we will discuss piezoelectric materials, magnetostrictive materials, and shape-memory materials.

Piezoelectric Materials

Piezoelectric materials produce a voltage when compressed or distorted. The converse reaction also occurs: Piezoelectric materials produce small movements in response to an applied voltage. Pierre and Jacques Curie discovered the piezoelectric phenomenon in 1880, termed "piezo" (Greek for "push"). Its stable mechanical oscillation combined with its piezoelectric properties makes quartz ideal for use in watches. Piezoelectric materials were for some time kept largely in the laboratory. Eventually, applications such as ultrasonic transducers, microphones, speakers, and accelerometers made use of piezoelectric materials properties. In recent decades, the number of piezoelectric applications hitting the marketplace has increased markedly. For example, ink-jet printers use piezoelectric materials on the print head to achieve greater precision and resolution for photographic printing applications.[408] Piezoelectric materials have also proven useful in countering vibrations to improve the performance of sporting equipment such as tennis rackets and skis.[409] Scientists have found similar applications for piezoelectric materials in baseball bats and mountain bike shocks.[410] The military has also pursued use of piezoelectric materials to extend the service life and reduce maintenance requirements for tail and wind components of fighter jets.[411] Piezoelectric materials have also been developed to improve sensors to study meteorology and improve remote sensing capabilities.[412] Advances in developing new piezoelectric materials from cellular polymers have opened the door for a variety of new or improved applications because of the ability of these materials to conform to almost any size or shape.[413] Researchers have built on the capability of piezoelectric materials, to convert electric stimuli into mechanical reactions to develop smart artificial muscles that are stronger than natural human muscles.[414] Concerns about toxicity of lead zirconium titanate (PZT), one of the most widely used piezoelectric materials, inspired the recent development of alternative lead-free piezoelectric materials that have equally good properties.[415]

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[408] "Ink-Jet Printer Utilizes Unique Drop-on-Demand Approach" (2000); "New Piezo-Type Printer Offers Wide Format, High Resolution" (2000).
[409] "At the Moment" (2003).
[410] Bogue (1998).
[411] Bogue (1998).
[412] Förster (2004).
[413] Bauer, Gerhard-Multhaupt, and Sessler (2004).
[414] Livage (2003).
[415] Cross (2004); Saito et al. (2004); Tani (2004).

Magnetostrictive Materials

Magnetostrictive materials are characterized by slight changes in size under the application of a magnetic field. The converse reaction also occurs; changes in size or shape of magnetostrictive materials generate changes to the surrounding magnetic field (called the Villari effect).[416] James Joule first discovered magnetostriction in 1842. The most common materials with magnetostrictive properties are nickel, iron, and cobalt. A magnetostrictive material, Terfenol-D, developed by the Naval Ordinance Laboratory (now called the Naval Surface Weapons Center), is being used in applications such as smaller sonar arrays and acoustically driven oil production. Terfenol-D also turned store windows into two-sided speakers for an enhanced audio experience in stores on Fifth Avenue in Manhattan. Researchers are developing new applications for this material in the food, pharmaceuticals, cosmetics, and energy industries.[417] Another application for magnetostrictive materials is in power-steering systems: A torque sensor system driven by a magnetostrictive component promises to provide a lightweight alternative to current hydraulic power-steering systems.[418]

Shape-Memory Materials

Shape-memory materials have the unique capability of restoring their initial physical shape after undergoing deformations. Shape-memory alloys can be bent and twisted into any orientation and subsequently heated to a threshold temperature to recover their original shape. These materials were first discovered in the 1930s. Today, they have been implemented in everyday applications such as eyeglass frames that are resistant to bending. Shape-memory alloys are being increasingly used in medical applications. Cardiovascular devices, such as the Simon filter, are being used to control flow through blood vessels to avoid pulmonary embolism in some patients.[419] Shape-memory devices have been used in orthopedic applications, such as shape-memory staples that compress broken bone components for accelerated recovery.[420] Shape-memory alloys have also been useful in developing surgical tools that are less invasive. These tools can be inserted into the body in a compact shape and then heated to restore their original shape to perform the intended procedure at a target location. Such techniques have been used to remove kidney, bladder, and bile duct stones.[421] Light-induced shape-memory polymers are being developed to enable shape recovery at ambient temperatures.[422] Many research efforts are under way to develop further applications for shape-memory materials. A group at Tohoku University is working on an implantable memory-alloy device to act as an artificial anal sphincter.[423] Continued advances in the development of shape-memory polymers promise to enable a myriad of noninvasive surgical techniques.[424] Shape-

[416] Nyce (2000).
[417] Dudley (2004).
[418] "Technology Could Be Lightweight Alternative to Hydraulic Power-Steering Systems" (2000). "A Magnetostrictive Torque Sensor" (2004); "Auto Sensor Make of Cobalt-Ferrite, Nickel, and Silver" (2000).
[419] Machado and Savi (2003).
[420] Machado and Savi (2003).
[421] Machado and Savi (2003).
[422] Lendlein et al. (2005).
[423] "Tohoku University" (2004).
[424] Langer and Tirrell (2004); Lendlein, Schmidt, and Langer (2001).

memory polymers can also be used to produce fabrics that are wrinkle-free.[425] The National Aeronautics and Space Administration (NASA) has supported research on noise-reduction applications for aircraft.[426] Shape-memory actuators have been developed as a durable, lightweight alternative to cable actuators or electromagnetic motors for door locks.[427] Shape-memory materials are also being considered for use as an intelligent fastener system, potentially eliminating the need for screwdrivers, wrenches, and rivet guns in high-end fastener applications.[428]

2020 Foresight for Smart Materials

By 2020, smart materials will be seamlessly incorporated into many aspects of everyday life. Smart materials will be used to construct structures that adjust materials properties to improve performance based on the conditions in the ambient environment. Examples include self-healing concrete structures for use in applications that require sustained performance over a long service life[429] and self-cleaning concretes that maintain aesthetic appearance and reduce airborne pollutants.[430] Such applications have the potential to drastically improve living conditions in poor communities around the globe, if they can be employed in a cost-effective manner. Applications for reactive materials are likely to be found for monitoring and surveillance of hazardous environments. There will be a continued growth of niche products that capitalize on desirable properties of smart materials (e.g., dampening unwanted vibrations). One of the most promising areas for smart materials is in medical applications. Smart materials will continue to decrease the invasiveness of current procedures. In addition, smart materials will provide new avenues to monitor and mimic biological processes.

Biomaterials: Integration of Inorganic and Biological Materials

Tissue Engineering

Tissue engineering, one of the most promising areas of biomaterials development, represents a multidisciplinary approach that combines materials and life sciences to create man-made tissues or organs. Support for tissue growth begins with core materials that act as a scaffold for growth of host cells. A variety of natural and synthetic polymers have been used as scaffolds. Natural polymers face the challenges of limited mechanical properties, degradation over time, and potential infection, or rejection by the body. While synthetic polymers offer greater versatility in mechanical and chemical properties, they face issues of biocompatibility. More recently, hydrogels have been used as scaffolds in tissue engineering. Hydrogels have fewer issues with biocompatibility, and their mechanical properties more closely mimic those of human tissue. In addition, hydrogels can be easier to administer because they can be injected as a liquid that will turn into a gel. Host cells must be provided to instigate the growth of tissue cells on the scaffold.

[425] "HK Scientists Invent Shape Memory Fabric" (2004).
[426] "Reshaping Noise Reduction on Aircraft" (2005).
[427] Ciferri (2004).
[428] Ogando (2003); "Design Engineering" (2004).
[429] Vernet (2004).
[430] Cassar (2004).

The specific application will determine the potential types of host cells that may be used. A recent review of tissue engineering suggests a wide variety of potential applications.[431]

One application area for tissue engineering that has received a lot of attention from researchers is developing methods to generate heart tissue. Survivors of a heart attack develop scarring on their heart tissue. Because damaged heart tissue cannot regenerate, survivors can experience a gradual degradation of the heart tissue, which can cause heart failure. One group has performed tests on rats and pigs using hydrogels as a scaffold for host cells to generate new heart tissue over the scarred area.[432] Achieving vascularization (i.e., rapid generation of blood vessels in the new tissue) is critical to the survival of host cells. Because human heart cells do not regenerate, host cells are taken from other tissue (e.g., bone marrow or muscle). Researchers might be ready to perform tests on humans in the next few years. However, it could take on the order of 15 years to achieve requisite goals.[433]

Bone Growth and Repair

Significant progress has been made over the past three decades in using bioactive glass to stimulate bone growth. Initially, the general consensus had been that no biocompatible material existed for bone growth applications. In 1969, a team of researchers led by Larry Hench (then at the University of Florida) developed a material that consisted of a series of soda lime phosphosilicate glasses, which did not cause scarring of tissue when implanted in mammal bones. 45S5 Bioglass was approved by the Food and Drug Administration in 1985 and has since been used in thousands of patients.[434] Further progress in the development of bioactive glasses for bone growth promises to improve treatment of specific bone ailments. Gene-activating glasses might be used in scaffolds for tissue engineering applications. Bioactive glass has also been used to provide a foundation for prosthetic teeth. However, development of such materials can take a long time because glass production facilities for this application must meet the hygienic standards of pharmaceutical facilities.[435]

Novel Blood Substitute Polymer

Northfield Laboratories, in Evanston, Illinois, has developed a novel material called PolyHeme.[436] Researchers extract hemoglobin from red blood cells and subsequently purify and chemically modify it to create a polymerized form of the hemoglobin. The oxygen-carrying polymerized form of hemoglobin can be used as a substitute for traditional stocks of blood when they are not available for transfusion. If such products continue to perform well, they could drastically improve medical care effectiveness during military operations and crisis response. PolyHeme has already been used in clinical trials, and further trials are planned to expand its use.[437]

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[431] Lavik and Langer (2004).
[432] Cohen and Leor (2004).
[433] Cohen and Leor (2004).
[434] Hench (2003).
[435] Karlsson (2004).
[436] For additional information, see Northfield Laboratories, Inc. (undated).
[437] Moore, McKinley, and Moore (2004); Guthrie (2004); Cothren et al. (2002).

Supramolecular Biomaterials

There is a class of supramolecular biomaterials—assemblies of biological molecules built up through molecular, noncovalent forces—that can be important for applications outside living organisms. One promising example is light-harvesting dendrimers. Dendrimers are polymerized macromolecules that grow in a sprawling, highly ordered branch-like pattern around a central core. Dendritic macromolecules display photonic energy collection and transfer properties similar to natural chromophoric photosynthetic systems. So-called light-harvesting dendrimers offer considerable potential for collection of solar energy if sufficient efficiency levels can be achieved.[438]

2020 Foresight for Biomaterials

The field of tissue engineering is likely to experience considerable advancement by 2020. However, successful applications for human health care are likely to be limited to a handful of tissue and organ repairs. Challenges confronting biomaterials development include targeting drug-carrying materials to specific cells, designing materials that can sense biological signals, and achieving biocompatibility of materials.[439] A select class of materials will be successfully designed that surmount these challenges over the next 15 years. Control of genes might be achieved through advances in bioactive glass for bone growth and tissue engineering, allowing for preventive treatment of bone degradation.[440] Blood substitutes are likely to be widely used in emergency medical care by 2020.

Nanomaterials: Tailored Functional Materials

Bionanomaterials

Functionalized nanomaterials are being used to enhance materials properties. Nano-meshes of polymers have been employed in tissue engineering for their anti-adhesive properties. Anti-adhesive nanofiber membranes prevent the body's tissues from sticking together, promoting faster healing and preventing scarring. In addition, these materials biodegrade over time, so they do not remain in the body and do not need to be removed.[441]

Nanotechnologies have made significant contributions to the development of targeted drug delivery systems. Nanoengineered materials can be functionalized to release drugs when the drug vehicle reaches a particular location in the body. This can reduce unwanted side effects of drugs interacting with nontargeted tissues and can also reduce the volume of drugs required to accomplish goals.[442] One of the most daunting challenges is tailoring the drug delivery system to release the active drugs at the appropriate rates.[443] Drug delivery vehicles that target only cancerous cells are being employed to more effectively treat cancer patients.[444] Targeted nanosystems have also been used in imaging applications. Polymer-encapsulated and bioconjugated quantum dot

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[438] Adronov and Fréchet (2000).
[439] Langer and Tirrell (2004).
[440] Hench (2003).
[441] Mason (2002).
[442] Allen and Cullis (2004).
[443] Sinha et al. (2004).
[444] Kane (2001).

probes have been used to target and image cancer cells inside living animals.[445] These techniques offer improved imaging capabilities over a longer time period through less-invasive means than conventional approaches. Detection of single viruses using a nanowire device has also been achieved.[446]

Nanocomposites and Functional Nanostructures

Composite polymer materials have been developed that incorporate functionalized nanoparticles. As nanoscale fractures develop in the material over its service life, nanoparticles are drawn to the fractured regions, thus patching the fracture. Such materials have the potential for a wide variety of applications such as optical communications, display technologies, and biomedical engineering.[447] Self-healing pavements, which contain an encapsulated healing agent and a catalytic chemical trigger, are being developed for road construction. When a crack begins to form, the catalyst is activated, instigating the release of the healing agent.[448] In sports applications, Wilson Sporting Goods, for example, has marketed tennis balls with a nanocomposite coating that retains inner pressure longer, as well as composite tennis rackets with improved strength and stiffness resulting from nanoscale particles that fill voids in the material.[449]

Nanocomposites have been developed for military use. InMat Inc. developed an oil- and flame-resistant coating for soldiers' gloves. Traditional gear used by the Army requires soldiers to wear a second layer of gloves to provide protection from fire. The nanocomposite coating allows the Army to achieve its safety goals without sacrificing dexterity of the soldier.[450] Nanoshells show promise for development of biological or chemical sensors.[451] Nanomaterials are also being explored for applications on military aircraft. Canopies on aircraft must be able to withstand debris crashing into them at high velocities. The goal is to develop a nanocoating capable of dispersing an electrostatic charge that tends to accumulate and anchor debris on the canopy.[452]

Filters and Catalysts: Tailored Surfaces and Pores

Nanotechnologies have raised the potential for development of filters that could improve capabilities to provide clean water to developing regions of the world.[453] Membranes created from nanofibers have the ability to filter out bacteria and viruses from water. Several companies already have nanofilters on the market, including space, industrial, residential, and recreational applications.[454] Nanofiltration of water may also provide a more efficient method of desalinization.[455]

Metal powders exhibit much stronger catalytic properties when ground down to the nanoscale. Nano-powder nickel is being pursued for application in fuel cells. If

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[445] Gao et al. (2004).
[446] Patolsky et al. (2004).
[447] Lee, Baxton, and Balazs (2004).
[448] Kuennen (2004).
[449] Cronin (2004); Paull (2003).
[450] Stuart (2004b).
[451] Jackson and Halas (2004); "Study Shows Nanoshells Ideal as Chemical Nanosensors" (2005).
[452] Stuart (2004a).
[453] Srivastava et al. (2004).
[454] "U.S.-Russian Nano-Filter Enter Space Technology Hall of Fame" (2005); Bradbury (2004).
[455] Choi (2005).

successful, use of nickel in place of the current platinum catalyst could cut costs by one quarter.[456]

2020 Foresight for Nanomaterials

Medical applications represent one of the most promising areas for employment of nanomaterials. Advances in nanomaterials are likely to enable widespread applications in tissue engineering, drug delivery, imaging, and noninvasive surgery techniques.[457] By 2020, smart drug delivery systems are likely to be in use for treatment of conditions such as diabetes.[458] Nanomaterials will be used in everyday items such as clothing by 2020. Nanofibers have enabled development of textiles that are water-, wrinkle-, and stain-resistant.[459] Functional textiles are also likely to be widely used in military and emergency response applications to increase safety of individuals. Nanomaterials are likely to enable development of functional building materials such as self-healing and self-cleaning concretes. Nanofilters are likely to be employed in developing regions of the world to provide potable water by 2020.

Fibers, Fabrics, and Textiles: Multifunctional Capabilities

Advances in materials science have enabled development of fabrics that do more than provide the traditional protection from the ambient environment. Multifunctional fabrics that can sense and respond to their surroundings are being developed for a range of homeland security and military applications. Selectively permeable materials are being used to develop protective gear that prevents transfer of hazardous substances while allowing transfer of moisture. New membranes hold promise for the development of self-decontaminating fabrics for chemical and biological environments. Conductive fabrics are being developed as early-warning systems for military and emergency personnel.[460]

Electronic systems are being integrated into textiles by weaving carbon nanotubes into fibers.[461] At Georgia Tech, the Smart Shirt is being developed as a garment that can collect and transmit medical data of the wearer. The Smart Shirt could be used to monitor the medical status of patients or soldiers in battle.[462] Electronic textiles are also being developed for recreational uses (e.g., a ski jacket with MP3 player controls embedded in the fabric).[463]

A myriad of other functional fabrics have been developed. A titanium dioxide coating for cotton that is triggered by sunlight may enable production of self-cleaning textiles.[464] New stain-resistant fabrics are already on the market that do not alter the texture of the fabrics as traditional stain-resistant methods did.[465] Fabrics are also being developed that will adjust properties in response to biological signals from the wearer and the environment. For example, one fabric being developed is modeled after pinecones.

[456] "Nano-Nickel Catalysts" (2005).
[457] Ben-Nissan (2004).
[458] Langer and Tirrell (2004).
[459] See, for example, Nano-Tex's Web site, http://www.nano-tex.com.
[460] Schreuder-Gibson et al. (2003); Schreuder-Gibson and Lynn (2003).
[461] Dalton et al. (2003); Li, Kinloch, and Windle (2004).
[462] Park and Jayaraman (2003).
[463] Service (2003).
[464] Daoud and Xin (2004); Peplow (2004a).
[465] Johnson (2004b); "Nanotech in Fashion" (2004).

The fabric senses the wearer and the ambient environment, and changes the level of airflow through the garment to keep the wearer at a more ideal temperature.[466]

2020 Foresight for Fibers, Fabrics, and Textiles

By 2020, smart fabrics may enable development of protective gear for military, emergency, and industrial workers that can act not only as a selective barrier to potentially hazardous environments but also as an early-warning system. Further developments of functional fabrics may provide immediate initial treatment for exposure to harmful substances. Electronic textiles are likely to be used in select applications to monitor health signals of at-risk patients. The military is likely to incorporate health-monitoring capabilities in fabrics.

Organic Electronics: Flexible Conductors

A new class of solar cells has emerged that rely on nanocrystalline materials and conducting polymer films. The conversion efficiency of these materials has increased recently, and their physical flexibility makes them available for a wide range of applications.[467] These flexible solar cells are being developed for use in cell phones, laptop computers, and military applications.[468] The current state of production and commercialization of organic electronics, including solid state lighting and light-emitting displays, has been reviewed in a recent focus section of the *Journal of Materials Research*.[469]

2020 Foresight for Organic Electronics

The flexibility of organic electronics will continue to be a key driver of their development. By 2020, organic electronics should provide for increased brightness of widespread lighting systems and displays. Organic solar cells are likely to achieve conversion efficiency levels sufficient for use in select applications such as mobile electronics. Depending on the achievement of manufacturing cost and efficiency targets, organic solar cells could also provide power for rural development and could see widespread use by the military as an energy source for operations in remote locations.

Manufacturing Methods: Efficient and Environmentally Friendly

The emergence and growth of sophisticated computer design tools have enabled advances in rapid prototyping, allowing designers to produce highly customized industrial products.[470] Recently, rapid prototyping techniques have also proven to be important for medical applications.[471]

Traditional manufacturing processes have addressed environmental concerns by attempting to control the release of pollutants. Recent approaches have sought to revise

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[466] Catchpole (2004).
[467] Gratzel (2001).
[468] Fairley (2004); Dume (2004); "Nanosys Awarded U.S. Defense Department Contract to Develop Flexible Solar Cells" (2004).
[469] Sheats (2004).
[470] "SolidWorks' New Print3D Feature Gives Designers Instant Access to Rapid Prototyping" (2003); "Rapid Prototyping Makes Technologies Affordable by Enabling Mass Customization" (2004); Bregar (2004).
[471] "Cranial Reconstruction" (2004); Sun et al. (2004); Tain et al. (2002).

the actual manufacturing process itself to reduce or eliminate waste streams and the production of pollutants. Such "green manufacturing" techniques include, for example, synthetic catalysts, bio-based processes, non-chlorine-based water purification, and biodegradable polymers.[472]

2020 Foresight for Manufacturing Methods

By 2020, green manufacturing techniques are likely to provide a variety of more environmentally friendly alternatives to manufacturing processes that currently use or produce hazardous materials. Using these methods, manufacturers will be able to sustain levels of production in what will likely be a stricter regulatory environment, while consuming fewer nonrenewable resources, creating less hazardous waste streams, and having reduced impact on the environment.

[472] Lempert et al. (2003).

APPENDIX D: INFORMATION TECHNOLOGY TRENDS TO 2020

Elaine M. Newton and Shari Lawrence Pfleeger

Introduction

This appendix presents a foresight of technological trends for the year 2020 based on current research and development in information technology (IT). As a result of the breadth of the field, the topics chosen are only a subset of the IT-related trends that could have substantial social and political effects sampled in the main report, but it provides a more in-depth discussion of specific areas.

The following trends are first briefly discussed: the convergence of technologies; growth in volume and types of personal data (e.g., through sensors, biometrics, cameras, and Global Positioning System [GPS]) and subsequent database issues; and trending toward smaller, mobile electronics devices. Within each of these discussions, trends are presented as follows: the development or trend in technology today; where it might lead to by 2020; and what the social and/or policy implications might be. By and large, the social issues raised by IT developments are privacy and anonymity, which are also being addressed through science and engineering by a growing number of researchers. This type of research will be discussed next, followed by a brief exploratory discussion of foresights in robotics, IT in education, IT in helping those with physical disabilities or ailments, and other areas.

Convergence of Technologies

Currently, many services and goods are coupled with information technology. For example, consumers can get broadband access to the Internet through their cable or phone provider. Or they may own a PDA/cell phone/camera that they also use to check email, surf the Web, and instant-message buddies. Researchers are also currently investigating the viability of providing broadband Internet access via electric power lines (known as BPL), with the intention of creating competition with the cable and telephone companies.[473]

Convergence of technologies [474] and functionality will continue to be a theme of mainstream digital products of the future. It will be facilitated by developments in wiring and materials that will carry digital information, possibly enabled by research and

[473] For example: "Homes could start being connected to the Internet through electrical outlets, and consumers and business may find it easier to make cheaper telephone calls online under new rules that the Federal Communications Commission…" (Labaton, 2004).
And: "Taken together, the new rules could profoundly affect the architecture of the Internet and the services it provides. They also have enormous implications for consumers, the telephone and energy industries, and equipment manufacturers" (Associated Press, 2003).
[474] Perry (2004c).

development of optical circuits.[475] Telephony, television, cable providers, radio, personal computers, Internet access, power, day planners, and even room lighting might be bundled into one product in the home supplied by a single vendor.[476] Clothing and computing will also converge with the emergence of smart clothing (which would react to weather with the help of sensors), wearable computers, and video lenses.[477]

Issues to consider include privacy (which will be discussed more in more detail below), security of the systems and transactions over them, and how to regulate combined forms of what were once separate functions, especially when conflicts arise over how the separate forms were regulated in terms of matters such as competition/ monopoly, indecency standards, and licensing.[478]

Data, Data Everywhere

By the year 2020, because of the many technologies being developed that will include mechanisms to monitor and sense, the amount of data produced about any particular individual's identity, whereabouts, habits, and behaviors will increase dramatically. The following categories—sensors, biometrics, cameras, and GPS—present some major themes and describe where research is heading.

Privacy and anonymity issues are common to the following scenarios: creating new data types about a person (i.e., surveillance where there was none before), tracking, determining what other data are linked to the data related to use of the sensor, using the data for secondary purposes, sharing or selling data and determining their purpose, assessing the user's transparency regarding data collection and usage, controlling how long the data are retained, and ensuring that the data are reliably destroyed. Several of these issues reinforce the need to understand the more general threats that data mining poses to personal privacy and anonymity. With vast amounts of data available, data quality problems must also be assessed and resolved. Quality refers not only to data duplication and correctness, but also to the ability to store large amounts of data and retrieve it in acceptable times. In the latter case, the field of subwavelength nanostructures is showing some positive results.[479] Additionally, researchers have determined that organic memory provides an improvement in capacity that is easier to manufacture, making it cheaper than current chips.[480] Such memory would also be more power efficient.[481] We discuss storage and database issues below, after the specific technologies.

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[475] Geppert (2004b).
[476] Perry (2004b).
[477] Goldstein (2004b). This also references Marculescu et al. (2003) and discusses wearable computers and smart clothes (e.g., they detect weather and change to accommodate the conditions).
[478] For example: IEEE-USA expressed concerns about interference to the licensed users of HF spectrum, and concerns about interference to Access BPL systems from those users. The organization noted the potential negative impact of such interference on the ultimate reliability of Access BPL as a means of delivering broadband service to users. It cited possible adverse effects on many uses that are critical to national security, homeland defense, and emergency and disaster communications (IEEE-USA, 2004).
[479] Hellemans (2004).
[480] Guizzo (2004).
[481] Guizzo (2004).

Sensors

Currently, relatively crude sensors such as radio frequency identification (RFID) tags[482] are being developed and tested for labeling many different products to aid functions such as making purchases at a store, confirming inventory, and combating theft.[483] These tags label a product with a unique code and transmit its information (a code that contains information about the product) a short distance away (between 1 and 10 meters, and possibly farther). Retail stores are particularly interested in the development of RFID tags for these uses, and grocery stores (and such larger retailers as Wal-Mart) have begun to use them to track pallets of products.[484]

By 2020, relatively simple sensors such as RFID, as well as smarter sensors with even more information and the ability to communicate with each other,[485] will be widely deployed. Whereas RFID tags are powered by the signal from the reader, the power supply for smart sensors is an issue yet to be resolved. (See “Micro and Mobile—Devices and Power Sources” below.)

Sensors like these create and transmit data about an individual (the more sophisticated, the more information), providing ways to track a person’s location once the individual possesses something with such a tag. Thus, privacy concerns must be addressed. Options for curbing the privacy objections to RFID include a (currently) cumbersome method of deactivating the tags at the point of sale.[486]

Biometrics

Biometric systems are automated tools used to recognize a person by a (relatively) static pattern of a body part or from a person’s behavior (a biometric or biometric identifier). Examples of biometrics include fingerprint, face, iris, and keystroke recognition.[487] These and other biometrics are compared in Table D.1; examples of likely applications are listed in the paragraph following Table D.1.

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[482] Bonsor (undated); Langheinrich (2004).
[483] Kumagai and Cherry (2004); Knowledge@Wharton (2004).
[484] Kumagai and Cherry (2004); Knowledge@Wharton (2004).
[485] Blau (2004).
[486] Kumagai and Cherry (2004).
[487] Woodward et al. (2001).

Table D.1
A Comparison of Various Biometrics

Example	Proximity	Key Strengths	Key Weaknesses	Identification Versus Verification
Fingerprint	Touching	Robust pattern and technology, relatively cheap	Stigma due to forensic use, unusable prints of many segments of the population, hygiene concerns	Either
Hand or finger geometry	Touching	Low data storage requirements, user-friendly	Patterns not distinctive, especially for large population applications; hygiene concerns	For verification only
Dynamic signature verification	Touching	Familiarity with users; less privacy concerns	Not robust technology; low distinctiveness	For verification only
Retina scan	1–2 inches	Robust technology	Intrusive; the pattern of the retina can reveal health status or medical conditions, such as pregnancy, diabetes, or the use of drugs	Either
Iris scan	10–12 inches	Very robust, proximity	Cost; data storage requirements	Either
Face recognition	>12 inches	Potential for long-range or clandestine use	Robustness issues; accuracy issues; cost	Either
Voice verification	Remote	Not intrusive; infrastructure in place	Not robust; less accurate; recognition tends to depend on pass-phrases rather than the subject	Verification; possibly identification
Keystroke dynamics	Touching	Familiarity with users; less privacy concerns; infrastructure in place	Not robust; less distinctive	For verification only

SOURCE: Adapted from Woodward et al. (2001).
NOTES: "Robust" means fairly static over time: A robust biometric is important for recognition of the same person over time (less false negatives). "Distinctive" indicates an infrequent pattern in the population: A distinctive biometric is one that "uniquely" (or close to uniquely) identifies someone.

Any of the above "mainstream" biometrics could potentially be used for the following example applications. However, listed below in parentheses after each application are educated guesses about which biometrics are more likely candidates based on current trends:

- Internet, e-commerce (fingerprint, keystroke, iris, face)
- Law enforcement/detecting criminals (fingerprint, face, voice)
- National ID (fingerprint, face, iris)
- Driver's license (fingerprint, face)
- PC access; network access (fingerprint, keystroke, iris, face)
- Immigration: frequent flyers and borders (hand geometry, fingerprint, face, iris)
- Health care (fingerprint, keystroke, face, iris)
- Benefit payments (fingerprint, dynamic signature)
- Parliaments (fingerprint, face)
- Voter registration (fingerprint, face)
- Access control (fingerprint, face, iris, hand geometry)
- Correctional institutions/prisons (fingerprint, face, voice, iris)
- Banking (fingerprint, iris, face, dynamic signature)
- Time and attendance (hand geometry, face)

It is difficult to say what will happen with biometrics by 2020. While there is certainly a push to use biometrics for security because it is a pattern that is inextricably linked to a person, that fact in and of itself causes problems of replacement (e.g., you can easily replace a password or magnetic stripe card if either is compromised, but you're stuck with your biometric identifiers). Similarly, if you want someone to act in your stead—in cases of emergency where a spouse is incapacitated, for example—it is easy to give him or her your password but usually impossible to give him or her your biometric identifier. Error rates—the incidence of false positives and false negatives—is the bigger problem with biometrics. Research in this area is not yet moving beyond the low-hanging fruit in terms of subjecting biometric algorithms and products to more stringent tests.[488] Assuming that a strong emphasis continues to be placed on security for the next few years or so, a biometric pattern on a passport will be required of every traveler around the world well before 2020. However, it may not be terribly useful and will likely become obsolete because of how the template (the digitized features of a biometric stored for verification) will be created (e.g., it may be proprietary, rendering it useless for use by other systems or problematic if the company folds). It will likely be used as a second "password" for most applications where it would be implemented—verifying or authenticating the identity of a person (a 1:1 search) rather than trying to identify a person (a 1:N search).[489]

With respect to privacy and security, important choices need to be made (before implementation) regarding what other types of data will be linked to biometric data.[490] With respect to security, there is also the nontrivial task of choosing a backup system that is also highly secure (because for any given biometric, there will be some part of the population that will not have the body part or will not be able to enroll their biometric pattern).[491] The backup system's performance, as well as the error rates of the primary biometric system, pose problems for privacy and security; they are likely to be tested in

[488] Phillips and Newton (2002).
[489] Woodward et al. (2001).
[490] Woodward et al. (2001).
[491] Woodward et al. (2001).

the courts (as opposed to being affected by government regulation or industry standards) once a major false accusation case has occurred (e.g., by a surviving family of the deceased after a major terrorist event occurs).

Cameras

More and more, cameras are getting smaller and being embedded in such everyday items as cell phones or badges.[492] At the same time, memory for storing photographic and videographic data is cheap. Video vaults are being created as well.[493] Because these data are richer in content and considered to be more invasive than other information, new rules to deal with camera phones have been established in such public places as gyms and court rooms.[494]

By 2020, small cameras will be many times more prevalent than they are today. Developments in imagery (such as the Grating Light Valve display[495]), data speeds over the Internet, and tiny sensors—some made to look like dust ("smart dust")[496]—will dramatically increase the amount of image and video data available for use in identification, authentication, and analysis.

When so much more is being observed and recorded, what will be the effect on our news sources and on law enforcement and crimes? Undoubtedly, images and video (especially given the explosion of digital cameras and video) will be used to solve crimes (or at least draw public attention and pressure to serious issues).[497] Privacy and anonymity[498] will be threatened, if not made obsolete in the public areas of highly monitored societies, especially as identification and tracking of individuals increases.

Global Positioning System

GPS is used to sense position information.[499] Currently, GPS is included in many products such as cell phones and some vehicles' safety and security systems (e.g., OnStar).[500] The use of GPS in hardware will continue to grow. These types of data pose threats to privacy and anonymity (as discussed above), especially tracking of individuals.

Database Technology

From an IT perspective, database technology is going to be much more important than ever before. IT researchers must revisit database technology in light of the likely changes to the nature and volume of information.

As the technologies discussed above can generate and transmit more and more data, we will need databases and technology to categorize, store, extract, and analyze information. These databases will be updated often and will need additional contextual information to describe the nature of the data. Current database technology often

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[492] For examples of lightweight and high quality camcorders, see Geier (2004).

[493] Rosenblatt (2004); Nishi (2004).

[494] Barr (2004); Also, a personal observation returning from Morocco into New York's JFK airport: All cell phones had to be turned off.

[495] Perry (2004a).

[496] Goldstein (2004a).

[497] Goldstein (2004a). The images that surfaced from Iraq's Abu Ghraib prison are one such example.

[498] Goldstein (2004a).

[499] Kumagai and Cherry (2004).

[500] Kumagai and Cherry (2004); OnStar's Web site, http://www.onstar.com.

emphasizes distributed databases, but we may very well move to large, centralized databases of information that will be stored until we have a need for it. What we are likely to have by 2020 is a notion of an *agile* database, where large warehouses of data can be easily partitioned or reconfigured by extracting only those items needed for a particular situation. For example, suppose that by 2020 there are RFID tags in everything, as well as sensors to report health information (blood pressure, pulse, hormone levels, etc.). The sensors and RFID tags notify a physician when his or her patient's levels are out of normal ranges. The physician then requests additional information from the database, which somehow generates a sub-database of information relevant to the patient. If the patient happens to be a soldier on the battlefield, then information is also generated to describe location, movement, outside temperature, type of clothing, humidity, etc. The soldier may be suffering from heat stroke, and the database can automatically generate a message to the soldier about what to do to address it. At the same time, the physician can be monitoring vital signs and making recommendations.

Users of such databases must be cautious in making claims based on their data. In particular, when determining and evaluating trends, analysts must take care to view the data in many ways, not just using norms or means. In many cases, the outliers are more interesting than clustered or similar information, because such points are more difficult to understand and predict. Moreover, care must be taken in basing decisions only on outlying behavior. Being an outlier or deviating from the mean can mark a person, subjecting him or her to scrutiny. Over time, the use of data-mining techniques may increase social pressure to "be like everybody else" to avoid unnecessary scrutiny.

However, as IT continues to view each individual only as a data point, individuals may want to make visible something to distinguish themselves clearly from other people. Consider, for example, the amount of money spent by young people on personalized "ring tones" for their cell phones. This trend toward identity is likely to permeate various IT applications, especially among products marketed toward the youth. Data-mining techniques used to customize recommendations to individual preferences may also be helpful in working against uniformity.

Micro and Mobile—Devices and Power Sources

Electronic devices are becoming smaller and more lightweight—and often wireless and mobile. A good example is the development of "smart dust",[501] discussed above. As this trend continues, there will be an increasing need for alternative power sources that are also lightweight, mobile, and long lasting. Research on alternative and renewable power sources will likely influence the further development of tiny mobile products.

In line with this trend, high performance computing could move from big machines to clusters of smaller, cheaper machines. Such configurations will make high-performance computing more agile, and the machines will be reconfigurable depending on the application to which they are to be put.

More generally, we will have "opportunistic IT," where notions of swarming are applied to networks and applications. Computer networks will reflect social networks and, as a need arises, the various hardware and software components will be reconfigured to address the particular need.

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[501] Goldstein (2004a).

The overall social effect of shrinking size and mobility of devices will be a continuation of current trends that allow for more access, communication, and freedom of movement—of both individuals and information.

Privacy and Anonymity Tools

Since the publication of *The Global Technology Revolution* (GTR2015) in 2001,[502] there have been advances and increased interest on the part of many researchers on ways to protect and assure privacy—so there is reason for optimism concerning the state of privacy in 2020. Interdisciplinary groups of computer scientists, engineers, and social scientists are developing tools that provide new technologies and algorithms to protect consumers' privacy. For example, researchers such as David Chaum [503] and Stefan Brands[504] have created algorithms for anonymous transactions with untraceable digital credentials and electronic cash.

Another example is a class of algorithms that has been developed, known as *k-anonymity*,[505] to identify efficient ways of essentially scrubbing data (including fielded text data and images) of identity information so that each individual is no more unique than *k*-1 data subjects. These types of algorithms offer alternatives to data disclosure or nondisclosure, leaving in information that can be used in other socially desirable ways, such as medical research. Recent work on anonymizing facial images lays the groundwork for searches of video surveillance footage by law enforcement without revealing the identity of innocent individuals; identity would be revealed only with specific, targeted warrants to "unlock" the faces of those known to be related to a crime.[506]

The community of researchers developing information technologies is increasingly aware that privacy, anonymity, and security are important aspects to take into consideration when designing a system.[507] For example, futuristic grocery stores can create and provide a lot of data about someone, as well as create a way to identify and track a person—that is, if the data handling systems are implemented without considering privacy concerns. Tags can be disabled at the point of sale, and payment, while done through some reference number, does not need to be linked to identity data.

With the right set of research and/or regulatory incentives, IT researchers and developers can create technology that embraces cultural norms and preferences for privacy and/or anonymity.[508] Researchers can apply their ingenuity to tools that take into account social implications of partial solutions.

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[502] Antón, Silberglitt, and Schneider (2003).
[503] Chaum (1985).
[504] Brands (2000).
[505] Sweeney (2002a); Sweeney (2002b).
[506] Newton, Sweeney, and Malin (2003); Newton, Sweeney, and Malin (2005).
[507] For example, Association for Computing Machinery (1997) and Association for Computing Machinery (undated). See also Workshop on Privacy Enhancing Technologies (2005) and Center for Discrete Matematics & Theoretical Computer Science (DIMACS) Workshop on Usable Privacy and Security Software (2004).
[508] Morgan and Newton (submitted).

2020 Foresights

Robotics

By 2020, we can expect to have robots that look and move in very human ways, thanks to advancements in areas such as electroactive polymers and biomedical engineering.[509] The field of artificial intelligence, however, does not appear to be advancing toward such an end goal as quickly.[510] Given these factors and the development of enhanced sensors, cameras, microphones, and the Internet, as well as increased demands on the average American worker's time, perhaps these robotic forms[511] can be used as proxies for an individual (called a proxy-bot or proxy-droid), allowing a person to be in multiple places simultaneously, an effect that could be particularly useful for facilitating interactions across distances, particularly for those confined to their homes. The individual being represented would essentially be the brain, transmitting signals of his or her own movements and speech that would be translated into electrical pulses for moving plastic muscles or vocal cords. The proxy could also record meetings or seminars when schedules do not permit actual attendance.

Technology and Education

Both informal and formal education could be aided by tools developed to scan light beams to the retina, creating a layer over what would be normally seen with the naked eye. Such technology could help give directions, label parts, explain how to fix a device, or have any number of other uses.[512]

Many IT developments, such as increasing use of the Internet and robotics (e.g., proxy-bots), could dramatically change higher education; for example, fixed meeting times and places for courses could become a thing of the past. A more mutable type of college degree could result, not affiliated with a university but instead resting on the reputation of the professors whose courses were purchased and passed.

Physical Disabilities and Ailments

By 2020, technological developments will provide more improvements for people with physical disabilities or ailments. For example, neural engineering and implants could enhance physical and mental abilities after injury, illness, or stroke.[513] Auditory imagers may allow the blind to "see" through different noises that indicate characteristics about an object in front of him or her.[514] Finally, with increased understanding about the brain and the ways in which different cell types work,[515] by 2020, improved IT devices will help to control bodily functions (e.g., insulin monitors) and prostheses.

Other Developments

By 2020, there will be more of an emphasis on customization. Items such as clothing or vases could be generated on demand in individual households. Similarly, printing on demand, which is already being used by publishing houses, will become a normal mode

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509 Bar-Cohen (2004); Kumagai (2004).
510 Sweeney (2003).
511 Geppert (2004a).
512 Lewis (2004).
513 Cavuoto (2004); "Would You Have a Neural Implant?" (2004).
514 Jones (2004a).
515 Stein (2004a).

of operation within that industry. Warehousing of books will be reduced; instead, many books will be ordered online and produced in response to the order.

Wearable computers and video monitor lenses will lead to new methods of hands-free typing and messaging. Researchers are currently testing many different ways to convey information electronically, including twitching, blinking, and voice.[516]

There has been a shift in the proportion of people living in rural areas, compared with their urban counterparts.[517] Urban areas are becoming more and more crowded, and this trend is likely to continue.[518] This crowding and its accompanying congestion will affect the ability of people to get around quickly and easily. Sub-subcompact, fuel-efficient modes of transport, such as large toy Q-cars in Japan[519] and Segway-like vehicles, may become more appealing to consumers, particularly if the coming congestion is accompanied by an increase in energy prices.

Final Thoughts

IT will be both a main character and a supporting player in the changes likely to occur by 2020. Contributing to increased speed, increased granularity of detail, and the ability to handle larger and larger amounts of information, IT will often be the linchpin in enabling emerging technologies to work together. However, the benefits of IT will still be limited to those aspects of human existence that can easily be expressed in a quantitative way. The more qualitative aspects, such as nuances of language and expression, will likely never be captured using automated techniques such as machine translation. Similarly, IT may be used to generate directions for using a piece of equipment but not to analyze the implications of email messages. Although today most knowledge engineering research emphasizes explicit knowledge, by 2020 there will be more focus on tacit knowledge.

Also, while developments in IT will at times provide the ability to run experiments using simulations instead of human (or living) subjects, there will always be a role for clinical trials due to unpredictable side effects. Control will be a big issue by 2020. For example, Daniel Boorstin's book, *The Discoverers*,[520] points out how, over time, the town church lost control as technology improved. At first, people let the church govern their day because church bells rang to signal commencement of the next set of activities. Once clocks were invented, the church lost some of its hold on the people. Similarly, once the printing press was invented, the church lost even more control. By 2020, who will have control over information, thought, and action? How will surveillance

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[516] Goldstein (2004b).

[517] Platt (2004). This article begins with an analysis of census data to illustrate the dramatic upward shift in the U.S. metropolitan population through the decades (between 1950 and 2000). In 1950, 55 percent of the U.S. population lived in a metropolitan area; in 2000, that rose to 80 percent. In 1950, there were 169 metro areas, 14 of which had at least 1 million residents, for a total of 45 million in those cities, or 30 percent of the U.S. population. By 2000, there were 347 metro areas, 49 of which had at least one million residents, for a total of 161.5 million in those cities, or 57 percent of the U.S. population. However, one interesting note is the decrease metro population density, which was 407 persons per square mile in 1950 but 330 persons per square mile in 2000—a statistic reflecting the increased average floor area per capita in single family homes as well as urban sprawl. Suburban populations also increased from 23 percent to 50 percent of the U.S. population. The article also touches on statistics of commuters' hours spent going to work increasing dramatically.

[518] Platt (2004).

[519] Nakao (2004).

[520] Boorstin (1985).

cameras, sensors, and other technologies force people to give up control over what they do and how they do it?

Finally, by 2020, data will be collected on everything (and mined for trends). At the same time, IT will encourage people to work and entertain themselves at home. Thus, there will be compelling reasons for people to retreat to their homes for both convenience and privacy. This change of venue for many activities will likely affect etiquette and social graces. Personal interaction will suffer further, as more interactions will occur with electronic devices and automated services. By 2020, traditional letter and memo writing may be long gone, replaced by instant messaging and email.

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APPENDIX E: CREATING NEW OPPORTUNITIES FOR IMPROVING EXISTING THERAPEUTICS: NANO-ENABLED DRUG DELIVERY SYSTEMS TRENDS TOWARD 2020

Natalie Rose Gassman

Summary

Genomics, proteomics, combinatorial synthesis, and rapid analytical methods have changed diagnostics, drug discovery, and drug development.[521] These systems have generated a wealth of information about disease etiologies, genetic dispositions, and the design of increasing specific drug candidates.[522] Yet, the conversion of this information to drugs has been limited because of the lack of suitable delivery vehicles. Solubility, bioavailability, and toxicity issues plague many of the new drug candidates generated from these technologies, and conventional formulations have failed to address these issues and bring these new candidates to market.

Drug delivery research has grown rapidly over the past two decades and has enabled drug development by designing suitable delivery systems that improve efficacy, lower dosing frequency, and improve patient convenience and compliance. The past 15 years has seen increasing integration of nanotechnology with drug delivery to address the new challenges presented by modern drugs.[523]

At the nanoscale of 1 to 100 nanometers, materials can have very different properties, and for active compounds and delivery systems, this reduction in scale increases surface area, dissolution rate, permeability, and intracellular uptake.[524] Creating nano-enabled drug delivery systems for modern drugs can address performance issues related to solubility and toxicity; improve bioavailability by increasing absorption and permeability through blood vessels and the gastrointestinal tracts; and allow specific targeting of drugs to cellular and intracellular compartments. These advantages have led to rapid growth in R&D of nano-enabled drug delivery systems over the past decade, and these systems are now poised to affect how drugs are developed and delivered to patients.

Here we have examined the R&D trends in the growing field of nano-enabled drug delivery systems to provide foresight into the potential opportunities of these systems and impact they will have on therapeutics in the next 15 years. Three areas have emerged in which nano-enabled drug delivery systems will have significant effects:

[521] Szuromi, Vinson, and Marshall (2004).
[522] Gershell and Atkins (2003).
[523] Orive et al. (2003).
[524] LaVan, Lynn, and Langer (2002).

- **Improving existing pharmaceuticals.** Innovative drug delivery systems have often been employed to make old drugs new.[525] Reformulation strategies can extend product lines and life cycles for pharmaceutical developers and can improve efficacy, dosing schedules, routes, and convenience for patients.[526] As companies continue to feel the pressure of patent expiration on blockbuster drugs, reformulations with nano-enabled drug delivery systems could see a marked acceleration in the next 15 years. Fast growth opportunities for these systems are predicted for anticancer agents and protein and peptide therapeutics, where shortcomings in existing formulations creates a large potential market.[527] Nano-enabled delivery systems offer improvements in toxicity, stability, specific targeting, and administration routes for these drugs, which will improve efficacy and specificity and translate into improved convenience and quality of life for patients.
- **Rescuing drug candidates.** Approximately half of new drug candidates have failed to reach the market because of problems with absorption, distribution, metabolism, and toxicity,[528] and the development of these candidates may not be possible without improved formulations.[529] Nano-enabled delivery systems, which can be used as platforms to reformulate a variety of drugs and address performance issues of new drug candidates, can migrate upward into the development process in the next 15 years to help pharmaceutical developers bring promising drug candidates to market. Integration of nano-enabled delivery systems into the development pipeline could bring more efficacious drugs to market in cases where current formulations create adverse side effects and cause failures in clinical trials, thus increasing the productivity of development pipelines, which have declined in recent years.
- **Creating new therapeutic opportunities.** Advances in nano-enabled drug delivery systems are not just confined to improving pharmaceuticals. As these systems continue to advance in the laboratory, they are opening new opportunities for the therapeutic delivery of DNA and RNA and creating multifunctional delivery systems. These new areas of research could significantly affect drug delivery but are considerably less advanced than the other two areas discussed above. While it is unlikely that they will appear on the market in the next 15 years, technological breakthroughs could occur that advance these systems faster than expected.

Nano-enabled drug delivery systems are offering attractive solutions for improving the efficacy and specificity of pharmaceuticals and for addressing the challenges confronting pharmaceuticals companies in managing life cycles and improving productivity. The first generation of these delivery systems has begun to emerge on the market, and the future path of nano-enabled drug delivery systems will be

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[525] Rosen and Abribat (2005).
[526] Fleming and Ma (2002).
[527] Sahoo and Labhasetwar (2003).
[528] Gershell and Atkins (2003); Hodgson (2001).
[529] Gershell and Atkins (2003); Allen and Cullis (2004).

greatly influenced by continuing interest and research investment in these technologies by both government agencies and pharmaceutical companies.

Introduction

In the past three decades, scientific advances in chemistry, biology, physics, engineering, and medicine have all come together to revolutionize drug discovery and delivery.[530] Genomics, proteomics, rapid DNA sequencing, and high-throughput arrays and ultra-sensitive labeling and detection technologies have been used to identify genes and proteins for biopharmaceuticals.[531] Combinatorial chemistry, cell-based assays, and automated high-throughput screening have led to the generation of active compounds from combinatorial "smart" libraries that can be rapidly screened and optimized.[532] With these new technologies has come an abundance of new chemical entities and protein and DNA therapeutic targets that could result in new drugs with potentially better specificity and efficacy than ever before. However, the number of new drugs approved by the Food and Drug Administration (FDA), while rebounding in the past year, has declined in recent years and has not reflected the generation of these new modern drugs.[533]

The challenge with new active compounds generated either from combinatorial methods or from biotechnology research is that they do not necessarily have the desired physicochemical properties to become drugs. They may be poorly soluble, have low bioavailability, or display limited chemical stability (half-life) in vitro and/or in vivo, introducing a strong potential for harmful side effects from metabolic products.[534] Recently, toxicity has replaced poor drug metabolism properties as a major cause of failure in the early clinical phases of drug discovery.[535] Some of these issues can be overcome by the addition of stabilizing agents, controlled dosing patterns or direct administration (i.e., injections), but adverse drug effects can increase with stabilizing agents, and complex dosing schedules or methods can result in low patient compliance.

Novel drug delivery systems offer a strategic tool for overcoming limitations in current formulations.[536] Drug delivery techniques were established to deliver or control the amount, rate, and location of a drug in the body to optimize its therapeutic effect, convenience, and dose.[537] Over the past decade, research into drug delivery has evolved into an interdisciplinary field that has been influenced by the potential opportunities of nanotechnology and nanofabrication.[538] At the nanoscale of 1 to 100 nanometers, materials can have very different properties, and for active compounds and delivery systems, this reduction in scale increases surface area, dissolution rate, permeability, and intracellular uptake.[539] These properties open up many new therapeutic opportunities for drug delivery systems.

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[530] Gershell and Atkins (2003).
[531] Gershell and Atkins (2003).
[532] Geysen (2003).
[533] Service (2004).
[534] Muller and Keck (2004); Lipinski and Hopkins (2004).
[535] Gershell and Atkins (2003); Lipinski and Hopkins (2004).
[536] Orive et al. (2004).
[537] Tsai (2002).
[538] Emerich and Thanos (2003).
[539] LaVan, Lynn, and Langer (2002).

Nano-enabled drug delivery systems could be used to optimize existing drugs on the market, improving their effectiveness or tolerability or simplifying their administration. Drug candidates and therapies, which previously failed to reach the market, can be reexamined and "rescued" by new delivery technologies. Integration of drug delivery systems earlier into the drug discovery cycle may open new avenues for screening new compounds, increasing drug targeting, and creating multifunctional carriers with integrated applications (targeting, imaging, and drug delivery).

With the potential opportunities of these systems ranging from lowering drug side effects to bringing new drugs to markets, what is the likelihood these opportunities can be reached in the next 15 years and what impact will these systems have on therapeutics?

A landscape of recent R&D is required to examine the potential impact of these systems and their growth trajectories. Several reviews have been published describing the array of technologies and applications that the integration of nanotechnology and drug delivery research has generated,[540] and while these technologies have many distinct features, examining their application to a common area provides a useful landscape for this foresight exercise. One area of fast growth for nano-enabled drug delivery systems is reformulating cancer therapeutics. Recent advances in reformulating one cancer therapeutic—paclitaxel—are described below.

Nano-Enabled Delivery of Paclitaxel

Paclitaxel (Taxol), one of the most important anticancer drugs developed in the past two decades,[541] is an excellent prototype drug for reformulation because of its therapeutic use against a wide spectrum of cancers and its billion-dollar-a-year commercial success.[542] Like many other anticancer drugs, paclitaxel is poorly soluble and requires organic solvents, such as Cremophor EL (castor oil) and ethanol, to be solublilized for therapeutic use.[543] Serious side effects, including hypersensitivity reactions, nephrotoxicity, cardiotoxicity, and neurotoxicity have been linked to Cremophor EL,[544] and recent research has indicated that Cremophor EL micelles may sequester paclitaxel and reduce its ability to penetrate cells and work effectively.[545] In addition to toxicity issues related to Cremophor, the cytotoxic activity of the drug itself destroys both healthy tissues and cancer tissues in its current administration. To overcome these shortcomings in formulation, nano-enabled drug delivery systems have been developed for paclitaxel to offer new solutions for improving solubility and efficacy.

Paclitaxel molecules have been successfully encapsulated in liposomes, micelles, and polymer nanospheres;[546] attached to dendrimers;[547] and adsorbed on surface of polymer nanoparticles.[548] These formulations have removed toxic excipients and

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[540] Orive et al. (2003); Allen and Cullis (2004); Orive et al. (2004); Mainardes and Silva (2004).
[541] Yeh et al. (2005).
[542] Zhang and Feng (in press).
[543] Yeh et al. (2005); Singla, Garg, and Aggarwal (2002).
[544] Yeh et al. (2005); Zhang and Feng (in press).
[545] Yeh et al. (2005).
[546] Brannon-Peppas and Blanchette (2004); Sahoo, Ma, and Labhasetwar (2004); Soga et al. (2005); Straubinger and Balasubramanian (2005).
[547] de Groot et al. (2003).
[548] Yeh et al. (2005); Zhang and Feng (in press); Singla, Garg, and Aggarwal (2002).

improved solubility, while producing comparable or improved activity levels.[549] Several of these reformulations are currently in clinical trials, and recently the FDA approved Abraxane, a suspension of paclitaxel-coated nanoparticles, for the treatment of metastatic breast cancer.[550]

Improving solubility through formulation is not the only capability of these technologies. Nano-enabled delivery platforms have been developed for controlled release and patterned delivery of paclitaxel. Biodegradable polymer nanoparticles with paclitaxel encapsulated or entrapped in their matrix have been developed for controlled release with release rates dependent on polymer structure and degradation.[551] Liposome, polymer nanoparticles, and dendrimer systems have also been developed that allow triggered release of active compounds.[552] These "smart" delivery systems have been developed to provide highly controlled drug release rates in response to stimuli, such as pH or temperature changes, small molecules, enzymatic reactions, magnetic fields, light, or radio frequencies.[553] These systems have been developing rapidly; several sustained and triggered-release formulations are entering preclinical development. One sustained release gel of paclitaxel polymer nanoparticles, Oncogel, is in clinical trials.[554]

Additionally, by harnessing molecular interactions and recognition systems, these delivery systems can be surface-functionalized with small molecules, antibodies, and proteins to target delivery to specific cells or increase intracellular uptake through receptor-mediated endocytosis.[555] Conjugation strategies for surface display are currently being developed for liposomes, micelles, polymer nanoparticles, and dendrimers. The most advanced area of this active targeting research has focused on conjugating anticancer antibodies to nanoscale liposomes to improve intracellular uptake of anticancer agents in cancer cells.[556] While these strategies are less mature for paclitaxel, the FDA has approved a liposomal conjugation system for targeting, Stealth (made by Alza), that has successfully encapsulated another cancer therapeutic, doxorubicin.[557]

Finally, researchers are also attempting to develop opportunities for oral delivery for paclitaxel.[558] While those efforts are still very early in development, alternative delivery routes with nano-enabled drug delivery systems such as oral, transmucosal, and transdermal are being pursued for a variety of drugs, vaccines, and proteins. Oral and pulmonary delivery of insulin nanoparticles is the most visible of these efforts.[559]

A large research effort has been devoted to creating nano-enabled delivery systems, as illustrated by the highlighted efforts to develop improved delivery systems for paclitaxel, and a wide array of technologies with varying levels of maturity have been generated. While these technologies continue to improve and evolve, nano-enabled drug

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[549] Zhang and Feng (in press); Singla, Garg, and Aggarwal (2002); Brannon-Peppas and Blanchette (2004).
[550] Weintraub (2005).
[551] Zhang and Feng (in press); Singla, Garg, and Aggarwal (2002); Brannon-Peppas and Blanchette (2004).
[552] Soga et al. (2005); de Groot et al. (2003); Gillies and Frechet (2005).
[553] Allen and Cullis (2004).
[554] Uchegbu (2005).
[555] Lee (2004b).
[556] Brannon-Peppas and Blanchette (2004).
[557] Uchegbu (2005).
[558] Dong and Feng (2005).
[559] Takei and Kasatani (2004); Walsh (2005).

delivery systems are already beginning to affect current pharmaceuticals and the drug development process.

Improving Existing Pharmaceuticals

With new discovery technologies increasing R&D expenses, and fewer new chemical entities receiving FDA approval, pharmaceutical companies have become increasingly dependent on billion-dollar-a-year blockbuster drugs to maintain their growth and enable continued investment in R&D.[560] Facing the loss of 30 of these blockbuster drugs, which stand to gross about $60 billion in the next five years,[561] pharmaceutical companies are being forced to reexamine existing drugs and invest in improved formulations to extend the life cycles, maintain market dominance, and reduce competition for these drugs.[562]

Reformulation strategies are not new concepts and have often focused on improving dosing frequency to improve patient convenience and, to some extent, their compliance with treatment.[563] While these strategies have proven successful for extending life cycles of some drugs, the changes are modest and often provide comparable levels of efficacy.[564] With the increasing competition from other pharmaceuticals with similar indications, the challenge of the generic market, and the increasing complexity of new therapeutics, conventional reformulation strategies will struggle to keep pace with the increasing desire to utilize life cycle management to maintain the market dominance of blockbuster drugs.[565]

Nano-enabled drug delivery systems offer reformulation strategies that can differentiate products by improving therapeutic indices and efficacy by reducing adverse side effects from excipients or toxic dosing cycles.[566] The systems can also extend product lines by providing more attractive administration routes, incorporating specific targeting, or creating tunable release profiles. Utilizing these systems as reformulation strategies could potentially provide a greater market share for drugs, reduce competition,[567] and further extend life cycles by qualifying old drugs as new chemical entities, or it could open up new markets by enabling repositioning of reformulated drugs for new indications.[568]

Drug delivery researchers and companies have positioned nano-enabled drug delivery systems as alternative reformulation strategies by focusing efforts on improving approved drugs (e.g., paclitaxel) that have shortcomings in their conventional formulations but have an established market share.[569] Successful reformulations of these drugs that address the shortcomings of conventional formulations could potentially capture part of the established market share,[570] demonstrating their market viability to pharmaceutical developers.

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560 Fleming and Ma (2002); Service (2004).
561 Chan (2003).
562 Ashburn and Thor (2004).
563 Fleming and Ma (2002).
564 Fleming and Ma (2002).
565 Allen and Cullis (2004); Lee (2004b).
566 Rosen and Abribat (2005); Allen and Cullis (2004).
567 Rosen and Abribat (2005); Fleming and Ma (2002).
568 Ashburn and Thor (2004); Moradi (2005).
569 Henry (2004).
570 Allen and Cullis (2004); Basu (2003).

The first generation of reformulations with these systems has started to enter the late stages of clinical trials, and some have already received FDA approval (see Table E.1). If these nano-enabled reformulations continue to emerge from clinical trials and receive FDA approval, they would be capable of transitioning from isolated reformulation efforts by drug delivery researchers and companies to becoming a reformulation strategy for pharmaceutical developers.

Though nano-enabled delivery systems are being positioned for success, barriers exist that may affect their potential to improve existing therapeutics. As demonstrated by the landscape of paclitaxel reformulations, a large number of technologies can be applied to a single active compound, but the viability and features of these individual reformulations could have dramatically different market value. To assess these different technologies as reformulation strategies and consider the risk of development, pharmaceutical companies may watch how these systems fare through clinical trials and in the market.[571] This places the risk and financial costs of development on drug delivery companies, whose resources may limit the targets they pursue and may limit the market share these reformulations gain. Conversely, if these systems provide successful strategies for gaining market dominance with lower development cost and risks than new pharmaceuticals, drug delivery companies may pursue reformulating generic drugs outside the pharmaceutical industry, limiting their use in life cycle management.

While these barriers may expand or limit the scope and impact of nano-enabled delivery systems on existing therapeutics, continued funding for nanotechnology and growing interest in improving efficacy for drugs with shortcomings in their conventional formulations will drive the continued emergence of nano-enabled drugs in the near term. Table E.1 shows some examples of nano-enabled reformulations that have received FDA approval or are in the FDA pipeline. Clinical trials are divided into phases. Phase I evaluates a drug's safety, determines a safe dosage range, and identifies side effects in small study populations. Phase II evaluates effectiveness and safety of the drug in a larger study population. The final stage before submission for approval, Phase III, employs a even larger study population to confirm the drug's effectiveness, monitor side effects, and compare it with commonly used treatments.[572]

Researchers and companies will continue to capitalize on approved drugs with established markets as candidates for reformulation. Anticancer agents, protein and peptide therapeutics, hormones, and vaccines fit this profile and are fast growth opportunities for nano-enabled systems.[573]

For delivery-modified cancer therapeutics alone, the next five years could bring FDA approvals for a variety of nano-enabled reformulations that improve efficacy, decrease dosing frequency, and improve patient quality of life. A potential market of $2.4 billion is predicted for these delivery-modified anticancer medicines in 2007.[574] Overall, the market for drug delivery systems is expected to reach $74 billion in 2010;[575] as nano-enabled systems continue to receive FDA approval, they could potentially make up a significant portion of that market.

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[571] Fleming and Ma (2002).
[572] National Institutes of Health (undated).
[573] Sahoo and Labhasetwar (2003).
[574] Uchegbu (2005).
[575] Moradi (2005).

Table E.1
Status in the FDA Pipeline of Nano-Enabled Reformulations

Drug or Therapeutic Agent	Technology	Company	Indication	Current Status or Year of Approval	Source
AmBisome®	Liposome	Gilead	Severe fungal infections	1997	"AmBisome Cleared for Marketing in the U.S." (1997)
Doxil® (doxorubicin)	Liposome	Alza	Anticancer drug for the treatment of metastatic ovarian cancer in patients	1999, updated February 2005	"US FDA Grants Full Approval to DOXIL® for Ovarian Cancer Progression Following Submission of Phase III Data" (2005)
Abraxane® (paclitaxel)	Protein and paclitaxel-coated nanoparticles	American Pharmaceutical Partners	Metastatic breast cancer	January 2005	Weintraub (2005)
Megace ES (megestrol acetate)	Nanomilling/ suspension	Elan and Par Pharmaceutical Companies	Anorexia, cachexia, or an unexplained, significant weight loss in AIDS patients	July 2005	"Par Pharma Gets FDA OK for Megace" (2005)
Paliperidone palmitate	Nanomilling/ suspension	Elan and Johnson & Johnson	Schizophrenia	Phase III	National Institutes of Health (undated); Elan Corporation (2005b)
Propofol IDD-D™	Nanoparticulate	Endo/ SkyePharma	Anesthesia/ sedation	Phase III	PhRMA (undated)
Vivagel®	Dendrimer hydrogel	StarPharm	Topical microbicide to prevent transmission of HIV and other sexually transmitted diseases (STDs)	Phase II	McCarthy et al. (2005)
BrachySil™ ^{32}P isotope	BioSilicon™ inorganic nanoparticles	pSivida	Brachytherapy; treatment of operable and inoperable cancer tumors	Phase II	PSivida (2005)

The next 10 to 15 years of utilizing these delivery systems for reformulation will be shaped by FDA approvals. If these systems continue to successfully emerge with approval, they could be increasingly employed by pharmaceutical companies to manage product life cycles in the face of lower productivity from R&D pipelines. Over this time frame, improvements in nano-enabled delivery systems that increase bioavailability and stability could bring compounds previously delivered by injection to market with oral, pulmonary, or transdermal delivery routes. Additionally, systems that incorporate specific targeting for cancer therapeutics may appear, but significant technological advances are required to bring these specific targeting systems to the market in this time frame. Funding efforts initiated by the National Institutes of Health, and particularly the National Cancer Institute, could push these advances forward more quickly, but the future of site-specific targeted delivery systems beyond cancer therapeutics is more indefinite.

Nano-enabled delivery systems are poised to change the way existing pharmaceuticals are delivered to patients. As these systems continue to advance in the laboratory and in clinical trials, their application areas will be better shaped and their market viability established. The establishment of market viability of these products in reformulation can provide firm ground for these systems to move upward into the development cycle and bring new compounds to market that would have previously failed.

Rescuing Drug Candidates

The pace of drug discovery research has accelerated with the integration of genomics, proteomics, combinatorial synthesis, and rapid analytical methods. While these systems have generated a deluge of information and data about active compounds and biological therapeutics, few drugs have actually emerged from this data in spite of the large increases in R&D investment.[576] Nearly half of all drug candidates fail because of issues with solubility, bioavailability, toxicity, and stability.[577] Drug candidates that make it past initial screens and perform well in preclinical and early clinical trials still often fail when they reach larger study populations in Phase II and Phase III trials.[578]

It is clear that increased investment in research efforts has not translated to increasing numbers of drugs reaching the market, and this decreasing productivity is forcing companies to examine reformulations of successful drugs and is also causing them to examine the development pipeline itself.[579] Combinatorial chemistry and high-throughput screening favors the selection of molecules that are more hydrophobic, increasing performance issues related to solubility and bioavailability.[580] Biotechnology advances create pharmaceutical candidates, such as proteins and peptides, that often suffer limitations in stability, as well as low solubility or bioavailability. Clinical development of these new drug candidates may not be possible without improved formulations that increase the solubility and stability of these molecules.[581] The same research effort that has generated nano-enabled delivery systems as market viable systems for overcoming limitations in current formulations has also positioned these systems to migrate upward into the development process to address the poor solubility, specificity, and stability in new drug candidates.

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[576] Szuromi, Vinson, and Marshall (2004).
[577] Gershell and Atkins (2003).
[578] Gershell and Atkins (2003).
[579] Szuromi, Vinson, and Marshall (2004); Ashburn and Thor (2004)
[580] "Getting Drugs to Their Targets: Delivery Strategies for the Future" (undated).
[581] Allen and Cullis (2004).

This upward migration is possible because some nano-enabled delivery technologies and methodologies, while developed and optimized for a specific drug, are capable of becoming platforms from which a variety of drugs can be optimized and delivered. These platforms offer pharmaceutical companies strategies for reexamining promising drug candidates whose current formulations limit efficacy, create adverse side effects, and cause them to fail in clinical trials.

Similar to individual nano-enabled technologies, the viability of these platforms is dependent on their ability to reformulate existing therapeutics and, more importantly, the ease by which multiple therapeutics can be reformulated. Several drug delivery companies have developed nano-enabled delivery platforms and have begun to position their technologies earlier in the development pipeline.[582] Two companies in particular, Elan and Alza, are excellent examples of this initial migration.

Elan's NanoCrystal system, designed particularly for poorly water-soluble compounds, has been employed to reformulate existing market compounds for pharmaceutical companies such as Wyeth (Rapamune) and Abbott Labs (TriCor) and to bring a new chemical entity to market for Merck (Emend).[583] This success sparked several pharmaceutical companies—Roche, Aventis, Janseen, and Bristol-Myer—to enter into a licensing agreement with Elan to employ the NanoCrystal technology in the development of their proprietary drug candidates.[584] Alza, which has a number of drug delivery systems, including the nano-enabled liposomal delivery platform Stealth, was acquired by Johnson & Johnson in 2001 and has been integrated into its development pipeline.[585] As more platform systems continue to develop, more pharmaceutical companies could begin to integrate these systems into their development pipelines.

While drivers like decreasing productivity and increasing complexity of new drugs may catalyze the upward migration of nano-enabled delivery systems initially, more long-term drivers could continue to bring drug development and drug delivery together. As new technologies continue to improve the data available about diseases and genomic profiles of patients, industry emphasis could begin to move toward more individualized drugs rather than blockbuster drugs. This narrower focus will drive companies to find cost-effective strategies for bringing these drugs to market, and nano-enabled delivery platforms could fit the bill. Additionally, the need to build up productivity and increase exclusivity could drive pharmaceutical companies to employ these drug delivery systems to bring "orphan drugs" to market and capitalize on the FDA and governmental incentives associated with the development of these drug candidates.

While these systems could increase productivity, there are also barriers to successful integration into development cycles. The volume of research and the large number of applicable delivery systems could limit their upward migration into development until the marketability of a platform is established. Also, the diversity in these nano-enabled systems makes characterizing the advantages and disadvantages of a platform for an application more difficult. For example, liposomal encapsulation strategies may offer better protection of drugs than nanospheres, but their release characteristics may be less desirable than polymer nanocapsule. Differentiating the

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[582] Henry (2004).
[583] Kayser, Lemke, and Hernandez-Trejo (2005).
[584] Elan Corporation (2005a).
[585] Henry (2004).

applications of these platforms and determining their potential value will be important to their effective integration into development cycles.

Additionally, the risks associated with the development of new chemical entities with these systems are largely unknown. While reformulation strategies allow for direct comparisons between free drugs and the nano-enabled drug delivery systems, the clinical process for nano-enabled systems with new chemical entities may not decrease cost or development time, and this could limit the development of more "personalized" or specialized treatments with these systems. Overall, until the risks can be better characterized, the cost-effectiveness and the perceived value of these strategies will be critical to their upward migration.

The emergence of nano-enabled reformulations in the next five years will shape the ability of these systems to migrate into development. While such companies as Elan and Alza have successfully integrated their nano-enabled platforms upstream, their ability to succeed in the development pipeline is dependent on these platforms bringing new chemical entities to the market. As competing systems continue to develop and emerge from clinical trials, pharmaceutical companies will most likely employ successful delivery systems on a candidate-by-candidate basis rather than incorporate one nano-enabled platform into their development pipeline.

Although more nano-enabled platforms will develop and their product opportunities will continue to increase, the integration of drug delivery and drug development beyond a candidate-by-candidate basis is unlikely in the next 10 to 15 years. Pharmaceutical companies will increasingly look at nano-enabled drug delivery systems as strategies to jump-start their development pipeline;[586] however, until these nano-enabled platforms can be better characterized and positioned to demonstrate their value in development, the risks associated with these new technologies could hold pharmaceutical companies back. If drug delivery companies develop high-throughput strategies for screening drug candidates against a suite of drug delivery technologies,[587] a more widespread integration of nano-enabled drug delivery systems with drug development could be possible in that time frame.

While nano-enabled drug delivery systems are unlikely to reinvent the drug development process, these systems could increase the development lifetime of failed compounds and may bring new modern drugs to market. These systems also have potential applications beyond reformulating existing drugs and bringing new drugs to market. Research efforts in nano-enabled drug delivery systems have also opened up newer, less-mature application areas that could significantly affect therapeutics in the future.

Creating New Therapeutic Opportunities

Nano-enabled drug delivery systems have been developed as highly adaptable vehicles capable of carrying a variety of payloads and incorporating desirable features such as controlled rate of release or specific targeting. As research efforts have improved these systems, other exciting application areas and technologies have emerged. While these systems are unlikely to reach the market by 2020, with research efforts and levels of interest in nano-enabled delivery systems increasing, breakthroughs could occur that

[586] Henry (2004).
[587] Uchegbu (2005); Henry (2004).

advance these technologies to a point at which they could have broad and substantial impact. These "wildcard" technologies include therapeutic delivery of DNA and RNA and the creation of multifunctional delivery systems.

Therapeutic Delivery of DNA and RNA

Unprecedented growth in the amount of genomic and proteomic information available has fueled the development of novel DNA- and RNA-based therapies to treat disease. While the most attention has been paid to gene therapy techniques, where delivered DNA is used to modify defective genes or replace missing ones, cellular delivery of DNA or RNA can also be used to silence expression of defective genes or stimulate immune response. These therapies have been billed as the medical treatments of the future,[588] yet after 15 years of investigation, few successes have been produced and concerns about the pathogenicity and toxicity of viral delivery vehicles remain. A critical factor in the realization of these therapies as medical treatments is the development of efficient nonviral delivery vehicles,[589] and nano-enabled delivery systems are providing new opportunities for these therapies.

Suitable delivery systems should be capable of condensing DNA or RNA into particles less than 200 nanometers for efficient intracellular uptake, protecting genetic material from degradation, and targeting delivery cell-specifically and intracellularly, with comparable efficiency to viral vectors.[590] Nano-enabled drug delivery systems, such as polymer nanoparticles, liposomes, lipid-polymer hybrid complexes, and dendrimers, have been used[591] to encapsulate DNA or RNA. While the efficiency of these systems has not yet reached comparable levels to that of viral vectors, they have been experiencing some success and are quickly becoming attractive alternative delivery systems.[592] Still, significant hurdles need to be overcome to bring these nano-enabled gene therapy systems to the clinic.

Transfer efficiencies of these systems need to be increased. Delivery vehicles need to be more specifically designed to address therapeutic goals by incorporating cell-specific or nuclear targeting strategies.[593] Additionally, cell-specific targeting strategies need to be examined to improve safety and efficacy of treatments by avoiding nonspecific incorporation of genetic material into immune cells, which can trigger severe immune reactions, lower therapeutic index for these treatments, and produce undesirable side effects.[594] Some new therapies have emerged to specifically target DNA and RNA products to immune cells as vaccines against cancer cells and invading organisms such as HIV, but careful reviews of these systems are necessary to evaluate the immune responses.[595]

As gene therapy applications continue to generate interest and funding, research efforts will continue to improve and advance nano-enabled gene delivery systems, and

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[588] Orive (2003).
[589] Check (2003).
[590] LaVan, Lynn, and Langer (2002).
[591] LaVan, Lynn, and Langer (2002); Gillies and Frechet (2005); Medina-Kauwe, Xie, and Hamm-Alvarez (2005).
[592] Nishikawa and Hashida (2003).
[593] Nishikawa and Hashida (2003); Pack et al. (2005).
[594] Nishikawa and Hashida (2003).
[595] Nishikawa and Hashida (2003).

significant therapeutic benefits could be brought to patients. Improved vaccines could result for DNA or RNA delivery to immune cells; proteins and peptides difficult to deliver could be produced in patients; and genetic diseases, such as hemophilia and cystic fibrosis, could be treated with new therapies.[596]

However, unexpected and unpredictable side effects have been created by gene therapy systems, and while these systems offer promising treatments, they do so at a significant risk.[597] Public perception and regulatory scrutiny are barriers to continued growth of these systems and their emergence on the market. While their appearance by 2020 is unlikely, if significant technological advancements are made and a clear demonstration of the safety of these systems is provided to regulators and the public, these systems could reach the clinic in that time.

Multifunctional Delivery Systems

In addition to providing suitable delivery vehicles for gene therapy applications, research efforts are also expanding the complexity of nano-enabled drug delivery systems to improve diagnostics and create more-tailored therapies by combining functional properties such as imaging and targeting with drug delivery.

As nano-enabled drug delivery systems have developed new opportunities for therapeutics, parallel research efforts have also developed these delivery systems to improve diagnostics. Imaging and contrast agents can be encapsulated, attached, or adsorbed by nano-enabled drug delivery systems to increase accessibility of imaging agents to tissues, improve signal sensitivity, and allow monitoring of complex cellular changes and events associated with disease.[598] Given the similarities in the delivery vehicles used for improving therapeutics and creating more powerful imaging agents, it is not difficult to imagine creating a multifunctional nano-enabled delivery vehicle capable of site-specifically targeting tissues and delivering both imaging agents and therapeutics.[599]

Liposomes, polymer nanoparticles, inorganic nanoparticles, and dendrimers are all being explored as multifunctional delivery systems. Liposomes and polymer nanoparticles could be utilized to encapsulate active compounds and display targeting ligands and imaging agents on their surfaces.[600] Dendrimers could be designed with distinct branches to conjugate targeting ligands, imaging agents, and active compounds,[601] and inorganic nanoparticles (silica, gold, or semiconductor materials) may be surface functionalized or used to encapsulate active compounds, imaging agents, and targeting ligands.[602]

While preliminary investigations of these multifunctional systems look promising, significant technological advances are still necessary. Robust conjugation strategies for attaching imaging agents and targeting ligands to single delivery vehicles need to be developed. Cell-specific targeting strategies need to be improved to increase intracellular

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[596] Pack et al. (2005).
[597] Pack et al. (2005).
[598] Sahoo and Labhasetwar (2003); Emerich and Thanos (2003); Sullivan and Ferrari (2004).
[599] McNeil (2005).
[600] McNeil (2005).
[601] Thomas et al. (2005).
[602] Akerman et al. (2002); Ozkan (2004); West and Halas (2003).

uptake and minimize nonspecific interactions. Efficient release strategies need to be incorporated to provide effective dosing levels to targeted sites, and better characterization of signal amplification and uniformity of these systems is needed.

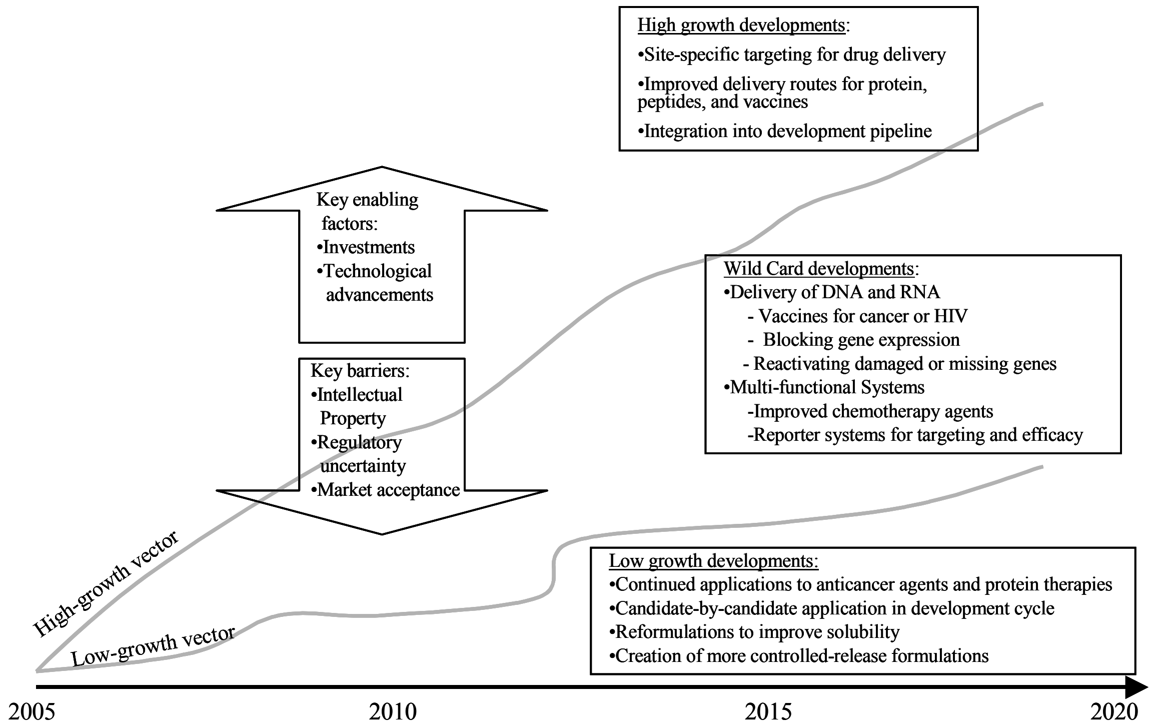
While it is more likely that functional combinations of targeting and imaging or targeting and drug delivery will reach the market in the next 15 years, as research efforts continue to improve conjugation strategies, targeting, and release profiles for nano-enabled reformulations, these improvements could accelerate the development of multifunctional delivery systems. These systems could then offer a range of new tools for tracking the distribution of active compounds through the body, providing dynamic feedback about drug release or accuracy of specific targeting, and monitoring and detecting molecular and cellular changes associated with disease states.[603] Additionally, new opportunities for "personalized medicine" could be developed by monitoring the efficacy of treatments and tailoring therapies to an individual's response.[604]

Discussion

Nano-enabled drug delivery systems have been growing rapidly over the past decade and are now poised to affect how drugs are developed and delivered to patients. These systems are offering attractive solutions for improving the efficacy and specificity of pharmaceuticals and addressing the challenges confronting pharmaceutical companies in managing life cycles and improving productivity. Although it is difficult to predict the influence these systems will have over pharmaceuticals in the next 15 years, the emergence of the first generation of these products on the market and the rapid pace of laboratory research gives some indication of their future growth opportunities and areas of impact. As discussed above, there are drivers and barriers for each area highlighted that could modulate the growth of nano-enabled drug delivery system and their impact in the future. Additionally, there are overarching drivers and barriers that will also determine the future path of these technologies. Figure E.1 shows the range of potential paths that nano-enabled drug delivery systems might take over the next 15 years and the relevant driver and barriers.

[603] McNeil (2005); Rudin and Weissleder (2003).
[604] McNeil (2005).

Figure E.1
Range of Possible Future Developments for Nano-Enabled Drug Delivery Systems



In an optimistic view, by 2020, technological advances and investments could drive nano-enabled drug delivery systems along the high growth trajectory. Site-specific targeting could be incorporated into delivery systems for anticancer agents and other drugs, improving delivery across membranes to the cellular and subcellular level. Oral, pulmonary, or transdermal administration routes could allow delivery of active compounds, proteins, and peptides without injection, so patients can safely treat themselves outside the clinic. Additionally, the incorporation of drug delivery platforms into development pipelines could bring more therapeutic candidates to market in a shorter amount of time and create new opportunities for more personalized therapies.

High-growth technological advances and investments could also drive the development of unlikely or wildcard technologies, such as nano-enabled gene therapy or multifunctional delivery vehicles. While it is more difficult to predict the future of these technologies, significant breakthroughs could bring nano-enabled systems that deliver therapeutic levels of DNA and RNA for vaccines or integrate functions such as targeting, imaging, and drug delivery to the market by 2020. However, certain barriers could slow the development of these nano-enabled systems and limit them to a lower growth trajectory.

Uncertainty in intellectual property status, regulatory reviews, and the market value of nano-enabled drug delivery systems could modulate their growth. Nano-enabled drug delivery systems that incorporate more modest changes or incremental improvements, such as increased solubility or controlled-release profiles, could see greater success in receiving approval at a lower risk to developers with these barriers. Drug delivery companies could continue to use these systems to incrementally improve the solubility or release profiles of high market share, off-patent drugs, such as anticancer agents or protein therapies. Pharmaceutical developers could use these systems to extend the life cycles of blockbuster drugs facing patent expirations, or they could integrate these systems into development pipelines on a candidate-by-candidate basis to bring potentially high market share, failed drug candidates to market.

Even with this range of potential growth paths, nano-enabled drug delivery systems could significantly change how pharmaceuticals are developed and delivered to patients, improving efficacy, quality of life, and convenience. As discussed in previous sections, many factors can influence the potential growth of these systems, but two key barriers, intellectual property status and regulatory uncertainty, can be addressed by policymakers to drive the development of these systems and ease their transition from the laboratory to the clinic.

Bringing new drugs or delivery systems to market is a time-consuming and expensive process. While reformulating off-patent pharmaceuticals can substantially lower costs,[605] there are still risks associated with pursuing nano-enabled delivery systems. As companies carefully examine their tolerance for risk and willingness to invest in these less-proven technologies, issues of intellectual property and regulatory barriers will affect future investments.[606]

Nanotechnology has stimulated a large growth in intellectual property patents, and the potential market value of nano-enabled drug delivery systems has driven companies to file for intellectual property patents at various stages of development for nano-enabled delivery systems, relevant technologies, processes, and methods of use.[607] These patenting strategies have resulted in broad and potentially overlapping patents being issued. While few disputes have been generated to date, as more companies try to commercialize their delivery systems, they face considerable uncertainty in patent protection.[608] Until court decisions or the U.S. Patent & Trademark Office clarifies the intellectual property status of these systems, this uncertainty could slow utilization of nano-enabled drug delivery systems in reformulation, delay investments in newer technologies, or restrict growth to systems with strong intellectual protections and exclusivity.[609]

In addition to concerns about protecting the exclusivity of these new delivery systems, the FDA approval process could also present significant barriers to the growth of nano-enabled drug delivery systems. Navigation through clinical trials to receive FDA approval is an area of high risk and cost for pharmaceutical developers. While the FDA has begun to streamline some of its processes and offer fast-track status to some pharmaceuticals, development times can still extend to as much as 12 years. Reformulations can often take an abbreviated path through the FDA pipeline and receive

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[605] Fleming and Ma (2002).
[606] Fleming and Ma (2002).
[607] Harris et al. (2004).
[608] Harris et al. (2004).
[609] Harris et al. (2004).

approval in two to four years.[610] For Abraxane, a nano-enabled reformulation of pacltiaxel, the FDA approval process took ten years.[611]

As more of these systems enter the FDA pipeline, regulatory issues about differentiating between similar technologies will arise, requiring approval processes for every combination or variation of drug and delivery systems and standards for new chemical entity status that will need to be met by these new reformulations.[612] If clear-cut guidelines do not emerge to smooth the regulatory path of these technologies in the future, the growth of these systems will be restricted.[613]

While regulatory bottlenecks, decreased investment, and slowing technological advancements could temper the growth of nanotechnology in the future, the development of increasingly specific drugs and the challenges confronting the pharmaceutical industry have developed firm ground for nano-enabled drug delivery systems to grow from in the future. Nano-enabled delivery systems will continue to bring improved formulations of off-patent drugs to the market, and while these systems may provide more incremental than high-impact improvements to therapeutics, as they continue to improve efficacy and convenience for patients, they will generate more research interest and investment.

[610] Fleming and Ma (2002).
[611] Weintraub (2005).
[612] Moradi (2005); Henry (2004).
[613] Basu (2003).

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APPENDIX F: TECHNOLOGY AND TERRORISM

Brian A. Jackson

Since the beginnings of modern terrorism in the 1970s, technological change has caused major shifts in the means applied by terrorist organizations and the context in which they must act to carry out their violence. With shifts in technology, the destructive potential of the weapons available to the terrorists has increased. With changes in the infrastructure and technologies integral to the functioning of modern societies, the targets they have available to choose from have shifted as well.

Over time, the characteristics of terrorism itself have changed. With the shift away from more-limited ideological, nationalist, or other self-constraining aims and toward apocalyptic or religious motivations, groups' desire to carry out attacks causing mass casualties has increased. This change has increased fears that such groups will pursue acquisition and use of unconventional attack forms such as chemical, biological, radiological, or nuclear weapons in an attempt to harm or kill increasing numbers of people. However, as the September 11, 2001, attacks on the United States revealed, such groups can also find ways to kill and injure large numbers of people without the need to resort to unusual weapons.

In the current environment of increasingly dramatic technological change, concern about how the terrorists of today and tomorrow may apply new technologies for malevolent ends are therefore understandable. At the same time that new technologies may provide capability and power to improve health and quality of life, they could also be applied in ways that damage or destroy, injure or kill. However, accurately predicting how terrorists might use technologies is difficult. For example, concern about widespread use of chemical and biological weapons by terrorist groups made over a number of years have, fortunately, not come to pass; conversely, as the actions of the September 11 hijackers and the insurgents in Iraq have shown, small groups can cause significant damage utilizing comparatively conventional means.

In an attempt to anticipate the potential impact of shifts in technology on terrorism over the next 15 years, this appendix addresses the following three topic areas:

- Technological change creating new vulnerabilities and targets
- Application of new technologies enabling or hindering terrorist operations
- New technologies providing potentially new weapons for terrorists.

Technological Change Creating New Vulnerabilities and Targets

Changes in technology, and the deployment of new technologies in society, can result in new vulnerabilities and targets for terrorist attack. Without an air transportation system, terrorists would have no planes to hijack. Without the Internet, cyberterrorism would not even be a meaningful concept, much less a risk.

Technologies are introduced because they are of value to individuals and to society. The use of the Internet as a medium for exchange of information, carrying out commerce, and communication creates significant economic value even as it creates associated risks. The concern over terrorist attack on petrochemical manufacturing infrastructure—turning an economic asset into a potential weapon of mass effect—is another example.[614] The economic benefit of efficient, centralized manufacturing brings with it the risks associated with large volumes of chemicals that could explode or, if released, harm people and property nearby. Similarly, the economic efficiencies that come from our efficient and centralized food production and processing system are part of what make it an attractive target for terrorist attack—either through introduction of pathogens that harm plants or animals or through contaminants that could potentially harm consumers of food products.

Technological change will likely continue to produce new systems that could be potential targets of terrorist attack. Increasing reliance on information technologies and databases to support economic activity could make computer systems and the Internet a more attractive target. While computer viruses that slow or freeze networks are now mostly a costly annoyance, if data being carried on these networks becomes increasingly time critical and valuable, such attacks could become much more impactful. Transition of telephone communications onto the public Internet (via VoIP [Voice over Internet Protocol] technologies) is one example. A transition toward technologies in which individual, decentralized devices communicate with the network to support their functioning—from the frequently cited example of a refrigerator that reorders food to home diagnostic devices that send medical information to doctors to monitor patient health—could similarly increase the costs of an attack on such networks. Just as terrorist contamination of consumer products or foodstuffs has the potential to cause harm, inspire fear, and produce economic damages, future biotechnology and nanotechnology products could similarly be targets of tampering. Attacks that successfully undermine public confidence in critical technological systems (successful spoofing of traffic in communications networks, misdirection or compromise of key financial transactions infrastructures, etc.) could affect the functioning of modern societies and economic costs that go well beyond the direct effects of the terrorists' actions.

The manner in which new technologies are introduced and developed could significantly reduce their vulnerability to attack or becoming vectors for terrorist attack on the nation overall. A significant concern about the vulnerability of national economies to terrorism is the dual impact that disruptions in transportation systems and the imposition of measures intended to prevent them could have on the production and distribution of products. Given the pressures on businesses to maximize efficiency, reduce inventories, and to streamline processes, many companies' inventory and production processes have become increasingly vulnerable to such disruptions. As technology develops and future products are introduced, increasing resilience could be introduced into supply chains to minimize the economic impacts of terrorism.[615] Some technology shifts could create inherently more robust production systems. For example, transitions to more-agile manufacturing systems or, more speculatively, decentralized

[614] Johnson (2002).
[615] "Terrorism's Impact on Supply Chain" (2004).

nanoscale manufacturing could involve much less dependence on vulnerable supply chain and transport systems.

Application of New Technologies Enabling or Hindering Terrorist Operations

Since September 11, 2001, the threat of terrorism has become a central driver for certain types of technology development. Efforts to improve sensors, develop new surveillance technologies, and construct new database systems are driven by societal desires to detect terrorist activities and identify terrorists before they have the opportunity to strike. The privacy-reducing components of many types of technologies—including some implementations of biometrics, use of interlinked databases to establish identity, etc.—could significantly reduce the ability of individuals to remain anonymous. Some of these changes have been driven by the market—without a direct connection to the threat of terrorism or efforts to combat it. As a result, some evolving trends in technology could make it significantly more difficult for terrorists to operate.

Such an outcome is not assured, however, even if such technologies are developed and implemented. At the same time that advances in sensing and surveillance attempt to weave a protective net around the nation, other technologies may facilitate slipping through those nets. For example, biometric technologies are not immune from impersonation attacks or the use of techniques to prevent them from identifying individuals. Today, terrorist groups have broadly adopted use of information and communication technologies, including encryption methods, to facilitate and safeguard their operational communications. The Internet, with the ability to broadly publish all types of information, provides the chance to share tactical and training information broadly, even among dispersed terrorist networks.

As well, nothing guarantees that all technologies intended to increase security will actually be beneficial, if they are confronted by a determined and adaptive adversary.[616] Even under persistent surveillance, if the terrorists can discover successful spoofing techniques to obscure their identity or adopt others' identities, it may be possible to continue operations unhindered. Depending on how much confidence is placed in such systems, the terrorist could have more operational freedom with the system than without it. Surveillance systems that can be penetrated or hacked by terrorists could even *enable* their operations—if surveillance cameras can be turned to their own use, the risk of being arrested carrying out video surveillance on potential targets will cease to be a concern.

New Technologies Providing Potentially New Weapons for Terrorists

While the opportunities that new technologies may present to terrorists as targets or as operational enablers are troubling, the potential for adversaries to actually use these technologies to develop new weapons and modes of attack is of even greater concern. Just as biotechnology and nanotechnology may transform society by their potentially beneficial effects, the power of those same technologies could provide malevolent actors with significantly increased capability to destroy property and cause injury or death.

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[616] Jackson et al. (2005); Jackson (2005).

Recent demonstrations such as the direct synthesis of viruses of concern from commercially obtained DNA strands, development of viruses that can circumvent vaccination, and other advances have led to concern that information reported in the open scientific literature may allow terrorists to develop advanced biological weapons.[617] Developments in nanotechnology have similarly raised fears about how those technologies might be applied by terrorists.[618] As increasing amounts of gene sequence data have become available with the completion of the human genome project, concerns have been raised that adversaries may be able to develop biological or other weapons that only affect specific target populations, reducing the chance that weapons would "blow back" and affect populations sympathetic to the terrorist group.[619] Past experience suggests, however, that such sophisticated use of these types of technologies by terrorist organizations would be far from straightforward and is therefore unlikely—especially within the next 15-year time frame.

The experience of Aum Shinrikyo, the Japanese apocalyptic cult that pursued both chemical and biological weapons and carried out the sarin attack on the Tokyo subway system, is instructive. Even possessing very significant material and technical resources, Aum's efforts produced more failure than success. In contrast to the highly technical activities described above, such as customizing natural biological agents or the de novo creation of agents designed based on the gene sequence of their intended targets, the activities Aum was undertaking were comparatively simple. Its failure to effectively produce biological agents or to generate and efficiently disseminate chemical weapons of known composition suggests that some serious roadblocks will hinder terrorist groups from carrying out the much more technical activities that would be required to fully take advantage of technological advances in these areas.

While the roadblocks to development of customized weapons of mass effect suggest that it is unlikely that non-state groups will successfully produce and deploy such technologies over the next 15 years, other technological changes could assist in reducing the height and impact of those barriers—and therefore merit attention and concern. The growing availability of commercial DNA synthesis, such as that used in the construction of the active virus described above, reduces the resources needed to access some types of biochemical capability. Further developments of laboratory equipment that automate or otherwise facilitate specific procedures, by encoding the needed knowledge in expert systems or in "off-the-shelf" kits for carrying out tasks, could similarly enable groups that otherwise lack the necessary expertise. Whether the scope of such developments will be sufficient to permit more advanced use of these technologies by clandestine groups is not clear, however. Similarly, such tools may make it possible for groups to make and deploy some types of agents—even if not the most sophisticated versions envisioned.

Furthermore, assessments must also consider "wildcards" that might allow malevolent actors to overcome or circumvent barriers that might otherwise make it difficult for a non-state group to independently acquire and use these technologies as weapons. Such a wildcard could be action by individuals who, because of their training or sensitive positions within institutions, already possess the knowledge needed to produce a technology of concern or already have access to "finished technologies" that could be

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[617] Smith, Inglesby, and O'Toole (2003).
[618] "Nanotechnology" (2003).
[619] Mates (2001).

used destructively. For example, a member of a laboratory who worked with dangerous pathogens (e.g., the recently synthesized 1918 pandemic strain of influenza[620]) could choose to use his or her expertise and access for malevolent purposes. The nature of modern technological training, research, and production will invariably produce individuals with knowledge that could be used destructively, an analog of the "insider threat" to all security regimes. This threat materializing will, however, depend on a range of factors, including the chance that individuals in such positions, either independently or through outside influence, choose to use their knowledge for destructive purposes or the ability of terrorist organizations to make longer-term investments in human capital and infiltration needed to generate opportunities where already sympathetic individuals could take such actions.

Even if terrorist groups are not able to use emerging technologies in ways that maximize their destructive potential, less-sophisticated applications of the technologies may still significantly contribute to the terrorist threat. In the past, terrorist groups have shown the creativity and willingness to use new technologies in nontraditional or unexpected ways. The use of airliners as a weapon and delivery system on September 11, 2001, is an obvious example; adaptation of cellular telephones and national communications infrastructures as explosives detonation mechanisms is another.

In these cases, the technologies are applied in ways that differ considerably from designers' original intent. In contrast, many of the concerns about biotechnology and nanotechnology assume that terrorists will apply these technologies in comparatively traditional ways. But groups could instead apply them in ways that differ considerably from traditional assumptions—"hacking" and adapting technologies rather than seeking to apply them in a standard way. Producing or modifying agents that, while not optimized for effectiveness, still strain and burden response systems is one possible scenario. As governments make additional investments in detection technologies in an attempt to protect their citizens from these weapons, terrorists might devote efforts to producing agents or materials that trip the detection systems, even if they pose little or no actual risk to individuals. Such strategies would be a way to turn a government's own efforts against itself by making the information streams coming from detection systems into a new avenue for attack.

Depending on the trajectory of the nano- and biotechnology fields, one could also envision terrorist actors simply capitalizing on societal uncertainty or discomfort about the technologies themselves to inspire fear. The potential impact of terrorist use of a radioactive "dirty" bomb is greatly magnified by general concerns about the dangers of radioactivity; as a result, even an attack with a comparatively small amount of damages and casualties initially could produce very large remediation costs during recovery from the incident. Concerns about the health impacts of nanoscale materials and potentially novel biological agents could be similarly used by terrorists to magnify the impact of an otherwise minor incident.

Similarly, appropriately trained individuals might be able to "hack" products or materials designed for beneficial purposes to hurt their users or, more broadly, to inspire terror in the population by demonstrating the possibility that technologies could be turned against us. Analogous to the contamination of Tylenol pain reliever capsules with cyanide in the 1980s, such product hacking could be particularly effective for new

[620] Tumpey et al. (2005).

technologies if consumers already harbor doubts about their safety and effectiveness. For example, if biotech treatments based on gene therapy are perfected and increase in usage, one could envision a group modifying a commercial product to insert a harmful gene rather than the intended beneficial one. The impact of such a strategy would build on preexisting societal discomfort with such technologies.

It should be noted, however, that use of advanced technologies and the development of more and more customized attack vectors can produce associated risks to the terrorist. Beyond the obvious dangers in working with and disseminating dangerous materials, increasing customization can provide counterterrorist forces with significant information to track and identify terrorist actors. In the past, such as in the conflict between the Provisional Irish Republican Army (PIRA) and British security forces, movement to more and more advanced weapons was a double-edged sword for the terrorist group. Although advanced bomb detonation technologies allowed PIRA more flexibility and the ability to circumvent many security measures, the incorporation of specialized electronic components also gave information to the security forces about the group's capabilities and aided in the apprehension of technical experts assisting the organization.[621] Similar arguments have been made regarding terrorist use of other customized weapons such as novel biologicals.[622]

[621] Jackson et al. (2005).
[622] Brown (2004).

APPENDIX G: SECTORAL IMPACTS OF TECHNOLOGY APPLICATIONS

This appendix provides additional information concerning the assignments of sectoral impact in Table 2.2 for technology applications with net assessment 5 and less (as noted in the main body of the report).

Hands-Free Computer Interface

Definition: The ability, e.g., via wearable computers, eyeglass lenses with video monitors, light beams scanned to the retina, and voice recognition, to process information and transmit and receive messages, while keeping hands free for other tasks.

Sectoral Impact: Products using this capability would likely serve a large global market. For example, the ability to create a personal "heads-up display" directly in the field of vision could be used to provide a map or directions, to identify or label parts, or to explain how to fix a device.[623] This would contribute to the economic development of countries and companies owning intellectual property or manufacturing, distributing, or selling components, devices, or systems. Hands-free computer interfaces could also be used in military applications—for example, to train and communicate with soldiers, to enable multitasking, and to support network-centric warfare.

In Silico Drug Research and Development

Definition: Drug discovery and development using computer modeling and simulation instead of laboratory research and clinical testing.

Sectoral Impact: The complexity of biological pathways and research choices, as well as designing, populating, performing, and evaluating clinical tests, is a key factor influencing the time required to discover and develop new drugs. The ability to use computer models and simulations to accomplish significant components of these tasks could greatly accelerate the development of new drugs, with potential influence on both individual and public health, as well as economic development of the pharmaceutical sector, and perhaps countries with significant unmet health challenges. This application could also potentially change the emphasis of drug development, allowing smaller companies to focus on less high-revenue pharmaceuticals.

Smart Textiles

Definition: Widespread availability of textiles that incorporate sensors and electronic processing, together with a means of actuation or communication to an actuator.

Sectoral Impact: Products made from smart textiles, such as clothing, carpets, upholstery, or wall or window treatments, could influence lifestyles by enabling monitoring and action at a distance—for example, controlling access to selected rooms, attending one event while participating remotely in another. Smart vests are already being used in a limited fashion for health monitoring. Smart textiles could make this a routine

[623] Lewis (2004).

and inconspicuous part of everyday life, with both civilian and military application. Both the textiles and their components would provide new opportunities for economic development.

Resistant Textiles

Definition: Widespread availability of textiles that are engineered to prevent adherence of contaminants.

Sectoral Impact: Textiles resistant to dirt and pathogens could be used in membranes to sanitize food and water sources and by food production and health care workers to prevent spread of infectious diseases. Textiles resistant to insects could also help to mitigate the spreading of disease. This could influence both health and population, especially in regions and countries with public health concerns that stem from unsanitary conditions.

Electronic Transactions

Definition: Widespread use of anonymous digital credentials and electronic cash.

Sectoral Impact: Online shopping and gift cards are precursors for this technology application. Adoption of electronic cash as the primary legal tender could have enormous influence on social structure, perhaps eliminating entire classes of jobs or requiring extensive retraining. Examples might include bank tellers, treasury workers, cashiers, and law enforcement personnel. Just as the availability of automatic teller machines changed schedules and enabled new types of crime, electronic transactions would change the way in which people deal with money, likely with many unforeseen consequences. New opportunities for economic development would also become available as financial structures change.

Genetic Screening

Definition: Capability to determine, by screening, whether an individual is more or less susceptible to specific diseases.

Sectoral Impact: Genetic screening could provide medical information that might affect lifestyle decisions and tailoring of preventative measures and treatments with potential influence on morbidity and mortality, and thus health and population.

Genetically Modified Insects

Definition: Genetic modification of pests so that, for example, they produce sterile offspring or do not carry specific pathogens.

Sectoral Impact: Elimination of agricultural pests such as bollworms could increase agricultural production and removal of pathogen-carrying capability of insects such as mosquitoes could address major public health problems of many developing countries, with influence on food, health, population, and economic development. Reduced need for pesticides would have a strong positive influence on the environment; however, the overall effect on ecosystems needs to be considered.

Unconventional Transport

Definition: Ultra-fuel-efficient means of transport through, for example, miniature cars or Segway-type vehicles.

Sectoral Impact: Such means of transport would reduce both energy consumption and environmental emissions while providing new transportation options for people in regions and countries lacking transportation infrastructure, as well as in rural areas, with potential influence on both social structure and governance. By providing means of transportation for people to jobs and for goods to market, this could also spur economic development.

Commercial Unmanned Aerial Vehicles (UAVs)

Definition: Commercial availability of remote-controlled, pilot-less aircraft with onboard sensors and specialized equipment.

Sectoral Impact: Commercial UAVs could be used to monitor resources such as forest and farm lands, wetlands, dams, reservoirs, wildlife (e.g., in nature reserves); fight fires; or direct environmental remediation, with influence on food, land, water, environment, and economic development. The military already uses this dual-use technology, so technological advances in commercial UAVs could have influence on defense.

Drug Development from Screening

Definition: Design and screening of molecules for drug development based on computational analysis of drug-related data.

Sectoral Impact: Improved computational methods that allow the real-time evaluation of vast quantities of drug-related scientific and clinical data could provide a means to screen large numbers of molecules to decide between different potential drug development programs, thus influencing the health sector, as well as life sciences and medical education.

Monitoring and Control for Disease Management

Definition: Widespread use of personal monitoring and on-demand drug delivery devices to control common diseases or medical conditions such as diabetes, epilepsy, hypertension, and elevated cholesterol.

Sectoral Impact: The capability for continuous monitoring and control of chronic conditions could free large numbers of people from medical-related restrictions and, for example, greatly reduce the need for blood samples, laboratory tests, and pill regimens—thus influencing both health and social structure.

Enhanced Medical Recovery

Definition: Use of advanced prosthetic devices (e.g., an auditory imager for the blind or devices that interact directly with the nervous system) to enhance physical or mental abilities after injury, illness, or stroke.

Sectoral Impact: Enabling a more rapid return to work would empower disabled individuals to play an active and productive role in society, thus influencing health, social structure, and economic development.

Secure Data Transfer

Definition: Widely accepted and routinely implemented means for removal of identity information, to allow secure transfer of personal data.

Sectoral Impact: The ability to protect identity information would enable increased growth of electronic commerce—influencing economic development—and could enable governments and financial institutions to access large data samples in order to analyze trends (e.g., money flows, extent of disease or medical conditions) and take appropriate actions, potentially influencing governance as well.

Print-to-Order Books

Definition: Publishing of individual books in response to specific orders only, with fast turnaround delivery.

Sectoral Impact: Publishing houses would respond directly to orders—for example, providing individual copies bound as requested or providing electronic files that could be used to print a specified number of copies in a specified format. In principle, the orders could come directly from consumers, from bookstores, or from distributors, so that this technology application would not *necessarily* have to radically change the way books are distributed. By potentially reducing costs associated with books that are printed and then either never sold or heavily discounted, it could affect economic development. By enabling more efficient distribution of specialized manuscripts and texts, it could potentially affect education as well.

Therapies Based on Stem Cell Research and Development (R&D)

Definition: Development of new medical treatments or drugs using results obtained through stem cell R&D.

Sectoral Impact: Because of the moral and ethical debate concerning stem cell R&D, decisions by government research sponsors and regulators will have a strong impact on both the performance of the R&D and the implementation of therapies based on R&D results. Stem cell R&D is focused on major debilitating diseases and injuries (e.g., dementia, Alzheimer's, paralysis from spinal cord injury), so therapies could have major impacts on health and social structure. Advances based on stem cell R&D could also potentially open up new avenues for medical research and education. Companies and countries with required technical or medical expertise, intellectual property, or pharmaceutical production capability could see increased economic development.

Chemical, Biological, Radiological, Nuclear (CBRN) Sensor Networks in Cities

Definition: Widespread implementation of networks of CBRN sensors in major cities to provide advance warning of public safety and health dangers from accident, attack, or natural sources.

Sectoral Impact: By providing advance warning, these sensor networks enable governments to take action to mitigate the effects of CBRN incidents, with potentially positive impacts on both health and environment. This technology also affects defense through its dual application in the civilian and military sectors.

CBRN Sensors on Emergency Response Technicians

Definition: Widespread integration of CBRN sensors into clothing or equipment used by emergency responders such as paramedics, firefighters, police officers, and hazmat crews.

Sectoral Impact: Integration of CBRN sensors into clothing or equipment would allow first responders to quickly evaluate their level of risk and take appropriate responsive action, affecting both their health and that of anyone else in the immediate vicinity. This technology application would also affect defense, since it could be used by military personnel as well.

Immunotherapy

Definition: Use of a patient's own immune cells to attack and destroy harmful substances in the body, such as tumors or microorganisms.

Sectoral Impact: By providing effective treatment for cancers that currently have a high mortality rate and potentially for such other serious diseases as AIDS, the successful development and widespread use of immunotherapy could affect both health and population.

Improved Treatments from Data Analysis

Definition: Development of improved medical treatments based on analysis of large standardized sets of data on individual patients and disease states.

Sectoral Impact: Improved medical treatments based on analysis of data would affect both patients' health and the education of medical professionals.

Smart Systems

Definition: Systems that respond to external stimuli or instructions—for example, buildings and roads that adjust properties based on environment, kitchens that cook with wireless instructions.

Sectoral Impact: Smart systems would provide opportunities for economic development of companies that own intellectual property or manufacture, distribute, sell, install, or maintain the systems, and of countries that lead in essential science, technology, or manufacturing, or provide large consumer markets.

Hydrogen Vehicles

Definition: Transportation systems that use hydrogen as a fuel.

Sectoral Impact: The replacement of petroleum-derived fuels (i.e., gasoline and diesel) and the internal combustion engine with hydrogen-based fuel cells could provide both individual and commercial vehicles with greatly reduced emissions, thus improving the environment, especially in urban areas. If efficient technology for the production, distribution, and storage of hydrogen is developed, hydrogen vehicles could also potentially increase the energy efficiency of the transportation sector.

Implants for Tracking and Identification

Definition: Widespread use of human implants that either emit or receive a signal that can be used for tracking and identification.

Sectoral Impact: Radio frequency identification (RFID) chip implants that contain a unique code have already been used to track school children and identify members of a private club. The FDA recently approved the use of an implantable RFID chip to hold personal medical records. Widespread use of this technology would raise serious privacy issues, provide opportunities for antisocial and criminal use of tracking information, and present governments with new regulatory challenges, influencing both governance and social structure. Potential impact on defense includes the military's use of this technology for tracking and identification of both friendly and hostile forces.

Gene Therapy

Definition: Therapies based on manipulation or alteration of the patient's genetic material.

Sectoral Impact: If gene therapy were successful in treating cancers—especially those for which other therapies have failed—and diseases of known genetic origin such as cystic fibrosis and muscular dystrophy, the impact on both health and population could be substantial.

Chip Implants for the Brain

Definition: Implantable computer chips that link directly to brain activity.

Sectoral Impact: By providing new options for disabled patients to reenter society (e.g., restoring sight or allowing motion through control of prosthetic devices), these chip implants could affect health and social structure. They would also provide for the development of new industries, both in treatment and in design and manufacturing, influencing economic development. They also could be put to military use.

Drugs Tailored to Genetics

Definition: Accelerated drug discovery and design tailored to genetic makeup.

Sectoral Impact: The tailoring of drugs to genetic makeup could potentially allow the development of drugs targeted for specific populations with specific health problems, with impact on both health and population.

Secure Video Monitoring

Definition: Capability to "lock" video surveillance images to allow viewing only after authorization (e.g., with a warrant).

Sectoral Impact: Secure video monitoring systems could potentially be used in many more places than current video monitors without compromising privacy, since access to the images could be controlled under strict legal requirements. This might provide more effective methods for investigating crime and fighting terrorism. It could also provide new options for increased use of surveillance by governments or criminals by defeating the security system using technical or other means. These developments could affect governance, social structure, and defense.

Biometrics as Sole Personal Identification

Definition: Biometric data (e.g., fingerprint, face recognition, hand geometry, iris) as sole requirement on all identification documents, such as passports and driver's licenses.

Sectoral Impact: Use of biometrics for identification would present governments with a means of positive identification to help monitor and control movement of people—for example, across borders. This could aid law enforcement in some countries and in others might be used by authorities against specific individuals or groups, with impact on governance and social structure. Defense applications include control of access to military bases.

Hospital Robotics

Definition: Widespread use of robotic tools to reduce stress and improve performance of hospital workers (but not to replace them).

Sectoral Impact: Use of robotic tools (e.g., to guide instruments or reduce unwanted movements) fits in well with current trends in medical procedures toward increased use of miniaturized devices and less invasive procedures using cameras inserted into the body, influencing both health and potentially the economic development of countries and companies that take the lead in developing, manufacturing, or using these tools.

Military Nanotechnologies

Definition: Use of nanotechnologies in ways that could potentially change the nature of warfare—for example, high-impact covert weapons or delivery of miniature payloads over large distances.

Sectoral Impact: If nanotechnologies were to emerge that could change the nature of warfare, governments and defense industries worldwide would likely invest substantial resources in addition to those already being spent on nanotechnology developments such as improved power systems, armor, sensors, medical treatments, and explosives, with impact on both defense and economic development.

Military Robotics

Definition: Use of robotic systems in military engagements.

Sectoral Impact: Military engagements using robots could in principle be fought under battlefield conditions in which human soldiers would not survive. If robotic systems were developed with superior capabilities to human-based systems, one could envision future battles (and perhaps conflicts) decided by robotic weapon systems. The technology would affect both defense and governance (e.g., decisions concerning the development and use of such advanced robotic weapon systems).

Xenotransplantation

Definition: Transplantation of animal organs or tissues into humans.

Sectoral Impact: Principal impact here is on health, since it is envisioned that xenotransplantation would be used only in very specific situations in which no viable human alternative exists and the procedure's efficacy has been clearly demonstrated.

Artificial Muscles and Tissues

Definition: Design and manufacture of fully functional muscles and other tissues, using molecular-level design and fabrication tools.

Sectoral Impact: Molecular design and fabrication of muscles and tissues could enable repair and replacement of damaged or poor-functioning organs, thus affecting health, and could enable treatment of wounded soldiers for rapid return to the battlefield, thus affecting defense.

Genetically Modified Animals for Research and Development

Definition: Animals whose genetic makeup has been specifically altered to serve as laboratory models for use in human disease research and development.

Sectoral Impact: By expanding the range of possible experiments and by allowing additional specificity to the experimental designs, genetically modified animals could facilitate the discovery of vaccines and therapies for diseases that affect large populations, influencing both health and population.

High-Tech Terrorism

Definition: Terrorism that attacks societal vulnerabilities arising from technological advances or that uses new weapons developed via technological advances.

Sectoral Impact*:* The potential for terrorist use of advanced technologies presents governments with challenges in assessing vulnerabilities and designing preventive strategies, including countermeasures and responses, affecting governance. High-tech terrorism threatens social institutions, affecting social structure, and requires consideration in defense planning and execution, affecting defense.

Memory-Enhancing Drugs

Definition: Drugs that strengthen memory or remove selected memories.

Sectoral Impact: By providing a means to overcome handicaps stemming from memory loss (e.g., age-induced) or recurring painful or damaging memories, such drugs could affect both health and social structure. They could also affect education by providing assistance in areas that require extensive memorization.

"Super Soldiers"

Definition: Soldiers with greatly enhanced capabilities—for example, strength, endurance, or enhanced senses.

Sectoral Impact: The availability of "super soldiers" would affect both defense and governance through the possible offensive and defensive uses of the enhanced capabilities and through the necessity of deciding when and under what conditions they should be used, respectively.

Genetic Selection of Offspring

Definition: Capability of parents to select the genetic makeup of their children.

Sectoral Impact: Because the capability simply to identify sex in the womb has already affected demographics in Asia (e.g., preponderance of males), there is little doubt that parents' ability to select the genetic makeup of their offspring would have significant impact on population. It would likely also affect health, by reducing the number of children suffering from genetically transmitted diseases.

Proxy Bot

Definition: A robot with human-like features and movements that could serve as a personal proxy.

Sectoral Impact: Such a robot could enable a person to be in "two places at once," which could significantly affect social structure, both by enabling new work patterns and by creating new forms of communication and interaction. The companies and countries that design, develop, manufacture, or perhaps provide services based on proxy bots could enjoy increased economic development, and defense applications might include use in accomplishing dangerous liaisons or in high-risk negotiations.

Quantum Computers

Definition: Digital computers that use quantum mechanical information to define the bits on which computation is based.

Sectoral Impact: It has been demonstrated that quantum computers would be able to easily perform certain operations that conventional computers would take impossibly long times to perform—for example, factoring of very large numbers. Their use to break codes would have substantial impact on defense and economic development (the latter through the banking and finance sectors, as well as through the development of a new industry). Quantum computers could also open up new fields of research, affecting education, at least at the graduate level.

Robotic Scientist

Definition: Robots that can perform self-defined experiments—for example, to test hypotheses on large data sets.

Sectoral Impact: Primary impact would be in the health sector, by significantly increasing the number of hypotheses that could be explored in searching for mechanisms of disease inception, progression, and spread, as well as new drugs and therapies.

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APPENDIX H:
INDEX OF SCIENCE AND TECHNOLOGY CAPACITY

Table H.1 provides detailed data on the science and technology capacities of various countries.

Table H.1
Country Index of Science and Technology Capacity

Country	(A) GNP per Capita	(B) Scientists and Engineers per Million Population	(C) S & T journal articles	(D) Expenditures for R & D (% of GNP)	(E) Institutions and Universities per Million Population	(F) Patents (USPTO and EPO)	(G) Adjusted Metric for Students Studying in USA
* United States	29240	3676	173233	2.6	63.65	315766	
* Japan	32350	4909	43655	2.8	1.74	117696	42198
* Germany	26570	2831	35294	2.4	6.59	61919	30475
* Canada	19170	2719	20989	1.7	91.75	12559	*25000*
Taiwan	*14634*	7710	4781	1.8	2.49	11289	15439
* Sweden	25580	3826	8227	3.8	9.78	7798	7415
* United Kingdom	21410	2448	39670	2.0	6.90	22081	25479
* France	24210	2659	26455	2.3	7.28	25730	14594
* Switzerland	39980	3006	6734	2.6	15.92	9076	7515
Israel	16180	*3977*	5227	2.4	30.17	3234	3589
* Korea, Rep	8600	2193	3960	2.8	0.97	9932	39470
* Finland	24280	2799	3786	2.8	30.58	3957	2318
* Australia	20640	3357	11830	1.8	24.79	4343	5332
* Iceland	*29946*	5339	*209*	1.5	4.34	39	388
* Denmark	33040	3259	3963	2.0	21.89	3001	2808
* Norway	34310	3664	2531	1.6	16.36	1321	3063
* Netherlands	24780	2219	10914	2.1	10.57	7877	4549
* Italy	20090	1318	16256	2.2	4.51	12021	6864
Russian Federation	2260	3587	17589	0.9	1.74	1103	12531
* Belgium	25380	2272	4711	1.6	12.35	4225	1803
* Ireland	18710	2319	1096	1.6	9.46	530	8732
* Austria	26830	1627	3269	1.5	22.47	3280	2628
Singapore	30170	2318	1082	1.1	5.31	523	1380
Slovenia	9780	2251	440	1.5	13.50	40	432
* New Zealand	14600	1663	2260	1.0	20.00	788	1921
* Spain	14100	1305	10557	0.9	3.07	1904	9040
* Luxembourg	*43475*	1305	*47*	0.9	1.11	209	95
Slovak Republic	3700	1866	1026	1.1	11.11	11	1912
Ukraine	980	2171	2428	*1.0*	0.58	105	3294
Belarus	2180	2248	589	1.1	1.18	15	775
* Czech Republic	5150	1222	1976	1.2	8.54	173	2717
Croatia	4620	1916	526	1.0	4.00	40	1171
Estonia	3360	2017	219	0.6	12.86	1	399
* Poland	3910	1358	4127	0.8	5.76	120	4081
Lithuania	2540	2028	181	0.7	2.43	7	877
Bulgaria	1220	1747	889	0.6	9.64	36	2326
Azerbaijan	480	2791		0.2	1.27	1	225
Cuba	*2194*	1612	147	0.8	2.16	12	80
China	750	454	7763	0.7	0.30	466	16175
Brazil	4630	168	3511	0.8	0.65	440	18127
* Hungary	4510	1099	1688	0.7	10.99	363	2312
* Portugal	10670	1182	968	0.6	4.20	77	893
Romania	1360	1387	721	0.7	2.67	240	1416
South Africa	3310	1031	2038	0.7	4.20	697	2999
India	440	149	8668	0.7	0.24	327	13064
* Greece	11740	773	2014	0.5	7.43	148	1842
Uzbekistan	950	1763	296	*0.3*	0.00	2	572
Latvia	2420	1049	148	0.4	9.17	4	474
Argentina	8030	660	1944	0.4	2.22	176	4255
Chile	4990	445	808	0.7	2.91	40	1530
* Mexico	3840	214	1758	0.3	0.56	272	12918
Moldova	380	330		0.9	0.93	3	451
Pakistan	470	72	254	0.9	0.43	2	2718
* Turkey	3160	291	1879	0.5	0.66	19	6160
Armenia	460	1485	166	*0.0*	1.05	1	330
Colombia	2470	0	178	*0.6*	0.56	20	5140
Macedonia	1290	1335		-	2.00	0	664
Venezuela	3530	209	398	0.5	1.34	109	3741
Mauritius	3730	361		0.4	7.50	1	85

Country	(H) GNP per Capita	(H) Scientists and Engineers per Million Population	(H) S & T journal articles	(H) Expenditures for R & D (% of GNP)	(H) Institutions and Universities per Million Population	(H) Patent (USPTO and EPO)	(H) Adjusted Metric for Students Studying in USA
* United States	2.42	2.20	13.15	2.72	5.72	11.13	
* Japan	2.75	3.15	3.15	2.94	-0.25	4.05	5.89
* Germany	2.15	1.55	2.50	2.43	0.22	2.06	4.13
* Canada	1.37	1.46	1.40	1.46	8.43	0.29	3.30
Taiwan	0.90	5.32	0.15	1.64	-0.18	0.25	1.86
* Sweden	2.04	2.32	0.41	4.19	0.52	0.12	0.65
* United Kingdom	1.61	1.25	2.84	1.84	0.25	0.64	3.38
* France	1.90	1.41	1.82	2.23	0.28	0.77	1.73
* Switzerland	3.55	1.68	0.30	2.68	1.12	0.17	0.67
Israel	1.06	2.43	0.18	2.36	2.49	-0.04	0.08
* Korea, Rep	0.27	1.05	0.08	2.97	-0.33	0.20	5.48
* Finland	1.91	1.52	0.07	2.91	2.53	-0.01	-0.12
* Australia	1.53	1.95	0.69	1.64	1.97	0.00	0.34
* Iceland	2.50	3.49	-0.21	1.27	0.00	-0.15	-0.41
* Denmark	2.82	1.88	0.08	1.84	1.69	-0.05	-0.04
* Norway	2.95	2.19	-0.03	1.36	1.16	-0.11	0.00
* Netherlands	1.96	1.07	0.62	2.01	0.60	0.13	0.22
* Italy	1.47	0.38	1.03	2.17	0.02	0.28	0.57
Russian Federation	-0.39	2.13	1.13	0.45	-0.25	-0.11	1.42
* Belgium	2.02	1.11	0.14	1.38	0.77	0.00	-0.19
* Ireland	1.32	1.15	-0.14	1.40	0.49	-0.14	0.85
* Austria	2.17	0.62	0.03	1.29	1.75	-0.04	-0.07
Singapore	2.52	1.15	-0.14	0.77	0.09	-0.14	-0.26
Slovenia	0.39	1.10	-0.19	1.20	0.88	-0.15	-0.40
* New Zealand	0.90	0.64	-0.05	0.66	1.51	-0.13	-0.17
* Spain	0.84	0.37	0.59	0.47	-0.12	-0.09	0.90
* Luxembourg	3.91	0.37	-0.22	0.47	-0.31	-0.15	-0.45
Slovak Republic	-0.24	0.80	-0.14	0.67	0.65	-0.15	-0.18
Ukraine	-0.53	1.04	-0.04	0.60	-0.36	-0.15	0.03
Belarus	-0.40	1.10	-0.18	0.69	-0.31	-0.15	-0.35
* Czech Republic	-0.09	0.30	-0.07	0.86	0.40	-0.15	-0.06
Croatia	-0.15	0.84	-0.18	0.64	-0.03	-0.15	-0.29
Estonia	-0.28	0.92	-0.21	0.04	0.82	-0.15	-0.40
* Poland	-0.22	0.41	0.10	0.30	0.14	-0.15	0.15
Lithuania	-0.36	0.93	-0.21	0.21	-0.18	-0.15	-0.33
Bulgaria	-0.50	0.71	-0.15	0.04	0.51	-0.15	-0.11
Azerbaijan	-0.58	1.52	-0.22	-0.42	-0.30	-0.15	-0.43
Cuba	-0.40	0.60	-0.21	0.40	-0.21	-0.15	-0.45
China	-0.55	-0.29	0.38	0.16	-0.39	-0.14	1.97
Brazil	-0.15	-0.51	0.05	0.36	-0.36	-0.14	2.27
* Hungary	-0.16	0.21	-0.09	0.19	0.64	-0.14	-0.12
* Portugal	0.48	0.27	-0.15	0.11	-0.01	-0.15	-0.33
Romania	-0.49	0.43	-0.17	0.24	-0.16	-0.15	-0.25
South Africa	-0.28	0.15	-0.07	0.21	-0.01	-0.13	-0.01
India	-0.58	-0.53	0.45	0.25	-0.40	-0.14	1.50
* Greece	0.60	-0.05	-0.07	-0.08	0.30	-0.15	-0.19
Uzbekistan	-0.53	0.72	-0.20	-0.31	-0.42	-0.15	-0.38
Latvia	-0.38	0.17	-0.21	-0.14	0.46	-0.15	-0.39
Argentina	0.21	-0.13	-0.07	-0.20	-0.21	-0.15	0.18
Chile	-0.11	-0.30	-0.16	0.19	-0.14	-0.15	-0.23
* Mexico	-0.23	-0.48	-0.09	-0.27	-0.36	-0.14	1.48
Moldova	-0.59	-0.39	-0.22	0.47	-0.33	-0.15	-0.40
Pakistan	-0.58	-0.59	-0.20	0.50	-0.38	-0.15	-0.05
* Turkey	-0.30	-0.42	-0.08	-0.11	-0.36	-0.15	0.46
Armenia	-0.58	0.51	-0.21	-0.64	-0.32	-0.15	-0.41
Colombia	-0.37	-0.64	-0.21	0.11	-0.36	-0.15	0.31
Macedonia	-0.49	0.39	-0.22	-0.70	-0.23	-0.15	-0.36
Venezuela	-0.26	-0.48	-0.19	-0.06	-0.29	-0.15	0.10
Mauritius	-0.24	-0.36	-0.22	-0.18	0.30	-0.15	-0.45

Country	(I) GNP per Capita	(I) Scientists and Engineers per Million Population	(I) S & T journal articles	(I) Expenditures for R & D (% of GNP)	(I) Institutions and Universities per Million Population	(I) Patent (USPTO and EPO)	(I) Adjusted Metric for Students Studying in USA	(J) INDEX
	1	3	2	3	1	1	1	
* United States	0.20	0.55	2.19	0.68	0.48	0.93		5.03
* Japan	0.23	0.79	0.52	0.74	-0.02	0.34	0.49	3.08
* Germany	0.18	0.39	0.42	0.61	0.02	0.17	0.34	2.12
* Canada	0.11	0.36	0.23	0.37	0.70	0.02	0.28	2.08
Taiwan	0.07	1.33	0.02	0.41	-0.01	0.02	0.16	2.00
* Sweden	0.17	0.58	0.07	1.05	0.04	0.01	0.05	1.97
* United Kingdom	0.13	0.31	0.47	0.46	0.02	0.05	0.28	1.73
* France	0.16	0.35	0.30	0.56	0.02	0.06	0.14	1.60
* Switzerland	0.30	0.42	0.05	0.67	0.09	0.01	0.06	1.60
Israel	0.09	0.61	0.03	0.59	0.21	0.00	0.01	1.53
* Korea, Rep	0.02	0.26	0.01	0.74	-0.03	0.02	0.46	1.49
* Finland	0.16	0.38	0.01	0.73	0.21	0.00	-0.01	1.48
* Australia	0.13	0.49	0.12	0.41	0.16	0.00	0.03	1.33
* Iceland	0.21	0.87	-0.03	0.32	0.00	-0.01	-0.03	1.32
* Denmark	0.24	0.47	0.01	0.46	0.14	0.00	0.00	1.31
* Norway	0.25	0.55	0.00	0.34	0.10	-0.01	0.00	1.22
* Netherlands	0.16	0.27	0.10	0.50	0.05	0.01	0.02	1.12
* Italy	0.12	0.09	0.17	0.54	0.00	0.02	0.05	1.00
Russian Federation	-0.03	0.53	0.19	0.11	-0.02	-0.01	0.12	0.89
* Belgium	0.17	0.28	0.02	0.35	0.06	0.00	-0.02	0.86
* Ireland	0.11	0.29	-0.02	0.35	0.04	-0.01	0.07	0.82
* Austria	0.18	0.15	0.00	0.32	0.15	0.00	-0.01	0.80
Singapore	0.21	0.29	-0.02	0.19	0.01	-0.01	-0.02	0.64
Slovenia	0.03	0.27	-0.03	0.30	0.07	-0.01	-0.03	0.60
* New Zealand	0.07	0.16	-0.01	0.16	0.13	-0.01	-0.01	0.49
* Spain	0.07	0.09	0.10	0.12	-0.01	-0.01	0.07	0.44
* Luxembourg	0.33	0.09	-0.04	0.12	-0.03	-0.01	-0.04	0.42
Slovak Republic	-0.02	0.20	-0.02	0.17	0.05	-0.01	-0.01	0.35
Ukraine	-0.04	0.26	-0.01	0.15	-0.03	-0.01	0.00	0.32
Belarus	-0.03	0.27	-0.03	0.17	-0.03	-0.01	-0.03	0.32
* Czech Republic	-0.01	0.08	-0.01	0.22	0.03	-0.01	0.00	0.29
Croatia	-0.01	0.21	-0.03	0.16	0.00	-0.01	-0.02	0.29
Estonia	-0.02	0.23	-0.03	0.01	0.07	-0.01	-0.03	0.20
* Poland	-0.02	0.10	0.02	0.08	0.01	-0.01	0.01	0.19
Lithuania	-0.03	0.23	-0.03	0.05	-0.02	-0.01	-0.03	0.16
Bulgaria	-0.04	0.18	-0.03	0.01	0.04	-0.01	-0.01	0.14
Azerbaijan	-0.05	0.38	-0.04	-0.11	-0.02	-0.01	-0.04	0.11
Cuba	-0.03	0.15	-0.04	0.10	-0.02	-0.01	-0.04	0.11
China	-0.05	-0.07	0.06	0.04	-0.03	-0.01	0.16	0.10
Brazil	-0.01	-0.13	0.01	0.09	-0.03	-0.01	0.19	0.10
* Hungary	-0.01	0.05	-0.02	0.05	0.05	-0.01	-0.01	0.10
* Portugal	0.04	0.07	-0.02	0.03	0.00	-0.01	-0.03	0.07
Romania	-0.04	0.11	-0.03	0.06	-0.01	-0.01	-0.02	0.05
South Africa	-0.02	0.04	-0.01	0.05	0.00	-0.01	0.00	0.04
India	-0.05	-0.13	0.07	0.06	-0.03	-0.01	0.13	0.04
* Greece	0.05	-0.01	-0.01	-0.02	0.02	-0.01	-0.02	0.00
Uzbekistan	-0.04	0.18	-0.03	-0.08	-0.03	-0.01	-0.03	-0.05
Latvia	-0.03	0.04	-0.04	-0.03	0.04	-0.01	-0.03	-0.07
Argentina	0.02	-0.03	-0.01	-0.05	-0.02	-0.01	0.01	-0.09
Chile	-0.01	-0.07	-0.03	0.05	-0.01	-0.01	-0.02	-0.11
* Mexico	-0.02	-0.12	-0.01	-0.07	-0.03	-0.01	0.12	-0.14
Moldova	-0.05	-0.10	-0.04	0.12	-0.03	-0.01	-0.03	-0.14
Pakistan	-0.05	-0.15	-0.03	0.12	-0.03	-0.01	0.00	-0.15
* Turkey	-0.02	-0.10	-0.01	-0.03	-0.03	-0.01	0.04	-0.17
Armenia	-0.05	0.13	-0.03	-0.16	-0.03	-0.01	-0.03	-0.19
Colombia	-0.03	-0.16	-0.03	0.03	-0.03	-0.01	0.03	-0.22
Macedonia	-0.04	0.10	-0.04	-0.17	-0.02	-0.01	-0.03	-0.22
Venezuela	-0.02	-0.12	-0.03	-0.01	-0.02	-0.01	0.01	-0.22
Mauritius	-0.02	-0.09	-0.04	-0.04	0.03	-0.01	-0.04	-0.22

Iran	1650	560	286	0.5	0.39	2	345			-0.46	-0.21	-0.20	-0.07	-0.38	-0.15	-0.41			-0.04	-0.05	-0.03	-0.02	-0.03	-0.01	-0.03	-0.22
Benin	380	176		*0.7*	0.34	0	103			-0.59	-0.51	-0.22	0.21	-0.39	-0.15	-0.45			-0.05	-0.13	-0.04	0.05	-0.03	-0.01	-0.04	-0.24
Yugoslavia, FR	*1124*	1099	487	-	1.79	13	1138			-0.51	0.21	-0.19	-0.70	-0.25	-0.15	-0.29			-0.04	0.05	-0.03	-0.17	-0.02	-0.01	-0.02	-0.25
Kuwait	*13976*	230	171	0.2	2.63	21	1056			0.83	-0.47	-0.21	-0.49	-0.17	-0.15	-0.31			0.07	-0.12	-0.03	-0.12	-0.01	-0.01	-0.03	-0.26
Hong Kong, China	23660	0	1743	-	1.49	1174	53			1.84	-0.64	-0.09	-0.70	-0.28	-0.11	-0.46			0.15	-0.16	-0.01	-0.17	-0.02	-0.01	-0.04	-0.27
Costa Rica	2770	532		0.2	4.00	23	1000			-0.34	-0.23	-0.22	-0.42	-0.03	-0.15	-0.31			-0.03	-0.06	-0.04	-0.11	0.00	-0.01	-0.03	-0.27
Bolivia	1010	172		0.5	2.15	2	580			-0.52	-0.51	-0.22	-0.05	-0.21	-0.15	-0.38			-0.04	-0.13	-0.04	-0.01	-0.02	-0.01	-0.03	-0.28
Egypt, Arab Rep.	1290	459	1192	0.2	0.64	5	2037			-0.49	-0.29	-0.13	-0.41	-0.36	-0.15	-0.16			-0.04	-0.07	-0.02	-0.10	-0.03	-0.01	-0.01	-0.29
Mongolia	380	910		-	3.46	0	726			-0.59	0.06	-0.22	-0.70	-0.09	-0.15	-0.36			-0.05	0.02	-0.04	-0.17	-0.01	-0.01	-0.03	-0.29
Turkmenistan	*582*	0		*0.6*	1.28	0	168			-0.57	-0.64	-0.22	0.08	-0.30	-0.15	-0.44			-0.05	-0.16	-0.04	0.02	-0.02	-0.01	-0.04	-0.30
Indonesia	640	182	*262*	0.1	0.31	37	11077			-0.56	-0.50	-0.20	-0.60	-0.39	-0.15	1.20			-0.05	-0.13	-0.03	-0.15	-0.03	-0.01	0.10	-0.30
Malaysia	3670	93	327	0.2	0.90	122	4760			-0.25	-0.57	-0.20	-0.38	-0.33	-0.15	0.25			-0.02	-0.14	-0.03	-0.10	-0.03	-0.01	0.02	-0.31
Uganda	310	21		0.6	0.24	0	326			-0.60	-0.63	-0.22	0.04	-0.40	-0.15	-0.42			-0.05	-0.16	-0.04	0.01	-0.03	-0.01	-0.03	-0.31
Thailand	2160	103	332	0.1	0.90	73	7549			-0.40	-0.56	-0.20	-0.53	-0.33	-0.15	0.67			-0.03	-0.14	-0.03	-0.13	-0.03	-0.01	0.06	-0.32
Kyrgyz Republic	380	584		0.2	0.00	0	332			-0.59	-0.19	-0.22	-0.44	-0.42	-0.15	-0.41			-0.05	-0.05	-0.04	-0.11	-0.03	-0.01	-0.03	-0.33
United Arab Emirates	17870	0		-	0.37	4	2107			1.24	-0.64	-0.22	-0.70	-0.38	-0.15	-0.15			0.10	-0.16	-0.04	-0.17	-0.03	-0.01	-0.01	-0.33
Togo	330	98		0.5	0.67	0	97			-0.60	-0.57	-0.22	-0.07	-0.36	-0.15	-0.45			-0.05	-0.14	-0.04	-0.02	-0.03	-0.01	-0.04	-0.33
Tajikistan	370	666		*0.1*	0.98	0	164			-0.59	-0.13	-0.22	-0.59	-0.32	-0.15	-0.44			-0.05	-0.03	-0.04	-0.15	-0.03	-0.01	-0.04	-0.34
Jordan	1150	94	157	0.3	4.35	8	827			-0.51	-0.57	-0.21	-0.36	0.00	-0.15	-0.34			-0.04	-0.14	-0.04	-0.09	0.00	-0.01	-0.03	-0.35
Tunisia	2060	125	158	0.3	1.51	1	252			-0.41	-0.55	-0.21	-0.31	-0.27	-0.15	-0.43			-0.03	-0.14	-0.04	-0.08	-0.02	-0.01	-0.04	-0.35
Philippines	1050	157	142	0.2	0.63	68	1486			-0.52	-0.52	-0.21	-0.41	-0.36	-0.15	-0.24			-0.04	-0.13	-0.04	-0.10	-0.03	-0.01	-0.02	-0.37
Uruguay	6070	0		*0.2*	3.64	11	319			0.00	-0.64	-0.22	-0.50	-0.07	-0.15	-0.42			0.00	-0.16	-0.04	-0.13	-0.01	-0.01	-0.03	-0.38
Kazakhstan	1340	0		0.3	0.71	3	1024			-0.49	-0.64	-0.22	-0.28	-0.35	-0.15	-0.31			-0.04	-0.16	-0.04	-0.07	-0.03	-0.01	-0.03	-0.38
Gabon	4170	234		*0.0*	5.00	1	95			-0.19	-0.46	-0.22	-0.70	0.06	-0.15	-0.45			-0.02	-0.12	-0.04	-0.17	0.01	-0.01	-0.04	-0.39
Saudi Arabia	6910	0	660	-	0.53	41	3848			0.09	-0.64	-0.17	-0.70	-0.37	-0.15	0.12			0.01	-0.16	-0.03	-0.17	-0.03	-0.01	0.01	-0.39
Sri Lanka	810	191		*0.2*	0.64	4	656			-0.54	-0.50	-0.22	-0.46	-0.36	-0.15	-0.37			-0.05	-0.12	-0.04	-0.12	-0.03	-0.01	-0.03	-0.39
Nepal	210	*40*		*0.3*	0.22	0	1041			-0.61	-0.61	-0.22	-0.33	-0.40	-0.15	-0.31			-0.05	-0.15	-0.04	-0.08	-0.03	-0.01	-0.03	-0.40
Burundi	140	33		0.3	0.15	0	42			-0.61	-0.62	-0.22	-0.29	-0.40	-0.15	-0.46			-0.05	-0.15	-0.04	-0.07	-0.03	-0.01	-0.04	-0.40
Guatemala	1640	104		0.2	0.83	5	774			-0.46	-0.56	-0.22	-0.49	-0.34	-0.15	-0.35			-0.04	-0.14	-0.04	-0.12	-0.03	-0.01	-0.03	-0.41
Congo, Dem. Rep.	680	*460*		-	0.04	1	33			-0.56	-0.29	-0.22	-0.70	-0.42	-0.15	-0.46			-0.05	-0.07	-0.04	-0.17	-0.03	-0.01	-0.04	-0.42
Iraq	*10195*	0		-	0.45	0	36			0.44	-0.64	-0.22	-0.70	-0.38	-0.15	-0.46			0.04	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.42
Peru	2440	233		-	1.01	10	1154			-0.37	-0.46	-0.22	-0.70	-0.32	-0.15	-0.29			-0.03	-0.12	-0.04	-0.17	-0.03	-0.01	-0.02	-0.42
Syrian Arab Republic	1020	30	*70*	0.2	0.46	1	374			-0.52	-0.62	-0.22	-0.44	-0.38	-0.15	-0.41			-0.04	-0.15	-0.04	-0.11	-0.03	-0.01	-0.03	-0.42
Central African Republic	300	56		*0.2*	0.57	0	15			-0.60	-0.60	-0.22	-0.44	-0.36	-0.15	-0.46			-0.05	-0.15	-0.04	-0.11	-0.03	-0.01	-0.04	-0.43
Vietnam	350	*308*		-	0.25	2	1433			-0.59	-0.40	-0.22	-0.70	-0.40	-0.15	-0.25			-0.05	-0.10	-0.04	-0.17	-0.03	-0.01	-0.02	-0.43
Ecuador	1520	146		0.0	1.31	11	1805			-0.47	-0.53	-0.22	-0.67	-0.29	-0.15	-0.19			-0.04	-0.13	-0.04	-0.17	-0.02	-0.01	-0.02	-0.43
Panama	2990	0		*0.1*	1.07	1	904			-0.32	-0.64	-0.22	-0.57	-0.32	-0.15	-0.33			-0.03	-0.16	-0.04	-0.14	-0.03	-0.01	-0.03	-0.43
Georgia	970	0		*0.1*	3.33	1	538			-0.53	-0.64	-0.22	-0.57	-0.10	-0.15	-0.38			-0.04	-0.16	-0.04	-0.14	-0.01	-0.01	-0.03	-0.44
Burkina Faso	240	17		0.2	0.28	0	70			-0.60	-0.63	-0.22	-0.45	-0.39	-0.15	-0.45			-0.05	-0.16	-0.04	-0.11	-0.03	-0.01	-0.04	-0.44
Guinea	530	*265*		-	1.27	0	261			-0.57	-0.44	-0.22	-0.70	-0.30	-0.15	-0.43			-0.05	-0.11	-0.04	-0.17	-0.02	-0.01	-0.04	-0.44
Madagascar	260	12		0.2	0.27	1	91			-0.60	-0.63	-0.22	-0.46	-0.39	-0.15	-0.45			-0.05	-0.16	-0.04	-0.12	-0.03	-0.01	-0.04	-0.44
Guinea-Bissau	160	0		-	7.50	0	25			-0.61	-0.64	-0.22	-0.70	0.30	-0.15	-0.46			-0.05	-0.16	-0.04	-0.17	0.03	-0.01	-0.04	-0.45
Oman	*5946*	0		-	0.43	0	482			-0.01	-0.64	-0.22	-0.70	-0.38	-0.15	-0.39			0.00	-0.16	-0.04	-0.17	-0.03	-0.01	-0.03	-0.45
Botswana	3070	0		-	3.75	0	265			-0.31	-0.64	-0.22	-0.70	-0.06	-0.15	-0.42			-0.03	-0.16	-0.04	-0.17	0.00	-0.01	-0.04	-0.45
Jamaica	1740	0		-	3.08	0	1524			-0.45	-0.64	-0.22	-0.70	-0.12	-0.15	-0.23			-0.04	-0.16	-0.04	-0.17	-0.01	-0.01	-0.02	-0.45
Lebanon	3560	0	*80*	-	1.67	6	786			-0.26	-0.64	-0.22	-0.70	-0.26	-0.15	-0.35			-0.02	-0.16	-0.04	-0.17	-0.02	-0.01	-0.03	-0.46
Nigeria	300	15	401	0.1	0.22	4	899			-0.60	-0.63	-0.19	-0.58	-0.40	-0.15	-0.33			-0.05	-0.16	-0.03	-0.14	-0.03	-0.01	-0.03	-0.46
Libya	*5930*	0		-	0.00	0	5			-0.01	-0.64	-0.22	-0.70	-0.42	-0.15	-0.46			0.00	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.46
Trinidad Tobago	4520	0		-	0.00	4	838			-0.16	-0.64	-0.22	-0.70	-0.42	-0.15	-0.34			-0.01	-0.16	-0.04	-0.17	-0.03	-0.01	-0.03	-0.46
Kenya	350	0	258	-	1.02	4	2780			-0.59	-0.64	-0.20	-0.70	-0.32	-0.15	-0.05			-0.05	-0.16	-0.03	-0.17	-0.03	-0.01	0.00	-0.46
Nicaragua	370	204		-	0.21	1	369			-0.59	-0.49	-0.22	-0.70	-0.40	-0.15	-0.41			-0.05	-0.12	-0.04	-0.17	-0.03	-0.01	-0.03	-0.46
Bangladesh	350	52	141	0.0	0.21	0	825			-0.59	-0.60	-0.21	-0.66	-0.40	-0.15	-0.34			-0.05	-0.15	-0.04	-0.16	-0.03	-0.01	-0.03	-0.47
Zimbabwe	620	0		-	2.91	1	573			-0.56	-0.64	-0.22	-0.70	-0.14	-0.15	-0.38			-0.05	-0.16	-0.04	-0.17	-0.01	-0.01	-0.03	-0.47
Namibia	1940	0		-	1.76	0	137			-0.43	-0.64	-0.22	-0.70	-0.25	-0.15	-0.44			-0.04	-0.16	-0.04	-0.17	-0.02	-0.01	-0.04	-0.48
Senegal	520	3		0.0	1.89	0	559			-0.58	-0.64	-0.22	-0.68	-0.24	-0.15	-0.38			-0.05	-0.16	-0.04	-0.17	-0.02	-0.01	-0.03	-0.48
Dominican Republic	1770	0		-	0.48	3	762			-0.44	-0.64	-0.22	-0.70	-0.37	-0.15	-0.35			-0.04	-0.16	-0.04	-0.17	-0.03	-0.01	-0.03	-0.48
El Salvador	1850	20		-	0.49	2	368			-0.44	-0.63	-0.22	-0.70	-0.37	-0.15	-0.41			-0.04	-0.16	-0.04	-0.17	-0.03	-0.01	-0.03	-0.48
Rwanda	230	35		0.0	0.62	0	87			-0.61	-0.62	-0.22	-0.64	-0.36	-0.15	-0.45			-0.05	-0.15	-0.04	-0.16	-0.03	-0.01	-0.04	-0.48
Morocco	1240	0	244	-	0.32	4	888			-0.50	-0.64	-0.20	-0.70	-0.39	-0.15	-0.33			-0.04	-0.16	-0.03	-0.17	-0.03	-0.01	-0.03	-0.48
Papua New Guinea	890	0		-	1.96	0	59			-0.54	-0.64	-0.22	-0.70	-0.23	-0.15	-0.46			-0.04	-0.16	-0.04	-0.17	-0.02	-0.01	-0.04	-0.49
Paraguay	1760	0		-	0.19	1	431			-0.45	-0.64	-0.22	-0.70	-0.40	-0.15	-0.40			-0.04	-0.16	-0.04	-0.17	-0.03	-0.01	-0.03	-0.49
Ghana	390	0		-	0.97	1	823			-0.59	-0.64	-0.22	-0.70	-0.33	-0.15	-0.34			-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.03	-0.49
Zambia	330	0		-	1.86	0	284			-0.60	-0.64	-0.22	-0.70	-0.24	-0.15	-0.42			-0.05	-0.16	-0.04	-0.17	-0.02	-0.01	-0.04	-0.49
Malawi	210	0		-	2.00	0	193			-0.61	-0.64	-0.22	-0.70	-0.23	-0.15	-0.44			-0.05	-0.16	-0.04	-0.17	-0.02	-0.01	-0.04	-0.49
Honduras	740	0		-	0.81	7	572			-0.55	-0.64	-0.22	-0.70	-0.34	-0.15	-0.38			-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.03	-0.49
Algeria	1550	0	140	-	0.10	1	188			-0.47	-0.64	-0.21	-0.70	-0.41	-0.15	-0.44			-0.04	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.49
Tanzania	220	0		-	0.75	0	752			-0.61	-0.64	-0.22	-0.70	-0.35	-0.15	-0.35			-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.03	-0.49
West Bank and Gaza	1560	0		-	0.00	0	240			-0.47	-0.64	-0.22	-0.70	-0.42	-0.15	-0.43			-0.04	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.49
Côte d'Ivoire	700	0		-	0.83	0	266			-0.56	-0.64	-0.22	-0.70	-0.34	-0.15	-0.42			-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.49
Cameroon	610	0		-	0.91	0	246			-0.57	-0.64	-0.22	-0.70	-0.33	-0.15	-0.43			-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.49
Bosnia and Herzegovina	*1061*	0		-	0.00	0	429			-0.52	-0.64	-0.22	-0.70	-0.42	-0.15	-0.40			-0.04	-0.16	-0.04	-0.17	-0.03	-0.01	-0.03	-0.50
Lesotho	570	0		-	0.95	0	16			-0.57	-0.64	-0.22	-0.70	-0.33	-0.15	-0.46			-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.50
Albania	810	0	*32*	-	0.00	1	396			-0.54	-0.64	-0.22	-0.70	-0.42	-0.15	-0.40			-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.03	-0.50
Gambia	340	0		-	0.83	0	152			-0.59	-0.64	-0.22	-0.70	-0.34	-0.15	-0.44			-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.50

Haiti	410	0		-	0.26	2	363	-0.59	-0.64	-0.22	-0.70	-0.39	-0.15	-0.41	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.03	-0.50
Congo, Rep.	110	0		-	0.71	1	197	-0.62	-0.64	-0.22	-0.70	-0.35	-0.15	-0.43	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.50
Ethiopia	100	0		-	0.33	0	401	-0.62	-0.64	-0.22	-0.70	-0.39	-0.15	-0.40	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.03	-0.50
Mali	250	0		-	0.57	0	143	-0.60	-0.64	-0.22	-0.70	-0.36	-0.15	-0.44	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.50
Mauritania	410	0		-	0.40	0	58	-0.59	-0.64	-0.22	-0.70	-0.38	-0.15	-0.46	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.50
Angola	380	0		-	0.08	0	231	-0.59	-0.64	-0.22	-0.70	-0.41	-0.15	-0.43	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.50
Sudan	290	0		-	0.14	0	219	-0.60	-0.64	-0.22	-0.70	-0.41	-0.15	-0.43	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.50
Yemen	280	0		-	0.00	0	306	-0.60	-0.64	-0.22	-0.70	-0.42	-0.15	-0.42	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.03	-0.50
Sierra Leon	140	0		-	0.41	0	76	-0.61	-0.64	-0.22	-0.70	-0.38	-0.15	-0.45	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.51
Niger	200	0		-	0.30	0	46	-0.61	-0.64	-0.22	-0.70	-0.39	-0.15	-0.46	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.51
Cambodia	260	0		-	0.09	0	130	-0.60	-0.64	-0.22	-0.70	-0.41	-0.15	-0.44	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.51
Myanmar	*282*	0		-	0.02	1	150	-0.60	-0.64	-0.22	-0.70	-0.42	-0.15	-0.44	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.51
Mozambique	210	0		-	0.18	0	99	-0.61	-0.64	-0.22	-0.70	-0.40	-0.15	-0.45	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.51
Korea, Dem. Rep.	*430*	0		-	0.00	0	32	-0.58	-0.64	-0.22	-0.70	-0.42	-0.15	-0.46	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.51
Lao PDR	320	0		-	0.00	0	75	-0.60	-0.64	-0.22	-0.70	-0.42	-0.15	-0.45	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.51
Chad	230	0		-	0.00	0	46	-0.61	-0.64	-0.22	-0.70	-0.42	-0.15	-0.46	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.51
Eritrea	200	0		-	0.00	0	44	-0.61	-0.64	-0.22	-0.70	-0.42	-0.15	-0.46	-0.05	-0.16	-0.04	-0.17	-0.03	-0.01	-0.04	-0.51
	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(H)	(H)	(H)	(H)	(H)	(H)	(I)	(I)	(I)	(I)	(I)	(I)	(I)	(J)

(A) Gross national product per capita for 1998 [World Bank, World Development Indicators, 2000. http://www.worldbank.org/data/wdi2000/pdfs/tab1_1.pdf] Data from other sources, including United Nations Statistics [http://www.un.org/Depts/unsd/social/inc-eco.htm], are indicated in italics.

(B) Number of scientists and engineers in R&D per 1 million population [World Bank, World Development Indicators 2000. http://www.worldbank.org/data/wdi2000/pdfs/tab5_12.pdf] Additional data obtained from the "Second European Report on Science and Technology Indicators" S-59, December 1997, EUR 17639 and the 1998 World Science Report, UNESCO, Paris., in all cases the most recent data accessible was used. Values from these additional sources are indicated in italics.

(C) Number of science and technology journal articles published in 1995-1997 average values [Science Indicators 2000, National Science Foundation]. Additional values (indicated in itallics) were obtained from "Second European Report on Science and Technology Indicators" S-59, December 1997, EUR 17639 and are measures for 1995 article publications.

(D) Expenditures on R&D as a percentage of the GNP, data for the latest year available 1987-1997 [World Bank, World Development Indicators 2000, http://www.worldbank.org/data/wdi2000/pdfs/tab5_12.pdf] Additional data (indicated in italics) obtained from varied sources including the 1998 World Science Report and are for the most recent year accessible.

(E) The number of scientific research institutions (universities, institutes, etc.) per million population [Research Centers and Services Directories, The Gale Group, http://galenet.gale.com/a/acp/db/rcsd and World Bank, World Development Indicators 2000, http://www.worldbank.org/data/wdi2000/pdfs/tab2_1.pdf].

(F) Total number of US patents filed 1997-1999 and EPO Patents filed 1992-1994 by Citizens of the Country (most recent years available) ["Patent Counts by Country/State and Year, All Patents, All Types, Jan 1, 1977-Dec 21, 1999" USPTO, DOC, March 2000 and "Second European Report on Science and Technology Indicators" S-59, December 1997, EUR 17639].

(G) Total Number of US F-1 and J-1 Student Visas issued minus 3/4 the number of student visas converted to US permanent resident status in 1998 [US State Department Internet Site, Data for FY 1997, http://travel.state.gov/1997niv.pdf and US Immigration and Naturalization Service Statistical Yearbook 1998, http://www.ins.gov/graphics/aboutins/statistics/imm98.pdf] Canadian number from parlimentary debate on the subject (1998) since visa numbers do not correctly reflect student exchange between the two countries.

(H) Values from the corresponding column (A through G) converted to a comparative index by determining the number of standard deviations which the value of the national characteristic is away from the international average in that characteristic. Positive values indicate that the nation's value exceeds the international average.

(I) Weighted values of the scaled index parameters (seven columns labeled H) using the weighting factors at the top of the column to generate each factor's contribution to the overall scientific capacity index.

(J) Overall Index of Scientific Capacity - calculated as a sum of the weighted factor values (seven columns labeled I).

NOTES: Values indicated in reduced boldface came from a number of unofficial Internet sources and should, at best, be considered educated estimates. * Indicates OECD member states.

APPENDIX I: 2005 FREEDOM RATING FOR 29 SELECTED COUNTRIES

Table I.1 presents data from Freedom House's Freedom in the World 2005 data.

Table I.1
Freedom in the World 2005 Country Ratings

	Country	Political Rights	Civil Liberties	Freedom Rating
1.	Australia	1	1	Free
2.	Brazil	2	3	Free
3.	Canada	1	1	Free
4.	Chile	1 (+)	1	Free
5.	Dominican Republic	3 (–)	2	Free
6.	Germany	1	1	Free
7.	India	2	3	Free
8.	Israel	1	3	Free
9.	Japan	1	2	Free
10.	Mexico	2	2	Free
11.	Poland	1	2	Free
12.	South Africa	1	2	Free
13.	South Korea	2	2	Free
14.	United States	1	1	Free
15.	Colombia	4	4	Partly free
16.	Fiji (–)	4	3	Partly free
17.	Georgia	4	4	Partly free
18.	Indonesia	3	4	Partly free
19.	Jordan	5 (+)	5	Partly free
20.	Kenya	3 (+)	3 (+)	Partly free
21.	Nepal	5 (–)	4	Partly free
22.	Pakistan	6	5	Partly free
23.	Russia (–)	5	5	Partly free
24.	Turkey	3	4	Partly free
25.	Cameroon (–)	6	6	Not free
26.	Chad	6	5	Not free
27.	China	7	6	Not free
28.	Egypt	6	6	Not free
29.	Iran	6	6	Not free

SOURCE: Freedom House (2005).
NOTE: Countries are listed from most to least free in alphabetical order. The freedom ratings reflect an overall judgment based on survey results. 1 represents the most free, and 7 the least free. (+) and (–) indicate a change in political rights or civil liberties since the last survey and indicate a general trend in freedom for these countries.

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APPENDIX J: HDI RANK, SCORES, AND DEVELOPMENT INDICATOR STATISTICS FOR 29 SELECTED COUNTRIES

Table J.1 presents data from the United Nations Development Programme.

Table J.1
Human Development Reports Statistics for 2005

Regions and Selected Countries	HDI Rank [out of 177 countries] and score in 2003[a]		GDP (per capita, PPP value, US$, 2003)	Population (total size in millions)		Population Under Age 15 (% of total)		Physicians (per 100,000 people)[c]	Population with Sustainable Access to Affordable Essential Drugs[d] (%)	Population with Sustainable Access to an Improved Water Source[e] (%)	Under-nourished People 1999/2001 Average (% of total population)	HIV Prevalence 2003[f] (% ages 15–49)	Internet Users in 2002 (per 1,000 people)	Public Spending on Education 1999–2001[g] (% of GDP)	R&D Spending (% of GDP)[h] 1996–2002	Electricity Consumption Per Capita in 2001 (kilowatt-hours)
	Rank	Score		2002[b]	2015[b]	2002[b]	2015[b]									
Asia																
China	85	0.755	5,003	1,294.9	1,402.3	23.7	19.4	164	80–94	75	11	0.1 [0.1–0.2]	46.0	N.A.	1.1	1.139
India	127	0.602	2,892	1,049.5	1,246.4	33.3	27.7	51	0–49	84	21	[0.4–1.3]	15.9	4.1	N.A.	561
Indonesia	110	0.697	3,361	217.1	250.4	29.9	25.3	16	80–94	78	6	0.1 [0.0–0.2]	37.7	1.3	N.A.	469
Japan	11	0.943	27,967	127.5	127.2	14.3	13.0	202	95–100	N.A.	N.A.	<0.1 [<.02]	448.9	3.6	3.1	8,203
Nepal	136	0.526	1,420	24.6	32.0	40.2	35.6	5	0–49	88	17	0.3 [0.2–0.5]	3.4	3.4	N.A.	63
Pakistan	135	0.527	2,097	149.9	204.5	41.5	38.1	68	50–79	83	19	0.1 [0.0–0.2]	10.3	1.8	N.A.	479
South Korea	28	0.901	17,971	47.4	49.7	20.3	15.5	180	95–100	93	N.A.	<0.1 [<0.2]	551.9	3.6	3.0	6,632
Oceania																
Australia	3	0.955	29,632	19.5	21.7	20.1	17.3	247	95–100	100	N.A.	0.1 [0.1–0.2]	481.7	4.6	1.5	11,205
Fiji	92	0.752	5,880	0.8	0.9	32.7	27.6	34	95–100	47	N.A.	0.1 [0.0–0.2]	61.0	5.5	N.A.	633
North Africa & Middle East																
Egypt	119	0.659	3,950	70.5	90.0	35.2	31.7	218	80–94	97	3	<0.1 [<0.2]	28.2	N.A.	0.2	1,129
Iran	99	0.736	6,995	68.1	81.4	32.6	26.8	110	80–94	92	5	0.1 [0.1–0.2]	48.5	5.0	N.A.	1,985
Israel	23	0.915	20,033	6.3	7.8	27.9	24.8	375	95–100	N.A.	N.A.	0.1 [0.1–0.2]	301.4	7.3	5.0	6,591
Jordan	90	0.753	4,300	5.3	7.0	38.0	31.6	205	95–100	N.A.	N.A.	N.A.	57.7	4.6	6.3	1,507

Regions and Selected Countries	HDI Rank [out of 177 countries] and score in 2003[a]		GDP (per capita, PPP value, US$, 2003)	Population (total size in millions)		Population Under Age 15 (% of total)		Physicians (per 100,000 people)[c]	Population with Sustainable Access to Affordable Essential Drugs[d] (%)	Population with Sustainable Access to an Improved Water Source[e] (%)	Under-nourished People 1999/2001 Average (% of total population)	HIV Prevalence 2003[f] (% ages 15–49)	Internet Users in 2002 (per 1,000 people)	Public Spending on Education 1999–2001[g] (% of GDP)	R&D Spending (% of GDP)[h] 1996–2002	Electricity Consumption Per Capita in 2001 (kilowatt-hours)
	Rank	Score		2002[b]	2015[b]	2002[b]	2015[b]									
Europe																
Georgia	100	0.732	2,588	5.2	4.7	19.2	15.2	463	0–49	79	26	0.2 [0.1–0.4]	14.9	2.5	0.3	1,379
Germany	20	0.930	27,756	82.4	82.5	15.2	13.2	363	95–100	N.A.	N.A.	0.1 [0.1–0.2]	411.9	4.6	2.5	7,207
Poland	36	0.858	11,379	38.6	38.2	17.9	14.6	220	80–94	N.A.	N.A.	0.1 [0.0–0.2]	230.0	5.4	0.7	3,595
Russia	62	0.795	9,230	144.1	133.4	16.5	13.7	420	50–79	99	4	1.1 [0.6–1.9]	40.9	3.1	1.2	6,081
Turkey	94	0.750	6,772	70.3	82.1	30.7	25.0	123	95–100	82	3	<0.1 [<0.2]	72.8	3.7	0.6	1,849
Africa																
Cameroon	148	0.497	2,118	15.7	18.9	42.4	37.8	7	50–79	58	27	6.9 [4.8–9.8]	3.8	5.4	N.A.	226
Chad	173	0.341	1,210	8.3	12.1	46.7	46.5	3	0–49	27	34	4.8 [3.1–7.2]	1.9	2.0	N.A.	12
Kenya	154	0.474	1,037	31.5	36.9	42.1	36.5	14	0–49	57	37	6.7 [4.7–9.6]	12.5	6.2	N.A.	140
South Africa	120	0.658	10,346	44.8	44.3	33.2	29.2	25	80–94	86	N.A.	[17.8–24.3]	68.2	5.7	N.A.	4,313
Americas																
Brazil	63	0.792	7,790	176.3	202.0	28.3	24.1	206	0–49	87	9	0.7 [0.3–1.1]	82.2	4.0	1.1	2,122
Canada	5	0.949	30,677	31.3	34.1	18.4	14.8	187	95–100	100	N.A.	0.3 [0.2–0.5]	512.8	5.2	1.9	18,212
Chile	37	0.854	10,274	15.6	18.0	27.8	23.6	115	80–94	93	4	0.3 [0.2–0.5]	237.5	3.9	0.5	2,851
Colombia	69	0.785	6,702	43.5	52.2	32.1	27.0	94	80–94	91	13	0.7 [0.4–1.2]	46.2	4.4	0.2	1,010
The Dominican Republic	95	0.749	6,823	8.6	10.1	32.5	28.3	190	50–79	86	25	1.7 [0.9–3.0]	36.4	2.4	N.A.	1,233
Mexico	53	0.814	9,168	102.0	119.6	32.8	26.4	156	80–94	88	5	0.3 [0.1–0.4]	98.5	5.1	0.4	2,228
United States	10	0.944	37,562	291.0	329.7	21.6	20.3	279	95–100	100	N.A.	0.6 [0.3–1.1]	551.4	5.6	2.8	13,241

SOURCE: United Nations Development Programme (undated a).
NOTES: (continued on next page)
N.A.: Data not available.

[a] Human Development Index (HDI) is a composite index measuring average achievement in three basic dimensions of human development: a long and healthy life (measured by life expectancy), knowledge (measured by a combination of adult literacy and combined primary, secondary, and tertiary enrollment ratios), and a decent standard of living (measured by real per capital gross domestic product).
[b] Data refer to medium-variant projections.
[c] Data refer to the most recent year available during the period specified.
[d] Data refer to a year or period other than that specified, differ from the standard definition or refer to only a part of a country.
[e] Year 2000 data.
[f] Data refer to point and range estimates based on new estimation models developed by the Joint United Nations Programme on HIV/AIDS. Range estimates are presented in square brackets.
[g] Data refer to the most recent year available during the period specified.
[h] Data refer to the most recent year available during the period specified. Data refer to UNESCO Institute for Statistics estimate when national estimate is not available.

APPENDIX K:
KNOWLEDGE ASSESSMENT (UNWEIGHTED) FOR SELECTED COUNTRIES, RANKED BY INNOVATION SCORES

Table K.1 presents data from the World Bank's Knowledge Economy Index.

Table K.1
Knowledge Economy Index Country Ratings

Country Rank in Parentheses by Knowledge Economy Index	Selected Countries[a]		Innovation	Economic Incentive Regime	Education	Information Infrastructure
8.81 (2)	1.	United States	9.91	7.97	8.28	9.09
8.41 (5)	2.	Japan	9.78	7.42	8.09	8.35
8.67 (3)	3.	Canada	9.19	8.21	8.53	8.73
7.84 (7)	4.	South Korea	9.13	5.39	7.86	9.00
4.95 (18)	5.	China	9.00	2.55	3.74	4.50
8.47 (4)	6.	Germany	8.88	8.10	7.88	9.01
6.26 (10)	7.	Russia	8.88	3.34	7.88	4.91
8.78 (1)	8.	Australia	8.82	8.31	9.11	8.87
3.97 (23)	9.	India	8.59	2.91	2.33	2.06
5.82 (13)	10.	Brazil	8.08	3.94	5.75	5.50
7.44 (6)	11.	Israel	7.44	7.31	6.78	8.21
7.05 (8)	12.	Poland	7.55	5.84	8.22	6.59
5.77 (12)	13.	Mexico	7.37	5.79	4.43	5.51
5.46 (15)	14.	Turkey	7.19	4.79	4.42	5.44
5.21 (14)	15.	South Africa	6.54	4.55	4.47	5.26
6.53 (9)	16.	Chile	5.67	7.73	6.13	6.59
3.68 (21)	17.	Indonesia	5.68	2.66	3.54	2.86
2.62 (24)	18.	Kenya	5.31	1.29	2.07	1.83
4.81 (11)	19.	Jordan	4.64	4.23	5.55	4.80
4.10 (19)	20.	Colombia	4.61	2.79	4.40	4.60
4.18 (20)	21.	Iran	4.73	3.27	4.00	4.69
2.05 (25)	22.	Pakistan	4.46	1.29	1.05	1.43

Country Rank in Parentheses by Knowledge Economy Index	Selected Countries[a]	Innovation	Economic Incentive Regime	Education	Information Infrastructure
3.88 (16)	23. Georgia	4.09	1.32	6.37	3.73
3.84 (17)	24. Egypt	3.98	3.34	4.47	3.56
1.65 (26)	25. Nepal	2.52	1.97	1.60	0.53
1.41 (27)	26. Cameroon	1.78	0.55	1.91	1.38
2.96 (22)	27. The Dominican Republic	0.35	2.65	3.93	4.92

SOURCE: World Bank's Knowledge Economy Index.
NOTE: The World Bank provides scores weighted and unweighted by population for each country. We choose to use unweighted scores because there are strong economies of scale in the production of knowledge and because knowledge is not consumed in its use. Populous countries, such as China and India, have a critical mass of innovative capacity, which is not reflected when scaled by population. Assessment and rankings for the Knowledge Economy Index are based on four criteria: national innovation system, economic incentive regime, education, and information infrastructure.
[a] Chad and Fiji, two selected countries in this study, are not in the World Bank Knowledge Economy Index.

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