Matter As Software

James C. Ellenbogen

March 1997

MITRE
McLean, Virginia

Presented at the Software Engineering & Economics Conference,
McLean, VA, 2-3 April 1997.

Matter As Software

MP 98W0000084
March 1997

James C. Ellenbogen, Ph.D.

Sponsor MITRE MSR Program
Project No. 51CCG89G
Dept. W062

Approved for public release;
distribution unlimited.

MATTER AS SOFTWARE

James C. Ellenbogen, Ph.D.
The MITRE Corporation
McLean, VA 22102
Phone: 703-883-5930
Fax: 703-883-5963
e-mail: ELLENBGN@mitre.org

ABSTRACT

In the next century, as the components of computers continue to shrink smaller and smaller, down to the molecular scale, their physical representation will become more and more like that of present-day computer data. It is explained in some detail how this ongoing process of miniaturization is likely to lead to a technology in which matter will acquire desirable physical and economic properties much like those of software. It will be possible to "read" and to "write" functioning computer components and logic structures at will; they will be manufactured locally, on demand, in a manner similar to the way we now "download" software onto disk drives. In addition, microscopic and submicroscopic mutable computer logic structures will be built into motile microscopic units of matter, putting the macroscopic properties, form, and function of matter itself under program control. Thus, in the next century, the technology developed for building dramatically smaller computational engines will evolve to have even broader technological and economic impacts than have been felt during the last half century of the digital computer revolution.

INTRODUCTION

Microfabrication methods were invented by the computer industry 30 years ago simply as means to place thousands of microscopic transistors on integrated circuit chips. However, these methods are evolving toward an all-embracing technology that is animating matter on the microscopic level, while providing mankind with sensitive, flexible control over all matter on even finer scales. This paper will outline the key elements of this ongoing revolution in miniaturization, and explain that its foreseeable conclusion will attribute to matter physical properties and economic properties much like those we now associate with software.

To understand why this is so, one first must appreciate fully that software is not as insubstantial a commodity as we sometimes tend to think or are led to believe by the rapidity and ease of its manipulation. All information is physical [Landauer, 1991]. It has an incarnation somewhere in matter, and the manipulation of information in modern software is dependent on the fine-grained manipulation of matter and energy. (An example is the ones and zeroes, or "bits," recorded by reorienting magnetic moments on microscopic iron particles embedded in plastic disks.) Thus, as we gain the capability to manipulate matter in more comprehensive and more sensitive ways on even finer scales, it would not be strange if matter itself were to become more like software.

Key elements of our evolving capability for the fine-grained control of matter are the emerging technologies for

- Microrobotics
- Nanofabrication

MICROROBOTICS AND NANOFABRICATION: TOWARD "SMART MATTER" AND "DOWNLOADABLE" OBJECTS

In laboratories all over the world, enormous strides are being made in applying the technology for microfabrication toward making sensitive, animate microscopic machinery termed microelectromechanical systems (MEMS) [Angell *et al.*, 1983; Stix, 1992; Gabriel, 1995]. Microfabrication--fabrication on the scale of microns (millionths of a meter) also is being advanced rapidly toward nanofabrication--fabrication on the scale of nanometers (billionths of a meter) [Campbell, 1996; Montemerlo *et al.*, 1996]. This is the scale of individual molecules, the building blocks of matter. These two new technologies are being applied with great imagination and creativity to construct an increasingly more complex array of silicon "chips" that someday may be as small as a grain of salt, with computer-controlled microscopic machinery and actuators on board. Also, smaller, denser more powerful--"smarter"--computers are being developed. Autonomous, motile microdevices clearly are on the horizon. This will result from a combination of these two developments--smaller, smarter nanocomputers embedded on chips with more complex and densely packed micromachinery. Thus, MEMS and nanofabrication may be regarded as the early steps in the evolution of a technology for "programming" the structure and properties of material objects at the microscopic and the submicroscopic levels.

Employing these new technologies, in the next century it will be possible to construct and deploy legions of micro-robots as small as a grain of salt or smaller. This possibility is made apparent by recent progress in the fabrication of tiny, tiny motors and leg-like actuators for MEMS [Gabriel, 1995; Pister, 1995] and by progress toward the fabrication of ultra-densely integrated electronic nanocomputers [Montemerlo *et al.*, 1996]. The integration of MEMS and tiny on-board nanoelectronic computer controllers for the construction of such micro-robots in vast numbers is an obvious application of the rapidly advancing techniques for the economical fabrication of nanometer-scale structures--i.e., "nanofabrication."

A variety of economically advantageous and technically interesting applications have been suggested for masses of micro-robots. One of these is their use in detecting, swarming upon, devouring, and "metabolizing" environmental contaminants, like oil and chemical spills. Another is the use of micro-robots as the motile, programmable *supra*molecular building blocks of "smart-matter" that changes its shape, rigidity, strength, and surface properties to suit its environment or its user [Schleier-Smith,1996].

Additionally, stunning advances have been made in the development and application of nanoprobes, such as atomic force microscopes (AFMs) and scanning tunneling microscopes (STMs) [Binnig and Rohrer, 1985; Hansma *et al.*, 1988; Park Scientific Instruments, 1996]. These devices, which were invented in the 1980s, function like remote imaging and manipulator arms for atomic and molecular-scale objects [Avouris,1995; Jung *et al.*, 1996]. Originally, though, STM and AFM machinery was large and relatively slow. Now, MEMS fabrication techniques also are being applied to miniaturize these AFM and STM manipulator arms and build faster microscopic arrays of them on silicon computer chips [Xu *et al.*, 1995; Minne *et al.*, 1995]. MEMS chips also are being built to perform microscopic chemical synthesis under computer control.

Matter manipulation chips such as these soon will proliferate to be available as a peripheral device on desktop workstations everywhere. There, they can be used to image and move around matter, atom-by atom and molecule-by-molecule to build or "write" very tiny structures under program control, much as the small magnetic arms or "heads" on disk drives now are used on every computer to reorient magnetic particles under program control in order to store software data on magnetic disks. However, micro-STMs , micro-AFMs, and MEMS apparatus for microchemical synthesis perform a much more broadly applicable form of matter manipulation.

Among the applications of being able to "write" and "read" matter on such a fine scale is likely to be the fabrication of the components of next generation densely integrated computers. That is, the molecular-scale components and structures of ultra-densely integrated next-generation computers may be "written" into place under computer control, perhaps even "on the fly", as a computation progresses. Such computers might also be manufactured remotely at many points in a distributed network. Computers or other material commodities might be "downloaded" from a network in the same way that software is now manufactured on demand at many locations at once on a network.

VISION FOR THE FUTURE: MATTER AS SOFTWARE

To understand the ultimate consequences of such developments, one must look beyond the question of what specific objects we would have such devices and technologies assemble,--i.e., what things we would make with them? One must ask, what would be the economic and societal impact of the fact that things can be made and, in all probability, changed, by large numbers of very small, self-directing, distributed devices?

The recent history of the computer and software revolution provides some insight into the answers to these questions. During this revolution, society has witnessed the art of computer engineering and programming become an art for the physical transformation of information from tangible, relatively static articles (e.g., books) to almost intangible, fast moving commodities generically termed "software." Of course, this physical transformation has been accompanied by a very real and sweeping change in the economics of information . Its vast and growing economic impact on individuals and modern society sometimes seems at odds with the way we tend think and speak of software and information as though it were something becoming more and more intangible and ephemeral.

Nonetheless, information still is substantive and "physical" [Landauer, 1991]. It is just stored, duplicated, manipulated, and transmitted ever faster, on ever finer scales, with ever less expenditure of energy and human effort. This is due, in part, to great advances in computational *hardware*, communications *hardware*, and in *material* media for the mass storage of information. Also, information is stored in a manner that puts its content or substance on an equal footing with the instructions that program the hardware and material media for its manipulation and display. This tight coupling between content and program helps information be responsive and adaptive to its environment, its users. It seems likely that new capabilities for engineering, controlling, and "programming" matter on ever finer microscopic and submicroscopic scales will impart all the above properties of software to material objects. That is, matter will become as software.

TWO KEY ELEMENTS FOR MATTER AS SOFTWARE

What are the key elements that will drive the transformation that will make human society come to regard matter as software? The answer to this question has two main parts. The first follows from a consideration of the physical characteristics of the technology. That is, matter in artificially made objects will be engineered from programmable or manipulable elementary microscopic and submicroscopic units. This will make its form and its surface properties mutable, like data, under the control of software programs and the user. Matter will become "soft" in the literal sense. Also, it will be commonplace to embed into objects microscopic sensors for the detection of the users' presence and commands. Matter will become interactive with the user and adaptive to its environment. Furthermore, as these nearly identical programmable subunits become smaller, they will approach the scale on which the "bits" of software information themselves are stored. Then, programmable matter and program, the mutable medium and the software message will become almost indistinguishable, physically.

The second key element of the transformation toward matter as software will not be so much in the physical characteristics of matter, but in its manufacture and economics. To see this, we must ask how we will be making microscopic and submicroscopic machinery and computers in the future. Even allowing for future technological advances, it seems likely that the design and prototyping process will remain slow for the initial copies of such small devices. One can envision the development of new software aids, virtual environments, and other tools to assist with the design, as well as new development tools such as computer controlled lithography and arrays of manipulators for nanoprobes, such as AFMs and STMs for microscopic and nanoscopic manipulation of matter to implement these designs. Still the evolution of the ideas and the manipulation of matter for prototype devices is likely to remain "arduous" and the costs high, just as they are in software development today.

The proliferation of advanced technologies for micro- and nanomanipulation is likely to have a stronger impact, though, on the process and the costs for the mass manufacture of microscopic and nanoscopic devices. New, more precise physical methods, such as microscopic arrays of nanoprobes under computer control will aid in automating and reducing the cost of manufacture on both microscopic and nanoscopic scales. Early experiments already have been performed in which nanoprobes have been used to "draw" nanometer-scale features on surfaces [Lyding *et al.*, 1994; Minne, 1996]. Undoubtedly, this capability will be refined and expanded, perhaps even to achieve the large-scale atomically precise fabrication of nanostructures by mechanosynthesis, as envisioned by Drexler [Drexler, 1992]. The projection in this work has been encouraged by such visionary thinking, but it does not depend on the complete fulfillment of such visions--only more modest, systematic refinement of existing technology.

For example, to build such small features and components, we also can anticipate the further development of the new, precise chemical processes that employ chemical self assembly [Whitesides *et al.*, 1991; Whitesides, 1995; Andres, *et al.*, 1996] and reactions analogous to the polymerase chain reaction (PCR) [Mullis, 1990; Mullis *et al.*, 1994]. These types of techniques already are making designed supramolecular nanostructures in quantity, and they might be applied to make vast number of cheap, perfect copies of submicroscopic systems and their subassemblies.

ANTICIPATED IMPACTS OF MATTER AS SOFTWARE

The great economic and societal impact of such refined, future-technology chemical and physical techniques will be felt, though, when they are implemented and proliferated as processes performed on micro-chips. As outlined above, present-day research already is implementing prototype, computer-controlled nanoprobes and chemical reactors on micro-chips. Soon, such computer chips for the production/fabrication of matter may be mass produced so that they can be supplied as a hardware accessories for a large numbers of general purpose workstations linked to a world-wide information network such as the Internet. Then, the control instructions for the use of the chips in performing fabrication processes could be made available to many locations in the world. This will permit their application for the asynchronous, widely distributed manufacture of material objects. This manufacturing of material objects (such as micro- and nanodevices) will take place much the way software is written or "manufactured" all over the world in an asynchronous, distributed manner on hardware accessories called disk drives. When it becomes possible to "write" and make duplicate copies of matter anywhere in the world using computer controlled (micro-) machinery, much as software is written and duplicated all over the world today, the economics of very finely constructed material objects should evolve to be much like the economics of software today.

Table 1 suggests the economic impact of this evolution by comparing and contrasting matter and software today with "matter as software" in the future. The analysis in this table was suggested by arguments set forth by the economist Paul Romer, who has analyzed the economics of ideas and innovation by comparing them to software [Romer, 1993; Romer, 1995; Romer, 1996]. As noted in the second column of each of the first two rows of the table, according to Romer the invention of ideas is like the development of software, in that

Table 1

Comparison and Contrast of Matter as Software
with Other Classes of Commodities

	Cost of Invention or First Copy	*Cost of Manufacturing Additional Copies*	*Primary Physical Characteristics*
Ideas	Usually High	Very Low	Rapid inexpensive mass dissemination
Software and Information	Usually High	Very Low	Rapid inexpensive mass dissemination; distributed mfg.; reusable media
Matter	Usually High	Medium to High Fixed Cost	Slow dissemination; central mfg., little reuse of materials
Matter as Software	Usually High	Low	Rapid dissemination via distributed mfg. & bulk reproduction, significant reuse of materials

the costs of these initial steps are high. Ideas and software also are alike in that after their initial conception, the cost of additional copies--i.e., dissemination--is relatively low. Here, we point out that for software this results largely from the fact that software can be manufactured at many loosely coupled distributed facilities with little in the way of new, unique materials requirements.

By contrast, the economics of material goods has been fundamentally different from that of ideas and software for almost the entire history of human civilization, as outlined in the third row of the table. The specially processed material used in manufactured goods often is scarce and expensive. In addition, this processed material usually is not readily reusable, and manufacturing to shape the material into finished goods usually is conducted only at a few centralized locations. These last two characteristics of the economics of material goods--non-reusability and centralized manufacture--have played a central role in restricting their availability and helping to place a floor of medium to high fixed costs under their prices, even when mass production and mass marketing techniques are employed.

In the future, however, according the argument outlined in the bottom row of the table, one may anticipate that the economics of material goods--i.e., of matter--will become much more like that of software. Via the technologies described above, distributed, asynchronous manufacturing should become possible. Eventually, it is likely to become the norm for key material commodities, just as it has with software, simply because it is cheaper. One may anticipate that this process of widespread distributed manufacturing for material products will start with products for which the value and the information content is high, but the material content is relatively low--e.g., computer chips and pharmaceuticals. Then, as the infrastructure spreads and becomes refined, distributed manufacturing should spread to other goods.

Eventually, the same future technologies for fabrication via precise control of microscopic and submicroscopic constituents that makes distributed manufacturing possible, also should facilitate considerable reuse of the raw materials or feedstock for the microscopically and submicroscopically engineered matter bits. Simple microscopic devices may be capable of self-assembling themselves and reassembling themselves numerous times to become components of a succession of different macroscopic objects and mechanisms.

On still smaller scales, molecules might be "written" onto a substrate with a nanoprobe to make a microscopic or submicroscopic component. Then, when one no longer needed that component, its atomic or molecular constituents might be "read" back into the reservoir of feedstock for future use.

CONCLUSIONS

A 21st century "matter revolution" is likely to follow the widely discussed "information revolution" that has taken place second half of the 20th century. This next revolution will transform everyday objects and every person's relationship to them. It will change the value of things.

Thus, the impact of such a matter revolution would be more sweeping and pervasive than the computer, software, and information revolutions in which we are now immersed. The development of smaller computers in this century may turn out only to be the "MacGuffin," the excuse, for a larger, more important story in which technological society has developed extremely precise and powerful techniques for the fabrication of structures and the control of matter on the micron and nanometer scales.

In the next century, the technologies for MEMS and nanofabrication will be extended and combined to make matter sensitive, smart, and animate on the same microscopic scale on which we now store information and software. This will attribute to matter physical properties that now are associated with software. It will permit matter to be programmed, deformed, and reused. Material objects may be "downloaded" from a network for distributed manufacturing on demand at the point of use.

The widespread distributed manufacture of material objects and the reuse of their microscopic and submicroscopic constituents would have sweeping economic consequences, however. These consequences are likely to have an impact upon the economics of material objects analogous to the impact that computers have had upon information. Thus, economically, as well as physically, matter will become like software.

ACKNOWLEDGEMENTS

Thanks are due to Johann Schleier-Smith, Michael D. Smith, and the other members of the MITRE Nanosystems Group for valuable discussions that led to this paper. The author's thoughts on this subject also benefited from attending a workshop, "Future Directions for Complex and Distributed Systems," sponsored by the Defense Advanced Research Projects Agency (DARPA), and held at Bishop's Lodge, Santa Fe, NM, on 18-20 April 1995. Thanks are due to Pradeep Khosla, Ken Gabriel, and Jane Alexander of DARPA for extending their invitation to attend, as well as to the other workshop participants for very stimulating discussions. Dr. Ken Kuskey of MITRE read a draft version of this paper and provided helpful suggestions. This work was sponsored by research grants from The MITRE Corporation's MSR Program and from the Core Research Program of the MITRE Economic and Decision Analysis Center. The author thanks Ronald Haggarty, Dr. Edward Palo, Dr. William Hutzler, and Dr. Karen Pullen of MITRE for extending this financial support, as well as for their personal encouragement of this effort.

REFERENCES

Angell, J. B., Terry, S. C., and Barth, P. W., "Silicon Micromechanical Devices," *Scientific American*, April 1983, p. 44-55.

Andres, R. P., *et al.*, "Self-Assembly of a Two-Dimensional Superlattice of Molecularly Linked Metal Clusters," *Science*, Vol. 273, 20 September 1996, pp. 1690-1693.

Avouris, P., "Manipulation of Matter on the Atomic and Molecular Levels," *Accounts of Chemical Research*, Vol. 28, 1995, pp. 95-102.

Binnig, G., and Rohrer, H., "The Scanning Tunneling Microscope," *Scientific American*, August 1985, pp. 50-56.

Campbell, S. A., *The Science and Engineering of Microelectronic Fabrication*, Oxford U. Press, Oxford, U.K., 1996.

Drexler, K. E., *Nanosystems: Molecular Machinery, Manufacturing, and Computation*, John Wiley and Sons, Inc., New York, 1992.

Gabriel, K., "Engineering Microscopic Machines," *Scientific American*, September 1995, pp. 118-121.

Hansma, P. K., *et al.*, "Scanning Tunneling Microscopy and Atomic Force Microscopy," *Science*, Vol. 242, 14 October 1988, pp. 209-216.

Jung, T. A., *et al.*, "Controlled Room-Temperature Positioning of Individual Molecules: Molecular Flexure and Motion," *Science*, Vol. 271, 12 January 1996, pp. 181-184.

Landauer, R., "Information is Physical," *Physics Today*, May 1991, pp. 23-29.

Lyding, J. W., *et al.*, "Nanometer-Scale Patterning and Oxidation of Silicon Surfaces with an Ultrahigh Vacuum Scanning Tunneling Microscope," *Journal of Vacuum Science Technology B*, Vol. 6, 1994, pp. 3735-3740.

Minne, S.C., Manalis, S.R., and Quate, C.F., "Parallel atomic force microscopy using cantilevers with integrated piezoresistive sensors and integrated piezoelectric actuators," *Applied Physics Letters*, Vol. 67, 1995, pp. 3918-3920.

Minne, S.C., Manalis, S.R., Atalar, A., and Quate, C.F., "Independent parallel lithography using an atomic force microscope," *Journal of Vacuum Science Technology B*, Vol. 14, 1996, pp. 2456-2461.

Montemerlo, M.S., Love, J.C., Opiteck, G.J., Goldhaber-Gordon, D.J., and Ellenbogen, J.C., "Technologies and Designs for Electronic Nanocomputers," MTR No. 96W0000044, The MITRE Corporation, McLean, VA, July 1996.

Mullis, K. B., "The Unusual Origin of the Polymerase Chain Reaction," *Scientific American*, April 1990, p. 56-65.

Mullis, K. B., Ferre, F., and Gibbs, R.A., eds., *The Polymerase Chain Reaction*, Birkhauser, Boston, 1994.

Park Scientific Instruments, *A Practical Guide to Scanning Probe Microscopy*, Park Scientific Instruments, Sunnyvale, CA, 1996. This publication also is available on the Internet World-Wide Web at the URL: http://www.park.com/contents.htm.

Pister, C., "Overview of Developments in the MEMS Fabrication of Limbs for Micro-robots," unpublished briefing, University of California at Los Angeles., Los Angeles, CA, 1995. Presented at ARPA Workshop on Future Directions for Complex and Distributed Systems, Bishop's Lodge, Santa Fe, NM, 18-20 April 1995.

Romer, P.M., "Implementing a National Technology Strategy with Self Organizing Industry Investment Boards," in *Brookings Papers on Economic Activity: Microeconomics (2)*, Baily, M.N., Reiss, P.C., and Winston, C. (eds.), 1993, pp. 345-390.

Romer, P.M., "Beyond the Knowledge Worker," World Link, January-February 1995, pp. 56-60. This publication also is available on the Internet World-Wide Web at the URL: http://www-leland.stanford.edu/~promer/wrld_lnk.htm.

Romer, P.M., and Nelson, R.R."Science, Economic Growth, and Public Policy," in *Technology, R&D, and the Economy*, Smith, B.L.R. and Barfield, C.E. (eds.), Washington: Brookings Institution and American Enterprise Institute, 1996. Reprinted in *Challenge*, March-April, 1996.

Schleier-Smith, J.,"Simulations of Self-Assembly for Nanosystems and Microsystems," MTR No. 96W0000043, The MITRE Corporation, McLean, VA, April 1996 (DRAFT). Not yet in the public domain.

Stix, G., "Micron Machinations," *Scientific American*, November 1992, pp. 106-117.

Whitesides, G. M., Mathias, J. P., and Seto, C. P., Molecular Self-Assembly and Nanochemistry: A Chemical Strategy for the Synthesis of Nanostructures," *Science*, Vol. 254, 29 November 1991, pp. 1312-1318.

Whitesides, G. M., "Self-Assembling Materials," *Scientific American*, September 1995, pp. 146-149.

Xu, Y., MacDonald, N. C., and Miller, S. A., "Integrated Micro-Scanning Tunneling Microscope," *Applied Physics Letters*, Vol. 67, 1995, pp. 2305-2307.