

Chapter 7

Implications: Societal Collective Outcomes, Including Manufacturing

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7.1 Vision

The fundamental tools and approaches in converging knowledge and technology described in earlier chapters will have a profound impact on societal collective outcomes. This chapter is focused on the impact of these outcomes on manufacturing, innovation, and long-term societal development.

7.1.1 Changes in the Vision over the Past Decade

“Passive” convergence of knowledge and technologies has had an important effect on manufacturing development. Manufacturing enterprises have evolved for the most part as centralized and concentrated urban complexes, primarily driven by the need to minimize manufacturing costs. Examples include the automobile industry of southeastern Michigan and the electronics manufacturing complex in Shenzhen,

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China, that hosts companies such as Foxconn with its estimated 450,000 employees (Focus Taiwan 2010). These manufacturing complexes have created a variety of societal problems, including those related to the environment, the conspicuous consumption of resources, land utilization, urban transportation, and continually changing patterns of employment needs and opportunities that precipitate other sets of social problems.

Converging knowledge and technology has supported a transition from mass production to mass customization in the “post-Fordism” of the last two decades, as evidenced by the shift from large-batch mass production in centralized factory settings to small-batch customized production of high-quality goods in more widely distributed locales (Kotha 1995; Vallas 1999; Zysman 2004). This transition has been driven by a number of factors, including mass customization needs (e.g., medical devices tailored to particular patients), cyberinfrastructure that changes the way people communicate, emergence of point-of-use (POU) technologies, and emergence of miniaturization technologies, to name a few. The evidence is strong that the mass customization model is well in place (Federal Reserve Bank 1998); for example, already between the 1970s and 1990s, the number of national TV channels rose from 5 to 185, the number of running shoe styles increased from 5 to 285, and the number of contact lens types increased from 1 to 36. These developments might be suggesting a swing to a more *distributed manufacturing model that might coexist with the centralized model* (DeVor et al. 2012). The United States has played a dominant role in this development due to its entrepreneurial spirit and research enterprise. The synergy that can emerge from the confluence of these forces has the potential to radically alter the future course of the world of manufacturing based on converging technologies.

Long-term societal development outlined in the first NBIC report (Roco and Bainbridge 2003) had a focus on science and technology feasibility. The adoption of advanced science and technologies raises a number of social issues that need to be explored, which include labor skill requirements and training. In the \$70 million

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National Additive Manufacturing Innovation Institute established in August 2012, workforce training constitutes one critical cornerstone (NNMI 2012). It involves nine universities and colleges, five community colleges, and professional society and nonprofit institutes specialized in standards and certificates.

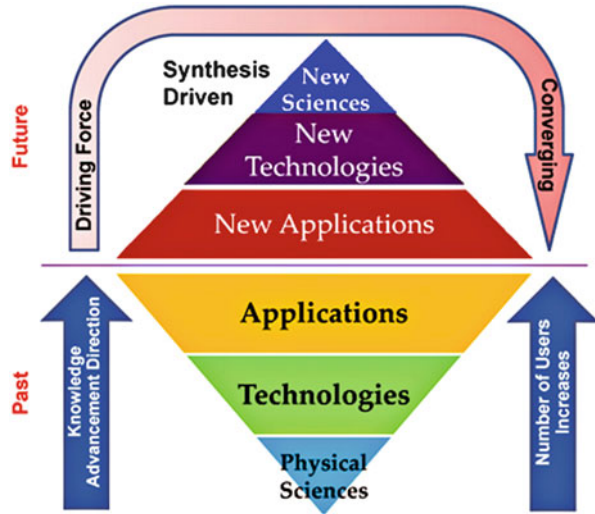
7.1.2 *The Vision for the Next Decade*

Convergence of knowledge and technology is envisioned to feed the gradual emergence of highly integrated and flexible manufacturing processes, enhanced by the extensive communication capabilities offered by the Internet and by their integration with nanotechnology, biotechnology, and cognitive technologies; ultimately, these changes may give rise to a fundamental shift in the way manufacturing is performed. The emergence of machines and systems with a much higher degree of autonomy, coupled with *in situ* functional metrology as well as remote diagnostics and maintenance capabilities, etc., allows one to draw parallels to the development of the personal computer (PC). Like the PC, these new emerging systems could be deployed in a highly dispersed manner and evolve into general-purpose technologies that enable new forms of production and creativity through the adoption of a more distributed approach to the creation of the future generations of manufacturing systems and enterprises. Such a “Distributed Manufacturing” model could become a disruptive and transforming paradigm that could forever change the landscape of the world of manufacturing that has been dominated by the centralized model. The interconnectivity and dispersion of such systems would allow new business models such as “manufacturing at the mall,” and “point-of-need-manufacturing” to coexist with the centralized model.

The distributed scenario with multiple technology sources would *shift manufacturing capabilities from the hands of the few into the hands of the many*, with a dramatic impact on the standard of living of a large portion of the planet’s population. This paradigm shift is likely to produce highly nonlinear behaviors with regard to both the engineering and socio-economics of the challenge. Without taking a broad perspective when managing the process, our ability to guide the process and identify early signals of potentially dangerous patterns and effects will be greatly inhibited.

Figure 7.1 illustrates the envisioned transformation in knowledge generation spurred by a distributed manufacturing and technology development landscape. In the past and at present, the advancement of knowledge has started from the basic understanding of fundamental physical sciences, typically initiated by people with doctoral degrees and many years of research experience. For example, the laser was first researched and characterized by physicists, among them, the 1981 Physics Nobel Laureate Arthur Schawlow. Once the physical science is better understood, technologies are developed through innovations by *many* researchers and engineers, such as those who dramatically increased the types, power, and sizes of lasers while lowering their costs—further stimulating new inventions, and adoption of laser applications by millions of users. The laser has found applications in laser cutting,

Fig. 7.1 Schematic of current and future knowledge development and adoption paths. The *right up-arrow* shows an increase in number of users as applications increase (Courtesy of Jian Cao)



laser welding, scanning, and printing, to name a few. The bottom half of Fig. 7.1 summarizes this currently prevailing scenario. The left arrow shows the path of knowledge advancement from physical sciences to technologies to applications, while the size of each block symbolizes the number of users in each category, i.e., fewer people engaged in physical sciences knowledge development than in application areas.

The distributed nature of manufacturing and use of converging technology platforms will alter the path of how knowledge is created, as illustrated in the upper half of the diamond in Fig. 7.1. For example, school-age students can now create “apps” (applications) for smart phones. New additive manufacturing processes will increasingly allow users to locally create one-of-a-kind parts, even from multiple materials, to meet specific needs across a wide range of applications, from aerospace to fashion to tissue engineering; data can be shared in the cloud. The ease of the user–machine interface will allow the general public to adopt technologies and to invent new technologies, which, in turn, may lead to new scientific discoveries and new sciences, in particular, synthesis-driven sciences. As indicated in the top half of Fig. 7.1, the driving force for knowledge creation may start from grass-roots applications then broaden to technologies and to converging sciences. This is in stark contrast from how it has been done in the current and past centuries. Newly discovered and developed converging sciences will support distributed manufacturing for economic, human-potential, and societal developments.

Finally, *new methodologies have to be developed to ease the knowledge burden in distributing convergence knowledge.* Critical challenges to be addressed are how to translate information into knowledge and education, how to accelerate learning and make it fun to learn, and how to restructure universities to provide quality education to all human beings who are interested in learning.

Long-term development of society will be affected by convergence that will become proactive and more systematic. Applications are envisioned to affect all sectors of human activity in the next 10 years and beyond. For example, understanding of how the brain functions can lead to new ways of defining manufacturing processes and systems tailored to people's choices, and hence spin off new manufacturing processes or create new enterprise business models.

7.2 Advances in the Last Decade and Current Status

The role of convergence in the last decade was generally was in response to coincidental collaborations. Main technological advances in the last 10 years are flexible manufacturing processes and systems, particularly in terms of *additive manufacturing* (Sect. 7.2.1) and *small-scale multifunctional manufacturing* (Sect. 7.2.2); robots for assisting in human motor control (Sect. 7.2.3); and *universal access to quality education* (Sect. 7.2.4). The weakness of social science advancement in the last 10 years has limited the role that social sciences could be playing in policy and physical sciences for convergence and human benefits. The discussion on aspects related to social science will be more focused in Sect. 7.3, where the goals for the next decade are discussed.

7.2.1 Additive Manufacturing

Additive manufacturing (AM) creates parts layer-by-layer directly from the digital computer-aided design (CAD) files in conjunction with a layered material deposition technology (Prinz et al. 1997; Beaman et al. 2004; Bourell et al. 2009). AM has evolved steadily over the last 30 years beyond its initial application for rapid prototyping; particularly in the last 10 years, it has grown to be competitive as a valid process for rapid manufacturing of final functional products. For example, Fig. 7.2 is a demonstration part of a hinge bracket used on the Airbus A320 in its original form (*rear image*) and the optimized design produced by AM (*front image*). Using the HyperWorks topology optimization tool, OptiStruct, engineers were able to



Fig. 7.2 Airbus hinge bracket in its original form (*rear*) and optimized form achieved by additive processing (*front*) (Courtesy of Jian Cao)

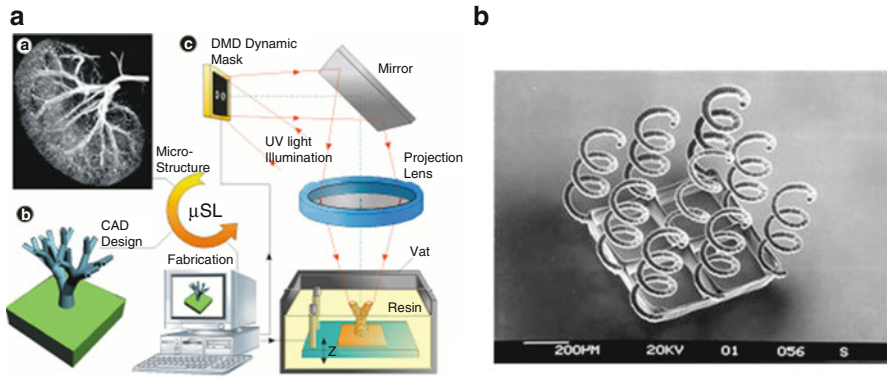


Fig. 7.3 (a) Fabrication of 3D microvasculature for tissue engineering and fractal antenna process using a dynamic mask projection system; (b) 3D micro-spring made by photolithography to demonstrate the ability to fabricate 3D structures at the micro-scale (Courtesy of Prof. Xiang Zhang of University of California, Berkeley)

merge AM capability in design to achieve a significant weight reduction of 64 % while retaining the same characteristics in terms of stiffness and bolt loading.

Additive manufacturing can also be performed with an increasing variety of materials, including polymers, ceramics, and metal alloys such as aluminum, titanium, and copper alloys. Innovations in high-throughput parallel dynamic mask projection enables AM at the microscale and even at the nanoscale to overcome time-to-manufacturing limitations of conventional serial AM processes, as shown in Fig. 7.3.

One major impact of additive manufacturing is that it links designers directly to manufacturers, putting manufacturing capabilities in the hands of even school-age individuals. Further research and development can further strengthen AM by providing seamless design tools, increasing processing speed, improving the surface finish, increasing accuracy, providing more material choices and means to recycle materials, strengthening the capabilities of predicting product performance, and reducing cost.

7.2.2 Small-Scale Multifunctional Manufacturing

The downsizing of manufacturing equipment and systems has the potential to totally change the application protocols of various sectors of the economy. For example, a desktop manufacturing (DM) system can literally reside in a room adjoining a hospital operating room, ready to manufacture a diagnostic probe or implant that is tailored to the precise size and needs of the person on the operating table. Such technology can not only significantly reduce healthcare costs but improve the quality of healthcare delivery as well. An example of a similar technology already in use is ceramic dental reconstruction, as practiced at Sirona Dental Systems (<http://www.cereconline.com/>). In a single visit, a patient's tooth can be scanned

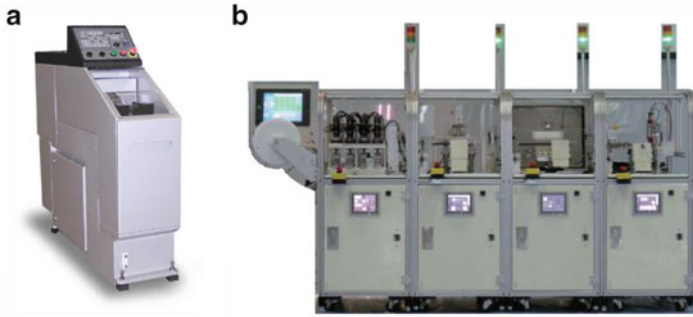


Fig. 7.4 Small-scale multifunctional machines developed in recent years: (a) Slim Lathe by Takamaz (300 (W)×1,225 (L) mm); (b) On-demand MEMS desktop factory (each unit or “cell” is 500 (W)×800 (D)×1,200 (H) mm), at the National Institute of Advanced Industrial Science and Technology (AIST), Japan, 2008 (Courtesy of Kornel Ehmann)

with a 3D CAD system, and a tabletop computer numerical control (CNC) machine tool in the next room can then manufacture a ceramic crown that is immediately put in place in the patient’s mouth. Point-of-use-manufacturing, and therefore DM, also has considerable applications for activities in remote locations, including military deployments or in space, (e.g., the International Space Station).

Ehmann et al. (2005) conducted a WTEC study on micromanufacturing that found that in 2004–2005, the trend toward miniaturization of machines was already evident in both Asia and Europe, with commercialization of desktop machine tools, assembly systems, and measurement systems well underway. Examples today of commercial developments of machines that fit the desktop manufacturing paradigm are numerous and are epitomized by significantly downscaled versions of their macro-level counterparts. One example is the “SlimLathe” by Takamaz (Fig. 7.4a). Another example is the Takashima Sangyo Company’s DM “plant,” where 120 desktop-sized machines operate in a mere 300 m² space (Endo 2005). Concurrently, a number of Japanese and European companies are starting to offer specialized products ranging from assembly, joining, and metrology, to NEMS (nanoelectromechanical systems) and MEMS (microelectromechanical systems) processing (e.g., Fig. 7.4b) and other equipment, along with supporting component technology products such as sensors, actuators, and controllers that support the desktop manufacturing paradigm (AIST 2006).

In the United States, a notable example is the microfactory developed at the University of Illinois at Urbana-Champaign (UIUC) in collaboration with Northwestern University, which has integrated a number of desktop-sized cutting, forming, and metrology devices. Figure 7.5 gives a photograph and schematic of the microfactory (Honegger et al. 2006a, b). Additional desktop or small-scale flexible manufacturing facilities have been developed at other universities, including but not limited to, the University of Michigan (Prof. Jun Ni); Georgia Institute of Technology (Prof. Shreyes Melkote); Carnegie Mellon University (Prof. Burak Ozdoganlar); and Massachusetts Institute of Technology (Prof. Martin Culpepper).

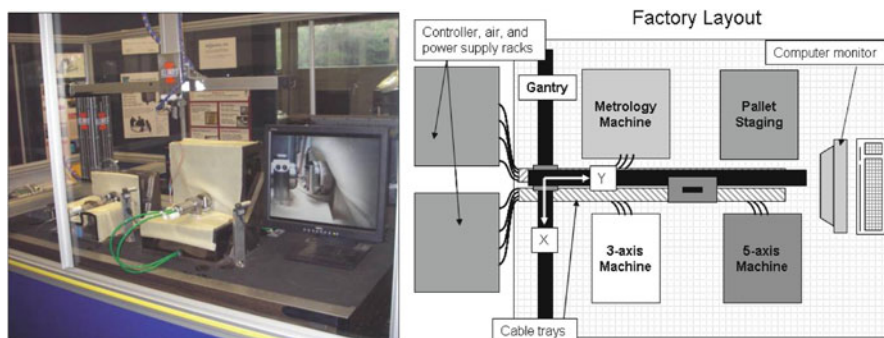


Fig. 7.5 Microfactory developed at University of Illinois (Prof. Shiv Gopal Kapoor) in collaboration with Northwestern University (Courtesy of Profs. Kornel Ehmann and Jian Cao)

Small-scale, distributed chemical production is emerging as a powerful development within industry. Such distributed production, localized production, and reduced capital investment models run counter to the maxim of “economies of scale,” but they offer economic and safety benefits. As Meredith Kratzer of UIUC has noted, “Novel microchemical systems will reduce the need for hazardous reactants, generating them [only] on demand.”

The above-mentioned flexible and compact systems possess the compactness, flexibility, modularity, and *in situ* metrology required for distributed manufacturing. The technology can be further enhanced by adding reconfigurability, multifunctional and multimaterial processes, multi-domain scale, high reliability and low maintainability, self-diagnosis capability, Internet connectability, and remote monitoring and/or control, to name a few.

7.2.3 Robots for Assisting in Human Motor Control

Development of actuators, sensors, lightweight materials, and power systems for limb prosthetics is making great strides toward achieving the goal of producing a prosthetic that is so human-like that a patient or an observer could not tell the difference from the wearer’s own limb. The march toward highly effective brain–prosthetic interfaces for brain–prosthetic communication of signals and the better understanding of brain processing of information is occurring at an amazing pace. The limitations lie within our inadequate understanding of the brain. Research has demonstrated the preliminary success of restoring various functions to persons with impairments such as spinal cord injury, brain injury, and stroke. Kevin Lynch at Northwestern University has been using functional electrical stimulation (FES), as shown in Fig. 7.6, to restore reaching motions to persons with high spinal cord injuries who have little or no voluntary control over their upper extremities. Obtaining signals from the brain with electroencephalography (EEG), magnetoencephalography (MEG), and functional magnetic resonance imaging (fMRI) has progressed at surprising rates, with research on interpreting these signals also progressing well.

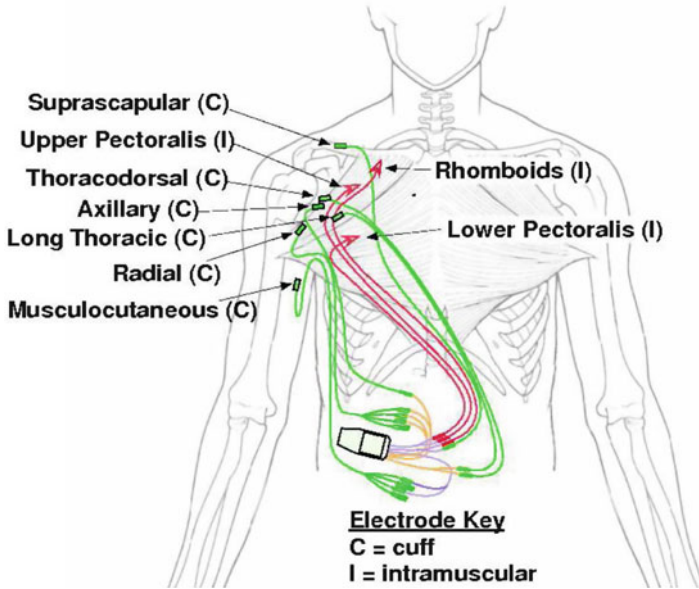


Fig. 7.6 Use of functional electrical stimulation to restore limb movement (Courtesy of K. M. Lynch, Northwestern University)

Co-robots such as the ASIMO robot by Honda (Fig. 7.7) demonstrate great progress in achieving human-like performance for assistive robots. This robot has 34 degrees of mechanical freedom in movements in its head, arms, hands, hips, legs, and feet (see demonstration video at <http://asimo.honda.com/>). “Intelligence” is demonstrated by ASIMO in its ability to see, hear, distinguish sounds, recognize faces and gestures, and chart a route to a specified location.

Even this level of co-robots promises huge advances in assistance for “direct support of and in a symbiotic relationship with human partners,” as envisioned by the National Robotics Initiative supported by multiple agencies of the Federal Government, including the National Science Foundation (NSF), NASA (the National Aeronautics and Space Administration), the National Institutes of Health (NIH), and the Department of Agriculture (USDA). For example, in space, profitable areas like geostationary satellite maintenance and resource extraction (e.g., mining minerals on asteroids or mining helium-3 on the moon) demand smart robotics. Integrating high-impulse and high-thrust rockets, robotics can be applied to industries beyond low Earth orbit.

Such co-robots as those described above will serve as critical elements in distributed manufacturing or point-of-need manufacturing in terms of extending human intelligence to difficult frontiers. However, much research is still needed in interpreting brain signals, from a multiplicity of sensors placed on either the brain or the skull, for prosthetics, bio-inspired sensing, and robot technologies.

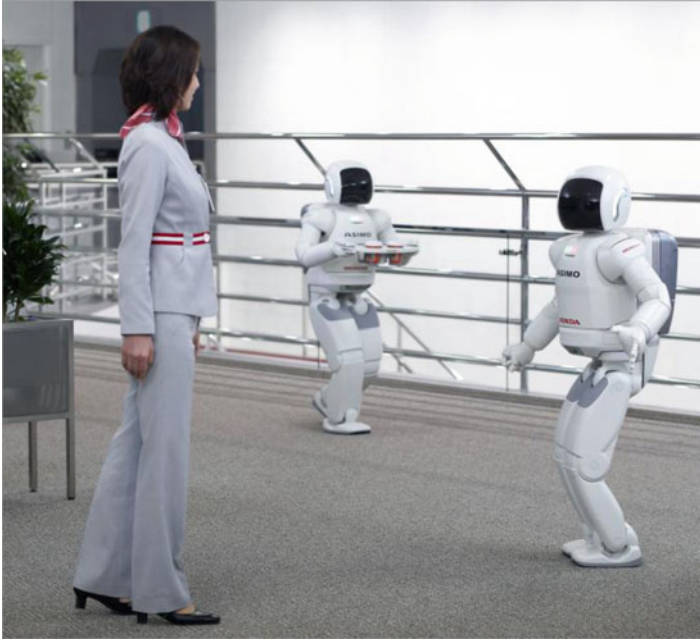


Fig. 7.7 Honda’s co-robot ASIMO “offers tea” and gestures (© 2007 Honda Motor Co., Ltd., courtesy American Honda Motor Co., Inc.)

7.2.4 Universal Access to Quality Education

Free online Internet access to thousands of high-quality lectures in science, technology, engineering, medicine, history, arts, philosophy, etc., is now being provided by a growing number of first-rate institutions around the world. Chapters 4 and 8 provide a number of examples in the United States. Such examples of universal access to quality educational materials are challenging conventional approaches to student learning systems. Delivery of high-quality lectures to students is being combined with such efforts as those by the Knewton Company to obtain real-time feedback from students’ learning activities in order to customize subsequent educational activities and materials. Could a computer tutor be sufficiently “intelligent” that a student could not tell the difference in comparison to a human tutor (Fig. 7.8)? Can a student selectively pick courses that will adequately prepare him/her for a unique career, for example, in the IT-assisted manufacturing framework? Answering these questions will require a new model of our education system.

It is worth noting that computer games and virtual worlds will also be part of the future educational landscape. For example, efforts at University of California–Irvine and Intel Research have produced and demonstrated how existing commercially available entertainment-oriented computer games and their associated “software development kits” can be modified into ones that are suitable for training adult

Fig. 7.8 Man or computer?
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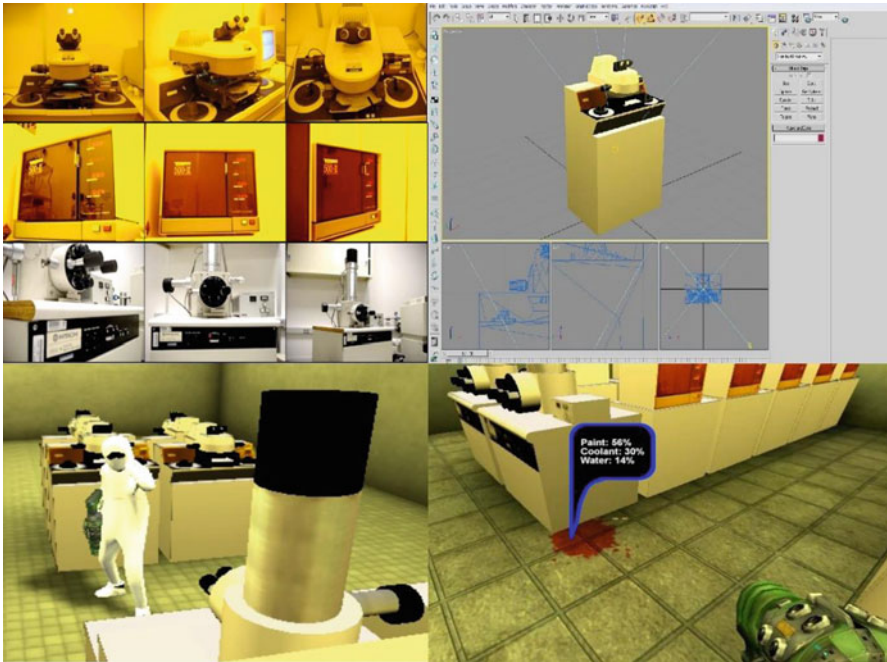
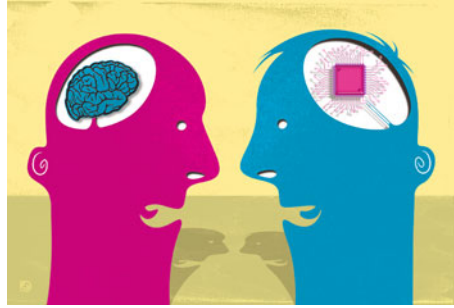


Fig. 7.9 Computer game for diagnosing problems in semiconductor fabrication operations (Scacchi 2010; courtesy of Walt Scacchi)

technicians in the operation and diagnosis of semiconductor and nanotechnology fabrication equipment and operations, as seen in Fig. 7.9. In this figure, the images in the upper left are photographs of different devices involved in fabrication operations (e.g., an electron microscope); the upper-right image is a 3D CAD model of one such device; at the lower left is a view into a virtual factory with different virtual devices visible, along with an operations technician; and at lower right is a diagnostic view of a liquid material that is leaking out of the bottom of a device. Similar techniques have also served to support the development and deployment of science learning games that address National Science Education Standards for targeted student grade or skill levels (Scacchi 2010).

7.3 Goals for the Next Decade

The attendees of the U.S. NBIC2 workshop in Breakout Session 7 identified three major challenges in convergence of knowledge and technology for manufacturing and societal benefits:

1. High productivity and automation reduces employment opportunities in a centralized manufacturing model; however, process flexibility, automation, and the Internet together have created an opportunity for making things that individuals want. How can this be done autonomously so that members of the general public can execute their own designs to meet their individual needs?
2. Weakness in social science development in recent years limits the role that social science could be playing in policymaking and physical science R&D for convergence and human benefits.
3. Advanced knowledge has been created in both traditional ways and in new ways, as indicated in Fig. 7.1. How do we translate new information into knowledge and education? How can we learn faster, and how do we make it fun to learn so much new information? How should universities adapt to this need?

To address those challenges, this section summarizes the goals for the next decade in distributed manufacturing to empower individuals and communities (Sect. 7.3.1), “manufacturing process DNA” (Sect. 7.3.2), integrated social and physical sciences (Sect. 7.3.3), and the individualized education model (Sect. 7.3.4).

7.3.1 *Distributed Manufacturing to Empower Individuals and Communities*

Innovation for advanced manufacturing, jobs, and competitiveness will be provided by personalized manufacturing, diy (do-it-yourself) manufacturing, and availability of manufacturing information as a service, which are all very good examples of the trend of integrating information, communications, materials, and economics in an evolving new paradigm for manufacturing. With automated processes for creating artifacts and assembling them, the skills and actions needed to create products are heavily discounted relative to the knowledge and information needed to create them. Downstream activities such as *design* and *manufacturing* can serve as important means of integrating diverse knowledge bases and converging knowledge and technology (CKT), specifically in the following areas:

- *Scalable models for distributed manufacturing*: The emerging idea here is the integration of small distributed facilities to obtain scaled-up manufacturing. Crowdsourcing is one new idea related to this trend. Technologies needed for this include tools built upon coherent design, manufacturing, and service platforms for easy transitions among sketch, manufacturability, and serviceability. The model needs to be able to service both paths of knowledge generation illustrated in Fig. 7.1.

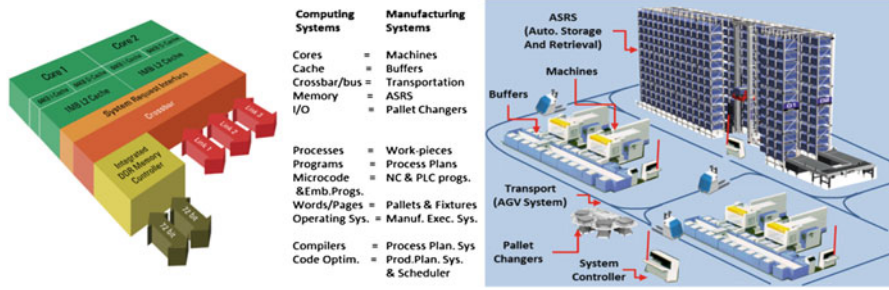


Fig. 7.10 Analog of distributed manufacturing systems with PCs (Courtesy of P. Ferreira, University of Illinois Urbana-Champaign)

- Info-inspired manufacturing systems:* Distributed manufacturing can follow an architecture similar to that used in computer systems, as illustrated in Fig. 7.10, using the concepts of cores, buses, peripherals, operating systems, networks, etc., in PCs (left column in Fig. 7.10) to design/architect the advanced manufacturing systems (right column in Fig. 7.10). What the new architecture enables is the interchangeability, integration, and hybridization of various manufacturing processes using different materials and operating at various length scales.
- Translational science-driven micro-/nanomanufacturing:* Technology innovations face prime challenges to continuously scale-down the devices in mass production and to heterogeneously integrate multiple functionalities for applications such as electronics, data communications, personalized medicine, and energy. Continuous harvesting of the capabilities of micro- and nanotechnology has to be developed. We especially need to pay attention to the new scientific-breakthrough-driven manufacturing innovations. Translational manufacturing examples in lithography technology—such as micro-factory, nano-imprinting, and plasmonic lithography based on scientific discoveries of metamaterial superlenses—are of great significance to many other technological sectors (Zhou et al. 2011; Fang et al. 2005; Liu et al. 2007; Valentine et al. 2008). Multidisciplinary research efforts bring together physics, mechanics, metrology, chemistry, material science, and electrical engineering to provide synergetic routes towards development of emerging manufacturing innovations. Key developments include achieving high-performance designs, improving reliability, improving management of data flow, and integrating additional ultra-high-accuracy metrology with automatic positioning control systems (Srituravanich et al. 2008). As key drivers, translational science-driven micromanufacturing and nanomanufacturing innovations will provide a foundation for economic growth.
- Predictive science and engineering:* One of the backbone elements in realizing the grand vision for distributed manufacturing is the ability to predict with confidence. For example, take additive manufacturing: bottlenecks for AM to replace existing processes in fabricating, particularly high-value-added metallic parts, are: (1) material powders design, and (2) ability to predict part performance such as fatigue behavior based on powder composition and process conditions, because

most AM processes involve complex melting and solidification or solid-state phase transformation. Only with credible microstructure prediction and residual stress prediction can a processing strategy be autonomously developed to compensate for potential shape distortion to achieve desired performances. Thus, new methods are needed in integrating physics-based models with various manufacturing processes and with new materials.

- *Human-machine interactions*: This technology will have a broad impact on society in terms of improving human performance, reducing risk and exposure of humans to dangerous situations, and improving the quality of life of people with physical challenges. For example, future space exploration mission scenarios include a greater reliance on human-directed robots to explore a planet surface, aid in the construction of permanent bases or habitats on a planet surface, or function as surrogates for humans in situations where it may not be possible to adequately protect astronauts from exposure to hazardous environmental conditions such as temperature extremes or radiation. Technologies developed for space exploration applications could also be utilized by manufacturing operations, firefighters, police, and in homeland security and defense applications.

7.3.2 Manufacturing Process DNA

Manufacturing, in this study, is defined as processes and systems that alter the structure, shape, surface, and function of materials. It includes a combination of mechanical, optical, and chemical processing in a broad domain, including but not limited to subtractive processes, additive processes, net-shape processes, pharmaceutical processes, refining processes, and self-assembly processes. This broad definition of manufacturing plays a particularly important role in the framework of establishing converging technologies and distributed manufacturing because scientists and engineers from different disciplines need to be able to communicate with each other using a common language. Here, we call this common language “manufacturing process DNA”.

The establishment of manufacturing process DNA will enable the co-design of products and processes; will integrate, intertwine, and synchronize multiple processes; and will require collaboration among multiple disciplines.

7.3.3 Integrated Social and Physical Sciences

Realizing artifacts and services of benefit to society necessarily requires the consideration of multiple factors: economics, technology, sustainability, the environment, societal effects, etc. As an example, nanomanufacturing not only seeks to create artifacts that exploit physical nanoscale phenomena, but it also motivates the study of these phenomena as the basis of manufacturing technology.

7.3.4 *Individualized Education Model*

The distributed manufacturing framework may also demand different job-performance skill set requirements from individuals. To address this need, the following recommendations were made by the attendees of the U.S. NBIC2 conference:

- Create participatory games and tools that enable new ways of learning science, engineering, technology, and manufacturing.
- Educate *all* people so as to enable even “disabled” and “disadvantaged” individuals to have the capabilities to be part of society’s growth and to participate in the distributed economic model.
- Reinvent higher education, i.e., to improve the weakest link in the higher education system, to attract bright new minds to all universities, not just the top-ranked ones.
- Establish a culture of renewed appreciation of “making things.” From a technological/societal point of view, it is important to be able to translate CKT inventions and R&D into valuable products that are accessible to as many people as possible. Many advanced countries are losing manufacturing skills because of outsourcing and over-emphasis on design, marketing, and financial “manipulations.” Making things is not very popular anymore. In the case of MEMS, the United States is not the main beneficiary of the tremendous investments it has made in the field. To reverse that trend will require that we reengineer the pathway from basic research to product realization, and reconnect with community colleges, the public, and the general workforce. We also need to find a way to influence political decisions more effectively.

7.4 Infrastructure Needs

Cyberinfrastructure has become an essential part of process-based manufacturing, and its role will grow dramatically. One of the more vivid projections is that of zero-risk, zero-emissions process manufacturing. Safe, clean operations will rely on high levels of process automation, abundant small sensor devices, and data analytics to detect key variances during steady-state operations and during transient operations like startup and shutdown. “Risk” refers here to safety, but economics will also be aided by real-time supply-chain management feeding relevant and timely data into process operations.

Similarly, *IT-supported citizen science* will enable ordinary people to engage more actively in economic and/or social development via cyberspace. The impact of realizing the scientific and technological goals described in Sect. 7.3, i.e., distributed manufacturing, process DNA, synthesis of social science and technology, and individualized education, will not be possible without a well-developed cyberinfrastructure.

The levels of advanced scientific equipment in most labs of U.S. institutions are now behind those of international counterparts in Korea, China, Japan, Switzerland, Germany, etc., as experienced by educators and indicated in the National Academy

of Engineering's *Rising above the Gathering Storm Revisited* report (NRC 2010). We need to reinvest now in the best available equipment here in the United States.

7.5 R&D Strategies

7.5.1 *Investment Strategies*

It was perhaps expected that private industry would invest in R&D and better equipment at R&D institutes once they started retrenching their own internal efforts away from R&D (see Bell Labs, IBM, etc.). That has not happened. As the current financial crisis has made clear, that will also not happen in the near future. In the meantime, competitors Samsung, LG, and many others are doing what those U.S. R&D houses used to do. The more applied U.S. national laboratories should perhaps be reconverted into nimble engines of economic survival. The more fundamental research arms of NSF, NASA, and the Defense Advanced Research Projects Agency (DARPA) should go back to investigating the most daring and far-reaching science goals instead of trying to address short-term industrial needs. We must expect vigorous international competition for these achievements, which worldwide are funded primarily by government entities rather than by industry. The advantages of such investment for the United States—and other countries—will be to develop the needed science, technology, and people with knowledge and skill to meet pressing emerging challenges and to transport society to improved collective technological constructs and broadly shared decent standards of living.

7.5.2 *Implementation Strategies*

Over the last decade, the vision and reality of converging technologies have gained momentum and acceptance among scientists and engineers; however, we have lost ground in terms of broad public support, and we are even less able to implement and exploit our national intellectual property (IP) position in converging knowledge and technologies than we were 20 years ago. At a time when sciences are converging with the promise of undreamed-of new technological opportunities, our nation is ill-prepared in terms of necessary resources, the support of politicians, and adequate workforce training. One cannot implement a long-term vision in an economic and political climate of shorter and shorter time horizons. Those societies that still have the resources and “educated” politicians with the patience and foresight to stick with a longer-term plan will reap the benefits of converging technologies.

We need to make the process of generating cutting-edge knowledge much more inclusive, and while deepening scientific interdisciplinary R&D, also place much more emphasis on the realization of physical products that can be seen by the public as both exciting and beneficial, for example, personalized medical devices or assistants. The goal of *universal access to quality education* needs to have two directions, pull and push. The technology and framework discussed in Sect. 7.2.4 illustrates the

push direction, i.e., how to *push* knowledge to people who have the desire to learn. The challenge is in the *pull* direction, how to obtain the attention of people without strong backgrounds in science, technology, engineering, and mathematics (STEM)—including the majority of politicians—to educate and excite them about these fields. The STEM community has to be more proactive to ensure that goals are measured and achieved, that none of the fundamental research institutes become political footballs, and to fill in the current blank to create a long-term political vision regarding the value of adequate and sustained U.S. investment in these areas.

7.6 Conclusions and Priorities

The U.S. NBIC2 workshop attendees evaluated the current manufacturing landscape, defined what “advanced manufacturing” means to society, recognized the emerging pattern of knowledge creation and absorption, and explored the possibilities for radical change in the landscape of manufacturing over the next decade or two via the emerging paradigm of distributed manufacturing. The research and education priorities they identified are noted briefly below.

Research priorities: Advancing manufacturing through converging technologies will be essential to progress in economic and quality-of-life indicators. Research needs were summarized by participants as (1) distributed manufacturing enabled by process flexibility, modularity, in-process metrology, predictive sciences and technologies, human–machine interaction, etc. (refer to Sect. 7.3.1); (2) manufacturing process DNA (refer to Sect. 7.3.2); (3) integration of the social and physical sciences (refer to Sect. 7.3.3); and (4) individualized education (refer to Sect. 7.3.4).

Education priorities: Financial pressures have pushed educational institutions into making shortcuts that are leading to students obtaining degrees in less time with weaker content. Understanding of advanced topics like structural colors (caused by the interaction of light with nanoscale structures in materials) requires not only a mastery of physics but also insights into advanced manufacturing. Therefore, education will require a better balance between theory and practice and between computation and experimentation. To meet the challenges of the modern era—i.e., how to gain knowledge accurately and fast enough to ease the knowledge burden, and how to disseminate STEM knowledge to the general public, including politicians—new methodologies of individualized education will be needed.

7.7 R&D Impact on Society

A science-based understanding of “making things” in a distributed fashion will enable an economic and societal transformation of productivity and creativity. The past decade of research and development on cyberinfrastructure, an essential part of all the converging technologies, has transformed public and private communications, business transactions, the conduct of science, and manufacturing,

largely for the better. Convergence of technologies creates innovative ideas and products that benefit all people.

At the same time, a consequence of these trends has been to redirect the wealth generated by industrial workers, altering the source of middle class income to be based more on service-sector employment. Industrial employment as percentages of U.S. and of international overall employment appears to have fallen due to a natural progression similar to the monotonic decrease in agricultural employment. Eventually, it will likely fall to some level consistent with high manufacturing productivity. A side effect is that industry-generated wealth then flows mainly to upper management and owners rather than into worker wages and salaries, altering the traditional flow paths of wealth back into the general population through consumer spending by the industrial employees. In order NOT to further the gap between rich and poor (or educated and uneducated), we will have to become much more inclusive and work on building a middle class that can participate in the benefits of CKT.

The impact on society of envisioned converging knowledge and technologies, and particularly distributed manufacturing, will be of the same order as the PC revolution. Three profound elements of the grand vision are to:

1. Shift manufacturing capabilities from the hands of the few into the hands of the many to spark innovations
2. Alter the paths of how knowledge and technologies are created
3. Ease the knowledge burden in distributing knowledge quickly and accurately

7.8 Examples of Achievements and Convergence Paradigm Shifts

Above we have discussed what the converging technologies are for manufacturing, and their societal impacts. Below, we will illustrate the process and impact through the case study of Xerox, including hybridization of disciplines, lessons from big data, and healthcare information systems for the future of social science research in industry. Then we will present an example of technology integration for wearable computers and sensors.

7.8.1 Social Science Research and Technology-Based Industry

Contact person: Marietta L. Baba, Michigan State University

Hybridization of Disciplines: The Initiation

Over the past 30 years, experts in anthropology, linguistics, psychology, design, and other disciplines linked to the social sciences have worked together with

members of the computer science and industrial engineering disciplines to form new interdisciplinary fields of research and practice referred to as *design ethnography* and *participatory design* that have reinvented the processes by which new products, services, systems, and spaces are conceptualized, designed, and implemented by industry (Blomberg et al. 1996; Suchman et al. 1999; Squires and Byrne 2002; Cefkin 2009). Design ethnography has its own annual conference (EPIC, or Ethnographic Praxis in Industry, in its eighth year in 2012), with global rotation of venues and refereed proceedings published through the American Anthropological Association. Sponsors include Intel, Google, Microsoft, and several other large technology firms. The emergence of this hybrid profession was one consequence of criticism regarding mainstream academic anthropology, especially charges that the discipline was too much wedded to studying former colonies (Marcus and Fisher 1986). These charges gave legitimacy to students who wanted to pursue research in venues other than typical remote locations. In the process of repatriation, anthropologists spread out over many different field sites and came into contact with a number of other disciplines and professions, and they hybridized their knowledge and practices as they worked with each other. Participatory design is a related field that is more specialized; its development will be discussed below.

The industrial roots of design ethnography and participatory design in the United States may be traced to the earlier efforts of Frederick Taylor and the Human Relations School to improve interactions between people and equipment in the production process. These early streams of investigation on the “human factor” in production eventually gave rise to the subfield of “*human factors*” research, a multidisciplinary offshoot of psychology that identifies aspects of human psychology and its context that must be taken into account in the design and development of new products. “Human factors” is both a field of study and an area of research and development in corporations that produce goods and services based on advanced technology.

Xerox PARC: A Case Study

In the 1970s, one company that was committed to pushing the envelope of knowledge on human factors (broadly defined) surrounding advanced computing was Xerox’s Palo Alto Research Center (PARC). PARC was interested especially in human–computer interaction and the development of artificial intelligence to support this interface; it also funded graduate student interns to work in this and other areas related to computing. One of the first interns was Lucy Suchman, who came to PARC in 1979, at first to study office work practices, but later she became intrigued with the idea of machine intelligence in a computing context.

In her doctoral research, Suchman conducted a Garfinkle-inspired ethnomethodological study of computer-supported work: she videotaped pairs of engineers attempting to make copies of documents using an expert help system and then compared the users’ conversations and actions during this process with the machine’s automated instructions (Suchman 1987). Contrasting the two points of view side-by-side (i.e., the users’ and the machine’s), Suchman portrayed communication

breakdowns between them, as humans moved fluidly among several different levels of conversation (e.g., simple requests for action, “meta” inquiries about the appropriateness of a procedure, and embedded requests for clarification of procedures), while the machine was severely limited to producing responses that its designers had programmed into it in anticipation of stereotypical responses that users “should” make. While these observations might not seem revolutionary now, they were a lightning bolt at Xerox PARC and led the corporation to change the design of its copiers to make them simpler to use. This research also gave Suchman a reputation for bold and fresh insight and enabled her to expand the role of social science at Xerox PARC.

Suchman attracted other social scientists and computer scientists to her group. A breakthrough came in 1989 when the Doblin Group of Chicago asked Xerox PARC to partner on a project for the office furniture manufacturer Steelcase (Reese 2002). Steelcase managers wanted to understand how the workplace of the future would evolve and what kinds of work environments and designs it should be thinking about over the long term. PARC agreed to co-fund the project that came to be known as the Workplace Project. The project was situated in an airport, which was believed to have properties reflecting the workplace of the future (e.g., high fluidity of people and information and workflow extending into multiple kinds of space via electronic means). Suchman served as lead on this project for several years, and through it she assembled a talented team of social scientists and designers who would revolutionize the design industry. One of the individuals involved was Rick Robinson, then at Doblin (an innovations consultant firm), who subsequently co-founded E-Lab in Chicago, an entrepreneurial firm explicitly dedicated to the concept of equally balancing product design projects with ethnographic research and design talent. The notion that all new product and service concepts should emerge from a contextually rich understanding of the client’s natural world, developed through ethnographic field research at client sites, captured on videotape and analyzed using social science theory and method, was first conceptualized by Suchman’s group at the Workplace Project, but it was Rick Robinson who took the concept to market. This was the beginning of design ethnography.

Suchman’s group at Xerox PARC also established the Work Practice and Technology area in 1989, which mobilized arguments centered upon the value of ethnographically informed design of prototype technology in research and development (i.e., participatory design). This group engaged in productive collaborations with members of other disciplines over more than a decade to address many important questions that relate to computer-supported cooperative work (CSCW), including engagement with an international network of computer scientists and systems designers committed to systems development in a more participatory form involving workers and other users.

This latter model of participatory design was drawn from and strengthened by interactions with colleagues in Denmark, Norway, and Sweden; academic computer scientists collaborating with Scandinavian trade unions developed union-sponsored demonstration systems informed by values of quality of working life and workplace democracy. At Xerox PARC, these values were not the ones emphasized; rather, the

potentially superior design outcomes were stressed, to produce information systems better suited to working practices.

One project that stands out was conducted by Xerox in the late 1990s at the headquarters of a state department of highways (Suchman et al. 1999). For 2 years, Suchman's group engaged in a collaborative effort with engineers charged with designing a bridge scheduled for completion by 2002. The prototyping effort was focused on collecting the engineers' documents, a heterogeneous assortment of paper documents, and understanding whether digital media might provide new and useful ways to access the information. As it was assembled on site, the prototype stood as a kind of developing description of how it was that engineers were interested in accessing their documents, and a provisional proposal for a way of working. The prototypes were working artifacts, not given in their specifications, but in the unfolding activity of cooperative design in use.

This approach illustrates one of the ways in which ethnographic practices became a resource for participatory design—two distinct fields that are complementary but not necessarily fully compatible. Despite the potential for incongruities, more than two decades of collaboration between ethnographers and participatory designers have enabled the two fields to develop several creative approaches to working their ways of knowing together, and this collaboration created a widening interest in ethnography in the field of design that has had important implications for industry and anthropology. A number of major technology corporations today have incorporated anthropologists and ethnographers into their R&D staffs (e.g., IBM and Intel) to support design operations, and smaller boutique firms that provide research and design for larger companies also employ anthropologists and ethnographers. This represents a significant development in industrial practice that does not appear to be a passing phase, but the permanent incorporation of a new set of knowledge and skills that heretofore were not available to industry.

Science and Technology Studies: A Critical Turn

Suchman's group at Xerox PARC was identified with an interdisciplinary tradition in the social sciences sometimes known as Science and Technology Studies or Sociology of Knowledge Studies, which became well established in anthropology during the 1980s and 1990s. This subfield included social scientists engaged in the study of artificial intelligence, human–computer interaction, and other related subjects sufficient to form an interest group in the American Anthropological Association.

The anthropologists and linguists who were involved conducted empirical field studies in which they attempted to document what was going on in science, engineering, and technology-intensive venues (e.g., laboratories); however, some of the researchers appear to have been rather naïve in failing to realize that their subjects would read what they wrote and interpret it through their own lenses (Hess 2001).

As it turned out, the social science “discovery” of what were considered “social” influences within the laboratory was sometimes taken as a discrediting maneuver by the some of the scientists (not those at Xerox) and led to a special kind of “science

war” between social scientists and natural scientists, one of the results of which has been a sharpening of the philosophical differences between these fields. Some social scientists lost their access to scientific sites as a result (e.g., see Rabinow 2012).

Science and Technology Studies continued into its second and third generations, but it has developed a very different form of practice because in many cases it is no longer welcome in scientific laboratories. The way this field works now is by attending scientific conferences, attending schools, going on virtual chat rooms, reading the technical literature, interviewing outsiders and laypersons about their perspectives on products, becoming part of social and activist organizations, and providing services to help the social issues community, such as by writing or lecturing on the social, historical, or policy aspects of the community (Hess 2001). In some cases, practitioners have developed a sustained engagement that has lasted for 5–10 years or more, gaining deep knowledge of the field and becoming expert commentators. These methodological practices have been developed at the same time that interpretive and critical theories were reaching their zenith within American anthropology and other academic fields.

Transcending the Distance: Lessons from Big Data and Healthcare Information Systems for the Future of Social Science Research in Industry

There are many reasons for hope that social scientists, both in industry and academia, will continue their collaboration with members of other disciplines such as computer science and engineering, following the transition that has been described above. It may not be that the cooperation occurs in the area of Science and Technology Studies, but there are many other areas of opportunity created by converging technology. At present, due to trends noted in the Xerox PARC case study, there are numerous social scientists in industry, both as a result of growing demand for understanding global consumers and the downsizing of academia. Industry practitioners such as those involved in EPIC (see Sect. ‘[Hybridization of Disciplines: The Initiation](#)’) are reaching out to academic social scientists to build intellectual bridges (Cefkin 2009).

More importantly, there are emerging challenges and opportunities for the social sciences in which other disciplines, and industry, must play a vital role. The most clearly articulated challenge is that of data analytics (or “big data”) and the role of computational approaches to the aggregation, analysis, and interpretation of such data. There is an increasing volume and detail of digital information captured by organizations with the rise of multimedia, social media, and the “internet of things” that is predicted to be involved in innovation and economic growth. A major challenge for social scientists will be the development of means to access, aggregate, analyze, and interpret the significance of such data for social and economic problems. These are not challenges that the social sciences can tackle on their own. They will need to partner with other disciplines in science and engineering, and academics will need to cooperate with industry and government, where much of this data is being collected (Manyika et al. 2011).

Social scientists are already working on large digital data sets in the areas of environmental science, and there are possibilities in cognitive science as well (i.e., analysis of fMRI data). An area with potentially more interest for industry may be in electronic health records, which have been mandated by the HITECH Act of 2009 (Health Information Technology for Economic and Clinical Health Act, Title IV of the American Recovery and Reinvestment Act). Currently, thousands of healthcare organizations around the United States are engaged in the process of adopting the “meaningful use” of electronic health records, as required by the HITECH Act. Electronic health records can improve the quality of healthcare and reduce its costs; McKinsey Global Institute has estimated that the creative and effective use of data analytics in healthcare could create an additional \$300 billion in value per annum, two-thirds of which would be in reducing healthcare expenditures in the United States (Manyika et al. 2011). The aggregation of health records in electronic form could provide avenues for research collaboration among social scientists and health industry practitioners, as researchers pose questions and search for patterns that help achieve the goals of quality care and cost reduction. Yet another somewhat ironic opportunity exists in the disappointing adoption rate of electronic health records (EHR) in the United States; hundreds of thousands of healthcare practices have not yet adopted the new technology, despite economic incentives and the threat of penalties (Fiegl 2012). The reasons for this delay are not well understood; however, they could be related to difficulties being experienced by adopters of EHR systems, for example, being plagued by embedded software errors and usually adopted by healthcare staff through “workarounds” that are inefficient and themselves the source of other errors (Koppel et al. 2005, 2008). Case studies of successful health information technology reveal that large healthcare organizations have developed their own information technology after lengthy learning processes or as a result of internal growth and development with a large base of consumers (see for example Scholl et al. 2011).

The vendor community for EHR generally has not been one of the leaders in participatory design. Much of the software used as a basis for EHR was developed for the accounting function, and this could explain some of the basis for its errors (Koppel and Kreda n.d.) Also, contracts for external vendors contain “hold harmless” clauses such that vendors are not liable for software errors (Koppel and Kreda 2009). These issues present important problems for society at large that cannot be resolved by any single discipline.

Studies of organizations that have been successful in developing EHR over long periods of time (e.g., Kaiser Permanente and the Veterans Administration) could disclose the principles and processes through which such systems have become institutionalized (including cognitive models) and possibly suggest alternative approaches to the implementation of EHR. The software industry, healthcare practices, and the social science community need a better understanding of the ways in which complex information systems can become successfully embedded in services systems that provide medical care to people, regardless of scale. This challenge will not be addressed without collaboration across disciplines, including the social sciences.

Lessons from the healthcare context for the social sciences in industry could be of value for other areas of research and development. Healthcare is a highly fragmented industry with many diverse actors whose interests are not necessarily aligned, and it is increasingly under public scrutiny, so there are opportunities for social science to become engaged. The same features characterize global supply chains that incorporate numerous and increasingly diversified actors, including transnational corporations, developing world entrepreneurs, migrant workers, affluent and conscientious consumers, and NGOs acting as self-styled certifiers of labor rights or other types of standards (Partridge 2011). Global supply chains require the development of standards to ensure quality and/or alignment of other values, yet standards are embedded within social contexts and relations of power, and thus their development and enactment may be fraught with conflict that requires understanding and amelioration (Busch 2011). The intertwining of technical and social factors in the construction and sustainment of global supply chains for manufacturing industries is one of the areas in which social science could collaborate with the natural sciences and engineering in the future.

7.8.2 Example of CKT: Wearable Computers and Sensors

Contact person: Dongyi Chen, Mobile Computing Research Center, University of Electronic Science and Technology, China

Wearable computers and sensors are becoming a greater possibility with the field of nanotechnology expanding and with the integration of body sensor networks, fiber assemblies, and interactive textile devices. Wearable electronics and photonic systems can be manufactured in regular facilities using low-cost, environmentally friendly processes. Once assembled, these wearable electronics and photonic systems can be programmed to operate as an extension of the humans wearing them, to enhance their capabilities, as well as to provide a unique mechanism of monitoring body conditions.

This field of wearable technology extended to implantable, or “body computing” devices can be classified into three categories: ultra-miniature electronic devices and sensors, flexible and planar printed electronics, and e-textiles. The *ultra-miniature electronic devices and sensors* are the implants that monitor physical body functions. The goal of these devices would be to improve intelligence (if implanted in the brain), power (if implanted in muscles), or basic functions (if implanted in cells or organs). A body sensor network would work together with the micro implants to create “intrabody networks” that could be used to measure pressure, flow, temperature; to stimulate nerves or tissues; and even to activate drug therapies.

The two categories flexible and planar printed electronics, and e-textiles, expand the areas where research and development will make body computing possible. “Printed electronics” can be flexible, stretchable materials with special single-cell-based “nano-ink” that can function as monitors, printed organic memories, electrochemical capacitors, or even batteries. “E-textiles,” also referred to as smart textiles, refers to

“intelligent” fibrous materials that can be developed to incorporate sensing as well as actuating, control, and transmitting of wireless data. There are still many opportunities to discover, develop, and expand this field of wearable computers/sensors and photonic devices. Dr. Xiao Ming Tao from The Hong Kong Polytechnic University divides these opportunities into four major research areas:

- *Intelligent fibers and fibrous assembly structures*: This entails creating fibers and fibrous assemblies from smart materials with single or multifunctional intelligence.
- *Interactive textile devices*: This entails engineering of fibrous products that can be used for sensing, communicating, memorizing, actuating, and energy harvesting.
- *Product integration and fabrication technology*: This entails investigating and developing ways to incorporate existing fabrication technologies with intelligent fibers and textile products.
- *Human-machine-clothing interaction and wearable technology*: This entails developing efficient sensing functions in order for the wearable computers to detect various human functions.

Developing these areas of research will expand the application of wearable computers/sensors to the extent that they will become essential to quality of life.

7.9 International Perspectives

The following are summaries relevant to this chapter of discussions at the international regional WTEC NBIC2 workshops held in Leuven, Belgium, September 20–21, 2012; in Seoul, Korea, October 15–16, 2012; and in Beijing, China, October 18–19, 2012. Further details of these workshops, including workshop agendas and experts who attended, are provided in Appendix A.

7.9.1 *United States–European Union NBIC2 Workshop (Leuven, Belgium)*

The discussions of NBIC2’s impact on manufacturing, innovation, and societal outcomes spread over several breakout sessions, for example, Working Group #1 on research and Working Group #2 on innovation. The summary below incorporates findings from the several breakout sessions.

NBIC2 was identified by Working Groups 1 and 2 to have direct impacts on water, energy and environment, and food and agriculture. The challenges are obviously so great that no single discipline can solve them alone. For example, in the area of food and agriculture for the EU, there is a balance between social acceptance of technology-based optimum distributions and culture-based existing distributions—a tension between sustainable development and individual preferences. Therefore, convergence technologies can contribute more in using technologies to enhance

productivity, such as refrigeration, sensors for water delivery systems, bio-systems to induce lateral root growth in desert plants or reduction of water usage, and in assisting governance by conducting comprehensive life cycle analysis.

While the above group discussions focused on the impact of NBIC2 on physical and environmental systems, another group examined the impact of NBIC2 on human capacity in terms of (1) using machines effectively to increase human capabilities, even perhaps, passing some human activities over to machines, including neuromorphic engineering; (2) understanding how the machines we create and use will modify ourselves, and understanding how learning occurs; (3) enhancing the way we do a variety of tasks (including imagination) and doing tasks we cannot currently do; (4) enhancing the ability of humans and machines to communicate with each other beyond language; and (5) changing the education models at all levels to advance personalized learning. NBIC2 technologies can effectively tie the tremendous work in understanding how the brain works with our engineering systems, for example, manufacturing processes and systems, and cyberspace security.

7.9.2 United States–Korea–Japan NBIC2 Workshop (Seoul, Korea)

Panel members/discussants

Co-Chairs:

Hak Min Kim, Korea Institute of Machinery & Materials (KIMM, Korea)

Masafumi Ata, National Institute of Advanced Industrial Science and Technology (AIST, Japan)

Jian Cao, Northwestern University (U.S.)

Others:

Eung-sug Lee, Korea Institute of Machinery & Materials (KIMM, Korea)

Sung-Hoon Ahn, Seoul National University (Korea)

Dae Maun Kim, Korea Institute for Advanced Study (KIAS, Korea)

Takashi Kohyama, Hokkaido University (Japan)

Kazunobu Tanaka, Japan Science and Technology Agency (JST, Japan)

Seiichiro Kawamura, JST (Japan)

Kuiwon Choi, Korea Institute of Science and Technology (KIST, Korea)

Yong Joo Kim, Korea Electrotechnology Research Institute (KERI, Korea)

Jo-Won Lee, Hanyang University (Korea)

The Korean government has invested heavily in convergence technologies, defined as the convergence of nanotechnology, biotechnology, information technology (IT), environmental technology, space technology, and culture technology. The Twenty-First Century Frontier R&D program was established about 10 years ago to fund R&D centers such as the Center for Nanoscale Manufacturing and Equipment

(CNMT). Each center received \$10 million per year for 10 years. The program was replaced by the Global Frontier R&D program, which has a funding level of \$10-30 million per year per center. Three such centers were established in 2010 (the Center for Bionics, Center for Biomaterials, and Center for Theragnosis) and four centers in 2011 (the Center for Multiscale Energy Systems, Center for Advanced Soft Electronics, Multi-dimensional Smart IT Convergence Systems, and Design and Synthesis of Biosystems). The new initiative “Nano-convergence 2020” was established for creating new industries and markets through the commercialization of nano-convergence technologies. The project duration will be 9 years, from 2012 to 2020 with a total budget of \$440 million, of which \$370 million in government funding is matched with \$70 million in private funding.

Panelists from Korea and Japan took the view that *in the last ten years* there has been particularly rapid and widespread integration among many individual manufacturing technologies, nanoscience, and biology, resulting in various hybrid processes for applications such as structural color and bio-inspired lotus leaves as self-cleaning mechanisms for glass, textiles, etc. With the aid of computer and information technologies, design and analysis of manufacturing have taken on more prominent and positive roles in increasing productivity. Conventional manufacturing processes have also been extended to biomanufacturing areas and small-scale multifunctional manufacturing. The semiconductor industry continues to push Moore’s Law. Robots have been increasingly advanced in terms of accuracy and flexibility. Success stories include automation in manufacturing environment, the da Vinci surgical system, and others.

Similar to the observations made at the U.S. NBIC2 workshop, panelists at this workshop also believe that mass customization of manufacturing and additive processing using functional materials will be promising *in the next 5–10 years*. Distributed IT-assisted manufacturing can empower individuals and communities. Specifically, research needs include scalable models for distributed manufacturing, info-inspired manufacturing systems, translational science-driven micro-and nanoscale manufacturing, predictive science and engineering from the nanoscale to the macroscale, human–machine interactions, and a unified description language for manufacturing processes. Robotics can assist human health and functionality. There will be more development in a system-level biomimetic-ecomimetic approach for societal and technology development, for example, convergence of a self-organization approach in developing new manufacturing processes.

To facilitate these changes, robust standards for data/material formats and faster IT network speeds were identified as infrastructure needs. Particularly, urban-appropriate technology with emphasis on practice and implementation was identified as an emerging topic with high priority. The impact of converging technology will be rapidly experienced by society in general, including the bottom majority of the income pyramid.

The R&D investment and implementation strategies suggested by this group include establishing pull-driven (needs-driven) R&D strategies; creating global open access to designer, engineer, and manufacturer; inspiring politicians and their staff about the NBIC concept and potentials through increasing communication

channels and effectiveness; having a better plan for disseminating NBIC information to the public; and establishing an intergovernmental platform for addressing Earth-scale issues in developing NBIC technologies, e.g., energy, pollution, water, etc.

7.9.3 United States–China–Australia–India NBIC2 Workshop (Beijing, China)

Panel members/discussants

Dongyi Chen (Co-Chair), University of Electronic Science and Technology (China)

Gordon Wallace (Co-Chair), University of Wollongong (Australia)

Jian Cao (Co-Chair), Northwestern University (U.S.)

Others:

Bin Hu, Lanzhou University (China)

Calum Drummond, University of Melbourne (Australia)

The Chinese government has invested heavily in nanotechnology and biotechnology. One example is the Suzhou Science and Technology town jointly established by the national Ministry of Science & Technology and the Jiangsu provincial and Suzhou municipal governments (SND 2010). The investment has been about US\$800 million. In the last 10 years, the integration among different disciplines has been increasingly seen in practice, for example, in integration between materials, design, and manufacturing. One example is 3D printing on soft materials such as textiles (Jost et al. 2011) or printing of single cell and growth factors. Manufacturing enterprises have evolved for the most part as concentrated urban phenomena.

A 2012 cartoon titled, “How babies will be born in the future” (<http://www.makeuseof.com/tech-fun/how-babies-will-be-born-in-future/>), and the key character Sun WuKong in the classical Chinese novel *Journey to the West* by ChengEn Wu in 1550, inspired lively discussions on the vision for the next 10 years. In summary, four areas were identified:

1. Distributed IT-assisted manufacturing to empower individuals and communities, used for point-of-need manufacturing, for example, printing conduits in surgery for nerve, muscle or organ repair in an operation room, or personalized medicine with doctor-prescribed formulation
2. Enhancing human sensing beyond current capabilities, e.g., body sensor networks, such as for biological signal sensing and environmental sensing, on jewelry, on the body, on hair mousse, or on watches
3. Integrating brain research with manufacturing research, e.g., electronic circuits/devices for understanding brain function, and then using the knowledge to enhance the speed and the process of determining successful outcomes for robots or for extension of human performance

4. Integrating environmental, health, safety, ethical, legal, and societal issues with technology development, e.g., regulation in machinery fabrication in the new paradigm where printers print printers; the new role of pharmaceutical companies in an era of personalized medicine

Cyberinfrastructure, collocated facilities, and personnel were identified as the *infrastructure needs* for the future development. In addition, new standards for NBIC needs, and manufacturing equipment in universities, community colleges, and high schools were also identified as needs.

The suggested R&D strategies included establishing mission-driven challenges to lead convergence; engaging scientists and engineers in the importance of manufacturing if real outputs from the convergence of NBIC are to be realized; having an open architecture to encourage the engagement and the contributions from scientists and engineers, e.g., application software and hardware modules; inspiring resource providers about the NBIC concept and potentials through increasing channels and effectiveness in communication; and establishing ongoing education and retraining of manufacturing workforce. Among those, the emerging priorities are identified as new manufacturing processes and systems for integrating different scales and the convergence of cognitive science and IT to create innovative manufacturing processes rather than the current ad hoc approach.

In terms of social impact, other than previously identified positive effects, one cautious point identified is the risk of having technology (for example, advanced 3D printing technology) land in the wrong hands, and measures to mitigate this.

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