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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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).

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[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 (– –)	Implementation Feasibility: May satisfy a need for a medium or large market, but raises significant public policy issues (–)	Implementation Feasibility: Satisfies a strong need for a medium market and raises no significant public policy issues (+)	Implementation Feasibility: 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.

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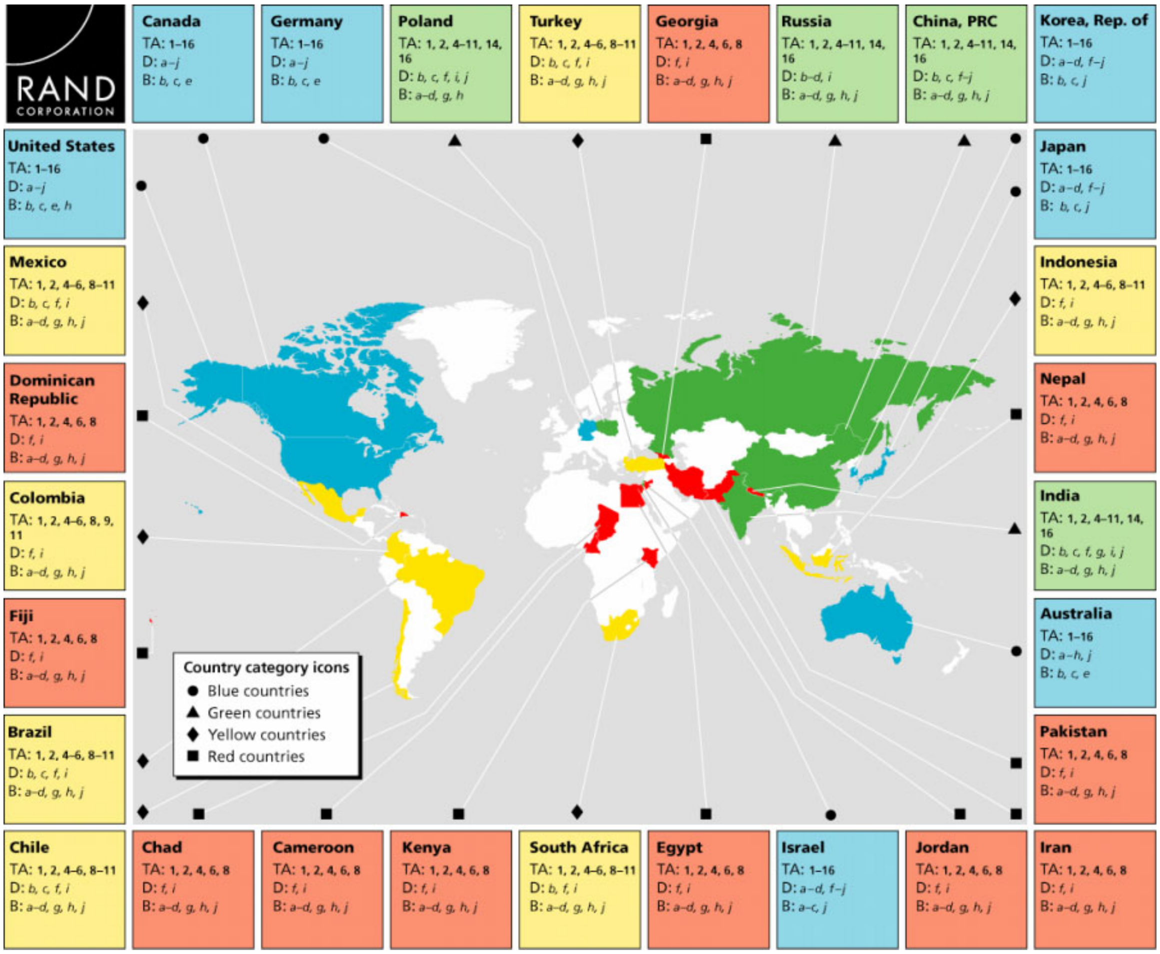
[7] A detailed analysis of where on each driver-barrier continuum particular countries fall was beyond the scope of this study. However, we did identify which drivers and barriers are present in specific countries, so that the percentage of drivers and the percentage of barriers that apply are the appropriate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

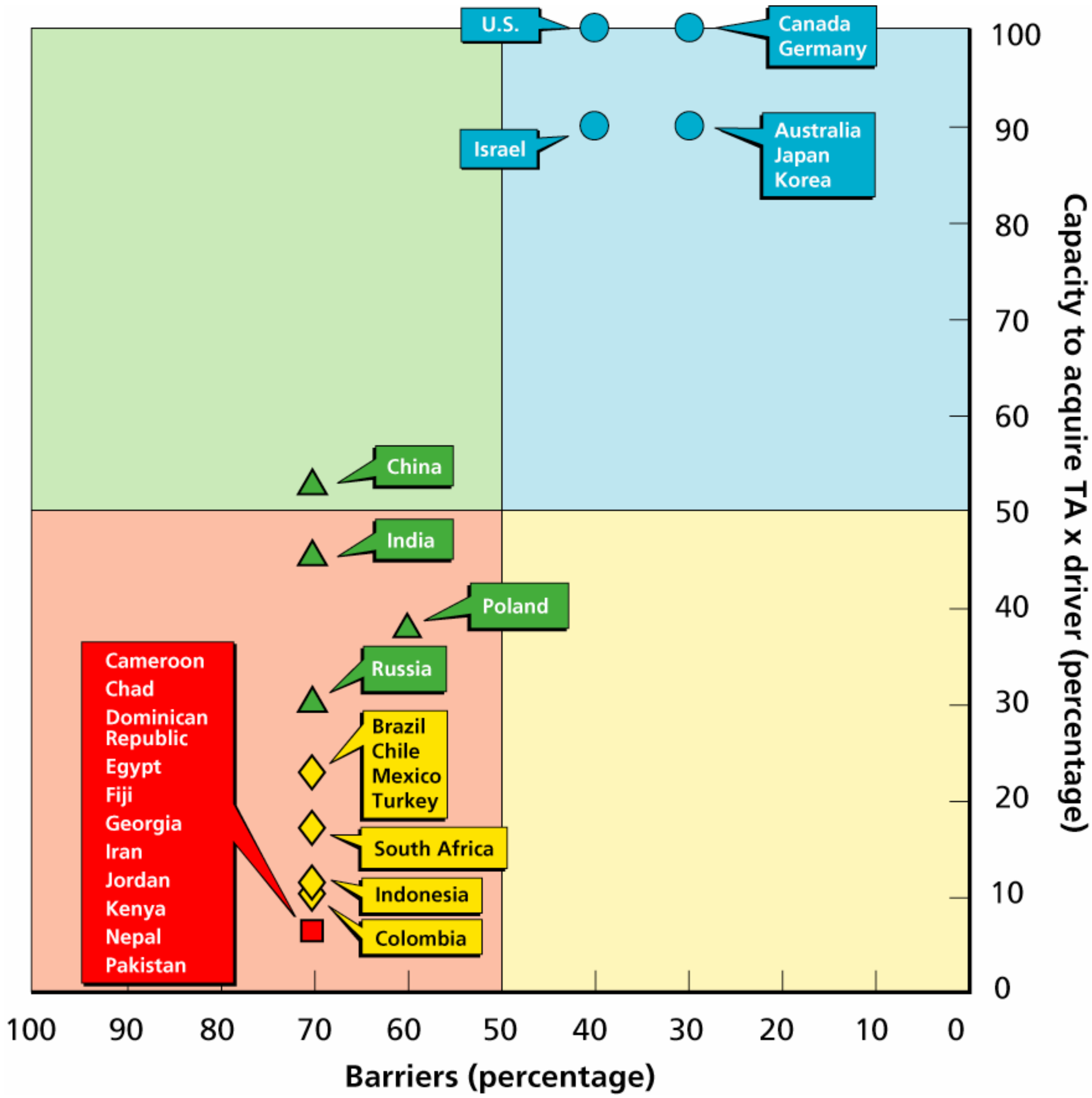
[8] That is, the capacity to acquire scaled by the percentage of drivers. Multiplying capacity to acquire by the percentage of drivers is consistent with the view that the absence of drivers reduces the probability that the TAs a country can acquire will be implemented.

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

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[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.