Futures Consortium

Technology Foresight

SPRING 2009
TF-2009-15

Coming of the Molecular Age

Lead Technologies: Changing of the Guard

Introduction

“Lead technologies” are clusters of technological innovations that tend to persist for a considerable period of time—a century or more. The emergence of information and communication technology (ICT) in the mid-20th century represents the most current of the lead technologies. Two technologies—biotech and nanotech—will form the core of the technological changes of the “molecular age” and will be central to the emergence of a new set of lead technologies between 2010 and 2050. Biotech is leading and nanotech lagging slightly, but over time we can expect to see a convergence of these two technologies with each other as well as with ICT.

The emergence of new lead technologies has typically been marked by significant changes to:

- **Business and industrial structures.** The changing of a technological era destroys existing business and industrial structures, while creating new opportunities as fundamental shifts occur in market demand for products and services.
- **Local and global economies.** In the transition from one lead technology to another, regions or countries can lose their positions as leaders in technological innovation as other leaders emerge.

Contents

Key findings

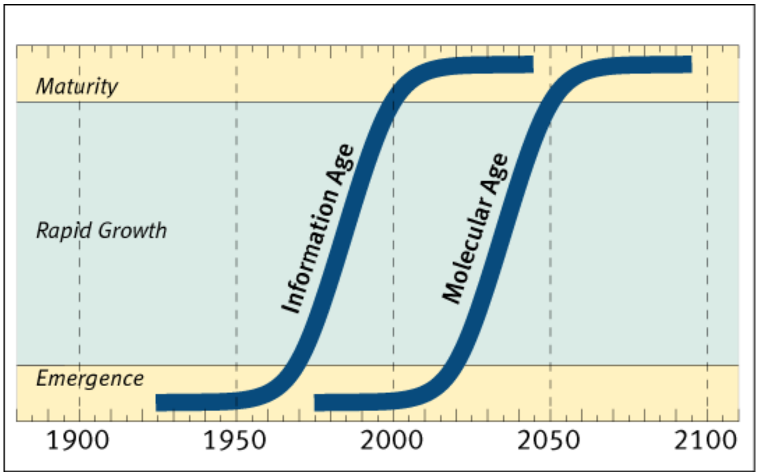
- A new technological era—the molecular age—is just beginning to emerge, while the information age is entering maturity.
- Commercialization of molecular age products has already begun. Around 2020, new technologies will begin to cause increasingly significant changes in business and economic structures.

© 2009 Social Technologies

New business landscape of the molecular age

New businesses and entire industries typically emerge during the transition from one lead technology to another. This is due to a number of factors, including adjustments to business practices, product lifecycles, and the competitive landscape that occur during the commercialization period of a new lead technology, as well as specific changes to production methods.

Figure 1. Three phases of the commercialization period



The commercialization period

The lifecycle of lead technologies can be divided into two major periods—pre-commercialization and commercialization.

The pre-commercialization period is focused on the R&D needed to move from a preliminary idea to a technologically feasible product. The molecular age's pre-commercialization period began in the 1950s. The discovery of the molecular structure of DNA in 1953 was the point at which genetic engineering and biotechnology began, although it would be another two decades before the first successful recombinant DNA experiments occurred. The first academic discussion of nanotechnology was in 1959, when physicist Richard Feynman presented a talk entitled "There's Plenty of Room at the Bottom."[1]

The commercialization period is focused on applied R&D that enhances the performance of the technology and furthers its marketability and adoption. The commercialization period of the molecular age began in the mid-1970s when genetically engineered bacteria were used to produce synthetic human growth hormone. Products that included nanoparticles began appearing in consumer products in the late 1990s, marking the initial commercial application of nanotech.

The commercialization period for a lead technology can be divided into three phases—emergence, rapid growth, and maturity—with each phase having distinct impacts on business structures and processes. Commercialization phases of the molecular age can be characterized as follows:

- **Emergence phase (~1975–2020).** First commercial technologies fit poorly, as the existing technological infrastructure is not designed to accommodate the new technology. Economic models, organizational structures, social and cultural institutions, and political policy and government regulation are built around the prior lead technology.
- **Rapid growth phase (~2020–2050).** A dominant design emerges, increasing the acceptability of the technology and helping drive its acceptance. The rate of adoption and productivity gains jump.

- **Maturity phase (~2050–2095).** As the lead technology approaches the end of its lifecycle, opportunities for its application to new products decrease, stalling the rate of adoption and productivity gains. Firms that remain in business begin to consolidate, looking for strategies that will help them maintain market share. New technologies emerge, and the cycle begins again.

Table 1. Key economic and business characteristics of the molecular age commercialization phases

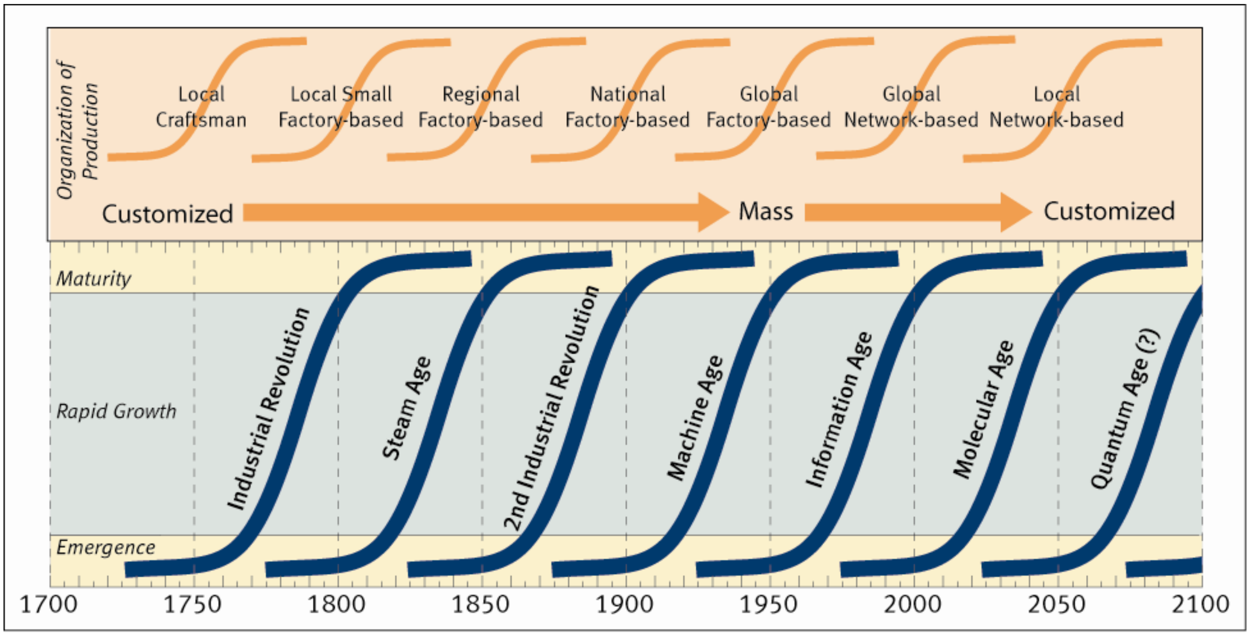
	Emergence Phase (~1975 to 2020)	Rapid Growth Phase (~2020 to 2050)	Maturity Phase (~2050 to 2095)
Innovation Processes	Primary focus on product innovation; radically new products with significantly new features and functionality	Shift from product innovation to process innovation using the new technologies	Primary focus on process innovation; process optimization to achieve cost reduction of products
Product Design	Radical new products, with frequent major changes in product design Competing products are highly diverse and may be customized Key competitive factor is the products' features and functionality	Stable product design (dominant design) emerges, with standardization of product features and functionality Competition focuses on a standardized set of product features, with cost becoming a key competitive advantage	Incremental product design focuses on cost reduction and quality improvements; introduction of innovative new features is rare Commoditized products with little differentiation in features and cost
Product Lifecycle	Short product life with frequent radical changes in features and functionality	A lengthening product life with few changes in product features and functionality	Relatively long product life; almost no changes in key features and functionality
Production Processes	Inefficient processes subject to major changes as product evolves Process changes are relatively inexpensive General-purpose equipment and machinery used in product production Small-scale production facilities, typically located close to R&D facilities	Improved processes with a focus on more efficiency Process changes become more difficult and expensive Some automated and specialized production equipment Production facilities increase in size and complexity	Highly specialized and efficient processes Process changes are expensive, difficult, and time-consuming Processes are highly automated and use highly specialized production equipment
Competitors	Relatively few initially with sharp growth likely toward end of emergence phase Low barriers to entry and frequent product changes make it relatively easy for new	Decline in number of competitors after emergence of dominant design Increased barriers to entry make it more difficult for	A few firms with stable market shares dominate the market Barriers to entry are high and the emergence of new competitors is rare

	competitors to appear quickly	new competitors to emerge Many earlier competitors go out of business or are acquired by other firms	The merger and acquisition of competing firms is a key strategy to gaining market share

Production of goods in the molecular age

The production of goods is dependent upon three key sub-systems: the technology used in the production of goods (i.e., machines, processes, etc.); the source of energy used to power the production technology; and the transportation technology and infrastructure used to move goods to market. As lead technologies change, these sub-systems can evolve with significant implications on how and where goods are produced. Since the Industrial Revolution, methods of production have changed significantly and will change again with the advancement of the molecular age.

Figure 2. Lead technologies and organization of production since the Industrial Revolution



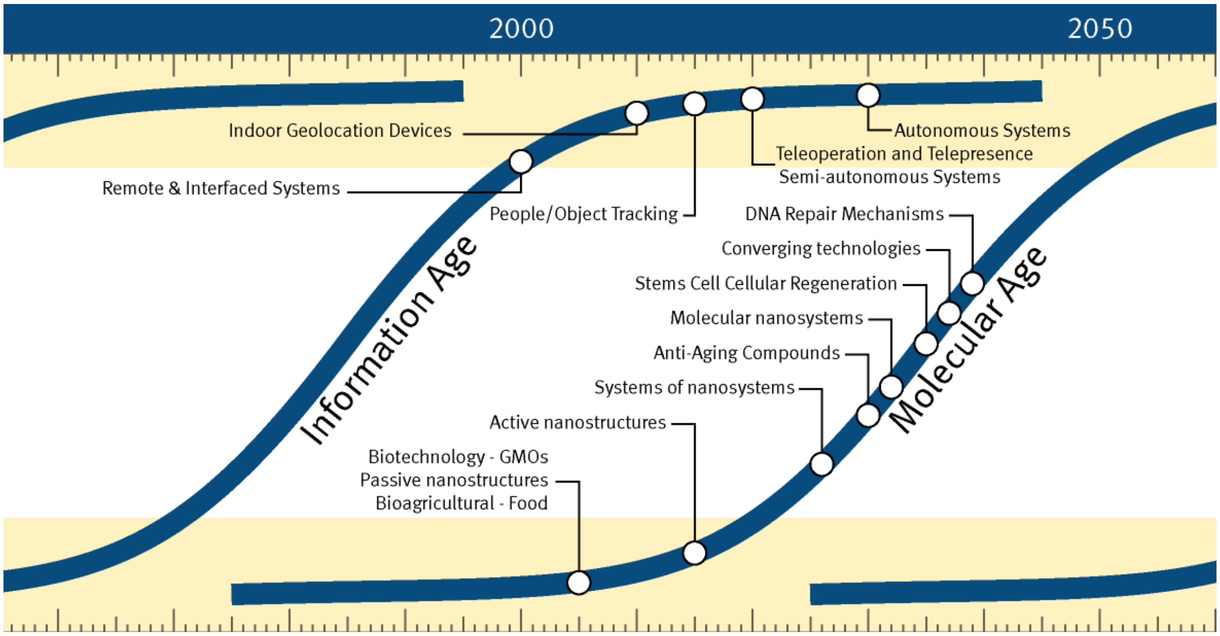
Current organization of production (1970s to 2020s) can be characterized as **global network–based**. The introduction of low-cost ICT enabled quicker and easier coordination of production among a variety of organizations, reorganizing production from the vertically integrated model of the Machine Age to a flexible and less-expensive network-based approach. The flexibility of this production system has enabled greater customization of products—“mass customization.” Extensive networks of highways enabled the fast, efficient movement of components from a network of suppliers. Jet aircraft capable of economically moving cargo from continent to continent made global network–based production possible.

The organization of production characterizing the peak of the molecular age (2020s to 2070s) will likely be **local network–based**. Advanced ICT, robots, and manufacturing techniques, along with industrial biotech and nanotech, could enable the local production of many products. Networked product designers could be located anywhere as specifications for products could be downloaded to specialized equipment that automatically creates the products. “Printers” capable of creating three-dimensional objects from computer-aided design (CAD) software are an early indicator of the potential for local networked–based production. By the mid-21st century and beyond, nanotech-based assemblers may be able to handle the production of increasingly complex products. Concerns about global climate change and the cost and availability of fuel to move products cross-country or internationally could be a driver supporting the development of local production facilities.

Roadmap of the molecular age

The rise of the molecular age will see the convergence of biotech and nanotech, resulting in an entirely new set of advanced products that will incorporate features and capabilities from each of these areas. The rise of the molecular age will be gradual at first, with the technology innovation landscape dominated by next-generation advances in ICT.

Figure 3. Roadmap of the molecular age with selected information, biotechnologies, and nanotechnologies



While many of these ICT innovations will undoubtedly have large impacts, it is important to note that these technology innovations will be part of the maturity phase of the information age. Despite their continuing impact on various industries and importance in enabling biotech and nanotech R&D, advances in ICT will gradually be eclipsed by innovations occurring as the molecular age accelerates. Examples of advanced ICT that will emerge through maturation of the information age include:

- **Services robots.** This category of robots performs useful services for either humans or other machines and does not include those used in manufacturing operations. Advanced service robots are anticipated for defense, healthcare, and domestic applications.[2] Three major stages of development of service robots include remote and interfaced systems, such as military remote-controlled aerial drones; semi-autonomous systems able to interact directly with humans, understand simple commands, and make basic decisions about performing tasks; and autonomous systems capable of useful decision-making in a variety of real-world settings.
- **Internet of things.** A roadmap for the development of the "Internet of things" will include key developments in indoor/ underground geolocation devices; advanced geolocation-enabled people/ object tracking; and teleoperation and telepresence for remote monitoring and operation of machines, appliances, and other types of equipment. This set of technologies will enable the automated identification of and communication between people, machinery, appliances, and everyday objects (i.e., groceries, clothing, toys, etc.) using RFID or similar systems.[3]

Lead technology S-curve

i It is important to note that a "lead technology" is a cluster of interrelated technologies. Therefore, the S-curve representing the commercialization period of the molecular age is actually a composite of the S-curves representing numerous individual technologies. These individual technologies will also go through phases of emergence, rapid growth, and maturity, although the time span for the phases of individual technology commercialization will be much shorter than the phases for the lead technology—The molecular age—as a whole.

Molecular age emergence and rapid growth: biotechnology

As the molecular age unfolds, developments in biotech will play an increasingly significant role. Biotech breakthroughs are enabling researchers to better understand the biochemical systems of plants, animals, and humans on a molecular level, opening new capabilities to modify and repair complex biological systems. Two areas in which biotech could see the commercialization of technologies are anti-aging applications, and bioagricultural and bioindustrial production:

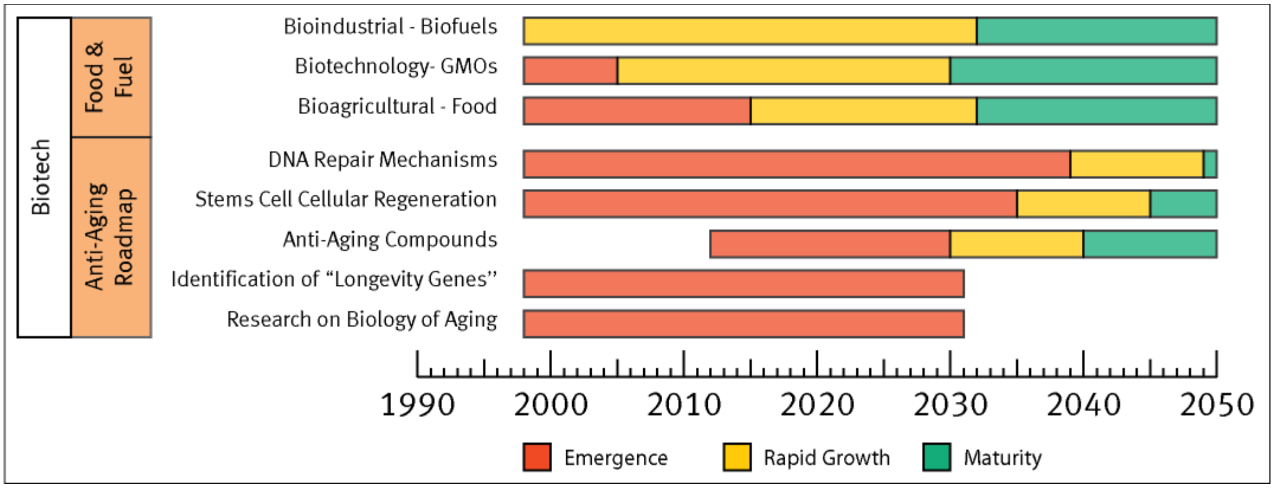
- **Anti-aging technology.** Also called biogerontechnology, this application of biotech would slow, halt, or reverse the aging process and its impacts. The roadmap for the development of anti-aging technology consists of five major steps:[4]
  - **Research on biology of aging.** The process of aging is not yet well understood, and research into understanding the biology of aging is likely to continue until 2030 and probably beyond.
  - **Identification of "longevity genes."** The genetics of longevity are also the focus of research as scientists attempt to discover the genetic factors involved in why some people live longer than others. This research is also likely to continue to 2030 and beyond.

© 2009 Social)Technologies

  - **Anti-aging compounds.** The first commercial introductions may occur about 2030.
  - **Stem cell cellular regeneration.** The regenerative possibilities of stem cells have attracted the attention of researchers for more than a decade. However, that research is still in its early stages, and it could be 2035 or later before the commercial introduction of stem cell–based regenerative technologies.
  - **DNA repair mechanisms.** The human body does a remarkable job of repairing itself, although that ability gradually degrades over a span of decades. Research is underway to understand the biological mechanisms by which damaged DNA might be repaired. Technologies based on DNA repair mechanisms will probably not be commercially introduced until 2040 or later.

- **Bioagricultural and bioindustrial production.** Biotech holds considerable promise for enhancing the production of food, fuels, and industrial materials. The basic technology involves manipulation of the genetic structure of plants, creating new varieties with characteristics that do not occur naturally (see TF-2007-43: Top 12 Areas for Inovation 2025—Engineered Agriculture). Three broad areas are shown on this roadmap:
  - **Genetically modified organisms (GMOs).** New technologies for genetic manipulation of plants could have a significant impact on the efficiency and safety of GM crop design (e.g., gene stacking, gene deletion, etc.).
  - **Bioindustrial—biofuels.** Biofuels have been produced commercially since the 1990s, but the use of biotech is expected to enhance production.
  - **Bioagricultural–food.** Biotechnology could enable next-generation food crops that have improved plant characteristics, such as better nutritional composition, greater tolerance for heat or cold, or greater tolerance for drought or high-salinity conditions.

Figure 4. Development timeline for emerging biotechnologies

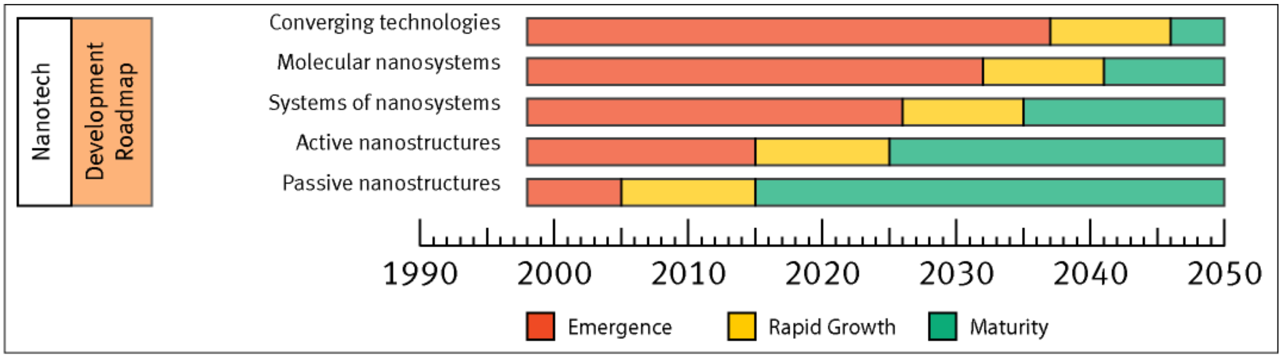


Molecular age emergence and rapid growth: nanotechnology

Nanotech and its convergence with infotech and biotech will drive significant technological changes over the next half-century. The National Science Foundation has identified five key types of nanotech that will shape the nanotechnological landscape.[5] These are:

- **Passive nanostructures.** First-generation nanomaterials—coatings, particles, polymers, and ceramics—became commercial in the early 2000s. The chemical, pharmaceutical, and electronics industries will be most impacted by these applications of nanotech.
- **Active nanostructures.** The properties, structures, or functions of active nanostructures change as they are used and include a broad range of potential products, including targeted drugs and nanoscale transistors, actuators, and other simple devices. This is considered the second generation of nanotech products. Target applications include nanomedicine, energy conversion and storage, environmental systems, and agricultural and food systems. Commercial introduction of the first active nanostructures is forecast for around 2015.
- **Systems of nanostructures.** Self-assembly of nanostructures consisting of interconnected components—building blocks that fit together to create larger nanostructures—will lead to new applications for nanotech, including guided assembly of nanostructures, creation of 3D nanoscale networks, and molecular robotics. This third generation of nanotech will have impacts in a broad range of industries. Commercial introduction of this technology is not likely to occur until 2025.
- **Molecular nanosystems.** The fourth generation of nanotech will involve the development of nanosystems with complex designs and may incorporate hybrid nano-bio assemblies. Applications include large-scale self-assembling systems, adaptive components in larger systems, and monitoring of cells using nanobiosystems. Commercial introduction of these nanosystems is forecast for sometime between 2030 and 2035.
- **Converging technologies.** If earlier milestones for development are met, commercial products that fully integrate nanotech, biotech, and infotech are expected to begin appearing on the market between 2035 and 2040.

Figure 5. Development timeline for emerging nanotechnologies



Local and global implications of the molecular age

New lead technologies also shift existing economic structures. In the transition from one lead technology to another, regions or countries can lose their position as leaders in technological innovation. Regions that are able to become the home of an emerging lead technology often experience a period of economic vitality as businesses grow and employment opportunities for skilled workers expand. The location of molecular age growth centers will be determined over the next decade as biotech and nanotech industries continue to develop.

- **Biotechnology hotspots.** Nine areas in the US—San Francisco, Los Angeles, San Diego, Seattle, Philadelphia, New York, Boston, Raleigh-Durham, and the Washington/ Baltimore area—have become leaders in biotech research and development.[6] Canada has five biotech clusters, located in Montreal, Toronto, Vancouver, Ottawa, and Edmonton/ Calgary. European leaders in biotech are the UK and Germany, with France, Switzerland, Denmark, Sweden, Netherlands, and Belgium playing smaller roles. Significant biotech players in the Asia-Pacific region are India, China, Singapore, Australia, and New Zealand, while Japan lags behind.[7] None of these has yet become dominant in biotech, and each faces a set of financial, regulatory, business, or other challenges that could determine which does become the global leader.
- **Nanotechnology hotspots.** The hotspots for research and development in nanotech are only now beginning to emerge. The US leads the world in the number of nanotech articles published in scientific journals. In Europe, leaders in nanotech research are Germany, Switzerland, Italy, Spain, and the UK. Japan leads Asian countries, but both South Korea and China are making significant strides in the field.[8] China in particular appears intent on developing significant capabilities in nanotech. It sees nanotech as a key technology in increasing its global economic competitiveness and ranks third, after the US and Japan, in the number of papers published on nanoscience.[9]

Numerous factors—including levels of government funding, availability of venture capital, intellectual property protection, regulations and standards, and the availability of skilled scientists, engineers, and technologists—are likely to have a significant impact on where the world's nanotech hotspots ultimately do emerge. In addition, while research leadership is important, capabilities in technology commercialization and adoption also impact a country or region's success (See TF-2009-14: Global Future S&T Readiness Comparison.) Because the emergence of new lead technologies tends to level the economic playing field, small initial advantages and disadvantages in research, development, and commercialization could have significant long-term impacts on the development of molecular age–based economies.

For more information...

i To learn more about the trends and forecasts in this report and what they mean for your organization, please contact Social Technologies at 202 223.2801 or info@socialtechnologies.com.

Business implications

- The molecular age will likely enter a period of rapid growth—marked by intense and rapid technology development and tremendous uncertainty—around 2020. Companies involved in the chemical, pharmaceutical, and energy industries are likely to experience the first impacts, but companies in all industries need to prepare for this period of rapid technological change.
- Given the history of companies like US Steel and GM, which once dominated their industries, dominant information age companies like Microsoft, Google, Apple, and others in the software, hardware, and Internet sectors could face significant difficulties as the molecular age enters a period of rapid growth post-2020 while the information age continues to mature. In the US, the contribution of the information industry—sectors that include broadcasting and telecommunications, publishing (including software), motion pictures and sound recording, and computer design, manufacturing, and services—as a percentage of US gross domestic product (GDP) fell from 4.7% in 2000 to 4.2% in 2007.[10] This could be an early indication that as the information age continues to mature, its share of GDP could continue to drop. Manufacturing, a mature industry in the US, has seen its contribution to GDP decline substantially since the early 1950s.[11] Identifying which companies will survive and which won't in the molecular age is premature, as an organization's response to the changing business environment is critically important. Companies need to recognize the challenges early and respond appropriately.

References

---

[1] Richard Feynman, "Plenty of Room at the Bottom," California Institute of Technology, 1960, http://www.nanoparticles.org.

[2] "Disruptive Technologies—Appendix E: Service Robots (Background)," *Disruptive Civil Technologies*, National Intelligence Council, April 2008, www.dni.gov.

[3] "Disruptive Technologies—Appendix F: The Internet of Things (Background)," *Disruptive Civil Technologies*, National Intelligence Council, April 2008, www.dni.gov.

[4] "Disruptive Technologies—Appendix A: Biogerontechnology (Background)," *Disruptive Civil Technologies*, National Intelligence Council, April 2008, www.dni.gov.

[5] M. C. Roco, "Defining Nanomanufacturing," National Science Foundation, March 10, 2005.

[6] Joseph Cortright and Heike Mayer, "Signs of Life: The Growth of Biotechnology Centers in the U.S.," The Brookings Institution, 2002, www.brookings.edu.

[7] Glen T. Giovannetti and Gautam Jaggi, "Beyond Borders: Global Biotechnology Report 2008," Ernst & Young, 2008, www.ey.com.

[8] Ronald N. Kostoff, Raymong G. Koytcheff, and Clifford G. Y. Lau, "Global Nanotechnology Research Literature Overview," Current Science, Vol. 92, Num. 11, June 10, 2007, www.ias.ac.in.

[9] James Wilsdon and James Keeley, "China: The Next Science Superpower?" Demos, 2007, www.demos.co.uk.

[10] "Gross Domestic Product (GDP) by Industry Data," Bureau of Economic Analysis, December 16, 2008, www.bea.gov.

[11] "Gross Domestic Product (GDP) by Industry Data," Bureau of Economic Analysis, December 16, 2008, www.bea.gov.

© 2009 Social Technologies