All but War Is Simulation: The Military-Entertainment Complex

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The box office smash from spring 1999, *The Matrix,* projects a vision of a world in which "real" world objects are actually simulations emerging from streams of bits. Finding himself pursued on a rooftop with no escape except a helicopter, the movie's hero asks his guide, "Can you fly that thing?" "Not yet," she says, as she calls their home base systems administrator for software that uploads just in time.

In a similar vein, one of Intel's 1999 ads for the Pentium II processor articulates the consumer's desire for ever-faster uploads, and ultimately for fusing the digital and the real. As a skydiver plummets to earth alternating anxious glances between the camera and his chute, which appears on the screen one agonizing row of pixels at a time, the voiceover asks: "Time for a Pentium II Processor?"

Such images are amusing fantasies. They are also reminders that we are becoming immersed in a growing repertoire of computer-based media for creating, distributing, and interacting with digitized versions of the world. In numerous areas of our daily activities, we are witnessing a drive toward the fusion of digital and physical reality: not the replacement of the real by a hyperreal—the obliteration of a referent and its replacement by a model without origin or reality—as Baudrillard predicted, but a new country of ubiquitous computing in which wearable computers, independent computational agent-artifacts, and material objects are all part of the landscape.

To paraphrase the description of the matrix by William Gibson in *Neuromancer,* data are being made flesh.[1] These new media are re-

1. William Gibson, *Neuromancer* (New York: Ace Books, 1984), p. 51.

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shaping the channels of our experience, transforming our conception of the "real," redefining what we mean by "community" and, some would maintain, what we mean by our "selves."[2] As we come to entrust more of our lives to Internet communications, and as we spend more time in virtual, electronic space, our notions of materiality and reality will inevitably change.

I am intrigued by the notion that we are on the verge of a new renaissance, that, like the Renaissance of the fourteenth and fifteenth centuries, is deeply connected with a revolution in information technology. That most celebrated Renaissance is frequently heralded as the birth of humanism. I sympathize with several contemporary theorists who characterize our renaissance as heralding a posthuman era in which the human being becomes seamlessly articulated with the intelligent machine. In the posthuman state, there are no demarcations between bodily existence and computer simulation, between cybernetic mechanism and biological organism.[3]

A minimal condition for a new, "post"-human state would certainly be a fundamental shift in our notions of material reality. By exploring the recent history of what I am calling the military-entertainment complex, I hope to suggest some of the pathways through which a so-called posthuman future might emerge. Our experience of materiality is deeply tied to technologies that affect how we experience space and time and how we use our bodies. Changes in these technologies have a profound impact on our sense of the real.

2. For discussions of computer-mediated communication and computational sciences, see Richard Mark Friedhoff and William Benzon, *The Second Computer Revolution: Visualization* (New York: Freeman, 1989). Other important discussions are in *Information Technology and the Conduct of Research: The User's View,* Report of the Panel on Information Technology and the Conduct of Research (Washington, D.C.: National Academy of Sciences, 1989); B. H. McCormack, T. A. DiFanti, and M. D. Brown, *Visualization in Scientific Computing,* NSF Report, published as a special issue of *Computer Graphics* 21:6 (1987). An equally impressive survey is the special issue on computational physics in *Physics Today,* October 1987, esp. Norman Zambusky, "Grappling with Complexity," pp. 25–27; Karl-Heinz A. Winkler et al., "A Numerical Laboratory," pp. 28–37; Martin Karplus, "Molecular Dynamics Simulations of Proteins," pp. 68–72. For a consideration of computer-mediated communication and computational science in relation to theory, see Timothy Lenoir and Christophe Lécuyer, "Visions of Theory: Fashioning Molecular Biology as an Information Science," in *Growing Explanations,* ed. M. Norton Wise (Princeton: Princeton University Press, forthcoming). For computer-mediated communication and notions of the self, see Sherry Turkel, *Life on the Screen: Identity in the Age of the Internet* (New York: Simon and Schuster, 1995), esp. chaps. 7 and 10; Brian Rotman, "Going Parallel: Beside Oneself," 1996: <http://www-leland.stanford.edu/class/history204i/Rotman/Beside/top.html>.

3. N. Katherine Hayles, *How We Became Posthuman: Virtual Bodies in Cybernetics, Literature, and Informatics* (Chicago: University of Chicago Press, 1999), pp. 2–3.

A sign of these posthuman times is the rapid fusion of the digital and the real going on around us, taking place in personal digital assistants, cell phones, and Palm Pilots™ (about to become wearable servers) that accompany us throughout the day. The sign is more clearly perceptible, perhaps, in technologies such as web-based personal shopping assistants that learn our preferences and then crawl the Web in search of software upgrades, information, and commodities that define us as consumers of information.

The Fusion of the Digital and the Real

No less important for effecting these changes in our notions and experience of material reality will be the implementation of research and development efforts to embed information technologies in the world around us, in objects other than communications devices. For a generation we have been used to thinking of the computer as the symbol of the information revolution, but one way to think about our present stage within this revolution is that the computer is in fact disappearing. If developments funded by military research agencies such as DARPA (Defense Advanced Research Projects Agency) at several research universities and at organizations like Xerox PARC come to pass, that large box we are used to staring into all day will vanish. In its place will be a world filled with special-purpose chips, "smart" devices, and agents that interact with us constantly. These agents and devices will not sit on our desktops, but rather will be embedded in wearable microdevices and implants, leading to a world of ubiquitous computing.

Since 1996, for instance, the DARPA Smart Modules program has been developing and demonstrating novel ways of combining sensors, microprocessors, and communications in lightweight, low-power, modular packages that offer war-fighters and small fighting units new methods to enhance their situational awareness and effectively control their resources on the battlefield. Smart modules are integrated into personal and portable information products that sense, compile, analyze, display, compare, store, process, and transmit information. The resulting products create opportunities to exploit data-rich battlefield environments at the individual war-fighter level. Instead of the normally limited set of information resources at the disposal of the individual war-fighter (maps, compasses, hand-held global positioning systems) and the limited connectivity (primarily by voice radio) to information infrastructures, Smart Modules allow individuals to better perceive their environment (see, hear, and feel the electromagnetic spectrum), augment their ability to remember and make decisions through the use of electronic devices, and provide mechanisms for connection to wireless distributed data networks. Modular information products are part of clothing, worn on a belt or put into a pocket. These products will capitalize on current rapid developments in micro electromechanical systems, head-mounted and small direct-view displays, optoelectronics, integrated sensors and video modules, energy storage, and low-power electronics.

DARPA's "smart matter" programs go beyond the wearable modular communication devices and information systems described above. Smart Matter research is based in large part on MEMS (micro electromechanical systems), very small sensors and actuators that are etched into silicon or other media using photolithography-based techniques. Integrated with computation, these sensors and actuators form a bridge between the virtual and physical worlds, enabling structures to respond dynamically to conditions in their environment. Smart materials and structures mimic the natural world, where animals and plants have the clear ability to adapt to their environment in real time. The designers and promoters of these "biomimetic" technologies dream about the possibilities of such materials and structures in the man-made world: engineering structures operating at the very limit of their performance envelopes and to their structural limits, without fear of exceeding either. "Smart" structures could give maintenance engineers a full report on their performance history, as well as the location of any defect as it occurs. Furthermore, that same structure could be given the capacity to self-repair, or to counteract unwanted or potentially dangerous conditions such as excessive vibration.

Sutherland's Holy Grail

The nexus between computer simulation and virtual reality for military purposes and the entertainment industry has a thirty-five-year history, tracing its origin to Ivan Sutherland's head-mounted display project.[4] The project usefully illustrates both the synergy between problem-focused environments of industry and government-funded (military and other) projects, and the less product-oriented research focus of university work that spills across disciplinary boundaries. In 1966 Sutherland moved from ARPA (Advanced Research Projects Agency, later changed to DARPA) to Harvard as an associate professor in applied mathematics. At ARPA he had partici-

4. The first reference I am aware of to the "military-entertainment complex" was the lead article in the first issue of *Wired Magazine* in 1993: Bruce Sterling, "War Is Virtual Hell: Bruce Sterling Reports Back from the Electronic Battlefield," *Wired Magazine* 1:1 (1993), online at http://www.wired.com/wired/archive/1.01/virthell.html?topic=&topic_set=; see esp. p. 7.

pated in implementing J. C. R. Licklider's vision of human-computer interaction, and he returned to academe inspired to pursue his own program of extending human capabilities.[5] One such project was his head-mounted display.

Funding for this project came from a variety of sources: the military, academe, industry. The CIA provided $80,000, and funds were also supplied by ARPA, the Office of Naval Research, and Bell Labs. Bell Helicopter provided equipment. The Air Force gave a PDP-1 computer, while MIT Lincoln Labs, also under an ARPA contract, provided an ultrasonic head-position acoustic sensor. Sutherland's experiments built on the network of personal and professional contacts he had developed at MIT and at ARPA, as well as on earlier work on head-mounted displays at the Bell Helicopter Company, centered on input from servo-controlled cameras that would move with the user's head and thus move the user's visual field. At Bell Helicopter, the head-mounted display was coupled with an infrared camera that would give military helicopter pilots the ability to land at night in rough terrain: the camera, which moved as the pilot's head moved, was mounted on the bottom of the helicopter. The pilot's visual field was the camera's.

The helicopter experiments demonstrated that a human could become totally immersed in a remote environment through the "eyes" of a camera. With the viewer inside a building, a camera was mounted on the roof, with its field of view focused on two people playing catch. The viewer immediately responded to the motion of the ball, moving the camera to follow the game of catch by moving his head. Proof of the viewer's involvement in this remote environment came when the ball was thrown at the camera and the viewer ducked. When the camera panned the horizon, the viewer reported a panoramic skyline. When the camera looked down to reveal that it was "standing" on a plank extended off the roof of the building, the viewer panicked.[6]

In 1966, as an associate professor at Harvard, Sutherland and a student, Robert Sproull, took the "Remote Reality" vision systems of the Bell Helicopter project and replaced the camera with computer-generated images.[7] The first such computer environment was no

5. Ivan E. Sutherland, "Virtual Reality Before It Had That Name," videotaped lecture before the Bay Area Computer History Association, Xerox PARC, Palo Alto, 1993.

6. Ibid.

7. Other head-mounted display projects using a television camera system were undertaken by Philco in the early 1960s. For a discussion, see Stephen R. Ellis, "Virtual Environments and Environmental Instruments," in *Simulated and Virtual Realities,* ed. K. Carr and R. England (London: Taylor & Francis, 1996), pp. 11–51.

more than a wire-frame room with the cardinal directions—north, south, east, and west—initialed on the walls; the viewer could "enter" the room by way of the west door, and turn to look out windows in the other three directions. What Sutherland and Sproull called the "Head-Mounted Display" later became known as Virtual Reality.

Sutherland later recalled that at the time he formulated the head-mounted display project he was clear that there was no hope of immediately realizing it. But the project was important, he recalled, "as an 'attention focuser' which defined a set of problems that motivated people for a number of years." VR was a target impossible to reach. It provided a holy grail, "a reason to go forward and push the technology as hard as you could. Spinoffs from that kind of pursuit are its greatest value."[8]

In Sutherland's view, the most important spinoff from such projects was the students; the personal and professional connections supported future work in the area. Sociologists of science talk about the importance of "core sets" of individuals who define the intellectual and technological direction of a domain. Certainly the bevy of students trained by Dave Evans and Sutherland constitute one of the most dramatic examples of such a core set in the history of computer science. Among those who worked on the "holy grail" of VR with Sutherland at Harvard were Charles Seitz, Bob Sproull, Ted Lee, Dan Cohen, and Quintin Foster. In 1968 Sutherland left for Utah, where he joined the Computer Science Department at the University of Utah founded by Dave Evans in 1965, the first computer science program to focus on graphics and graphical interfaces. Sutherland had known Evans from his ARPA days, and together they founded Evans & Sutherland Computer Corporation in 1968, which manufactured graphical display systems and constructed military flight and tank simulators under government contract. A number of Evans's and Sutherland's students worked on an ARPA-supported project on 3-D graphics, and several worked at Evans & Sutherland on simulations. Of the original Harvard group, several came with Sutherland to form Evans & Sutherland—including Chuck Seitz, who joined the faculty in 1970, and remained until 1973 when he moved to Cal Tech and founded Myricom with Dan Cohen, another of the original Harvard team who contributed to the head-mounted display. The interaction between the research on basic problems and development-directed hardware and software systems for government and military projects at E&S was an important feature of work at Utah.

8. Sutherland, "Virtual Reality Before It Had That Name" (above, n. 5).

At Harvard briefly, and then at the University of Utah from 1968 to 1974, Sutherland set out a research program for work in interactive computer graphics that guided the field in much of its early development and continues to be relevant for the discussion of current trends in medical graphics.[9] For Sutherland, the display screen was to be considered a window, through which the user looks at a virtual, *conceptual* 3-D universe. Sutherland's program called for inventing ways to make the image in the window more and more realistic, until at last it becomes indistinguishable from the image in a real window—a real window augmented, that is, by "magical" powers of scaling, labeling, rotating, and cross-sectioning.

In addition to visible realism, Sutherland sketched two other directions. A second class of graphical applications related purely to representing abstractions—such as force fields, molecules, mathematical objects, and data graphing—for which visual realism is irrelevant. But in this context Sutherland considered that it would be useful to extend the domain of information available to the user by incorporating information from other sensory modalities. He coined the term "virtual worlds" for systems in which users are immersed in scenes created completely by computer graphics; and he urged that the goal of this work should be to make the objects in the scene "look real, sound real, feel real, and move realistically as the user interacts with them."[10]

The third form of interactive graphics that Sutherland outlined is one particularly relevant to current medical applications such as virtual surgery: namely, the ability to superimpose abstract representations on an object, as in cartography, where abstractions are superimposed on a realistic rendering of a geographical space. One of Sutherland's first attempts at practical application of the head-mounted display was in fact in pursuit of this third form of graphical interface. The first published research project deploying the head-mounted three-dimensional display engaged problems of representing hemodynamic flow in models of prosthetic heart valves; the goal of this research was to generate the results of calculations involving the application of physical laws of fluid mechanics, using a

9. Ivan E. Sutherland, "The Ultimate Display," *Proceedings of the International Federation for Information Processing Congress* 2 (1965): 506–508; idem, "Three Kinds of Graphic Data Processing," *Proceedings of the International Federation for Information Processing Congress* 2 (1965): 582–583. These ideas are elaborated in Ivan E. Sutherland, "Computer Displays," *Scientific American* 222:6 (1970): 56–81.

10. Sutherland, "Ultimate Display" (above, n. 9).

variety of numerical analysis techniques, in order to generate a synthetic object that one could walk toward, around, and even into.[11]

The period from the late 1960s through the late 1970s was a golden era of computer graphics at Utah, and students of the Utah ARPA-funded program contributed to a number of exploratory systems in computer graphics and the identification of key problems for future work. Among these were various efforts to develop fast algorithms for removing hidden surfaces for color and 3-D graphics, a problem identified as a key computational bottleneck.[12] Two important contributions in this field made by students of the Utah program were an area search method by John Warnock,[13] and a scanline algorithm developed by Garry Watkins that was constructed into a hardware system.[14] Perhaps the most important breakthrough came just at the close of the decade with Henri Gouraud's development of a simple scheme for continuous shading.[15] Unlike polygonal shading, where an entire polygon was tinted with a single level of gray, Gouraud's scheme involved the interpolation of surface normals to describe continuous shading across a single polygon, and thus a closer approximation to reality. The effect made a surface composed of discrete polygons appear to be continuous.

The list of alumni from the Utah program in the years 1968–1978 is impressive indeed (see Table 1). The work of these individuals alone suggests the high level of fundamental research that was done at the University of Utah under federally sponsored projects in a variety of graphics fields, including surface rendering, simulations, computer animation, graphical user interface design, and early steps toward virtual reality.[16] The number of significant commercial firms

11. Harvey Greenfield, Donald Vickers, Ivan Sutherland, et al., "Moving Computer Graphic Images Seen from Inside the Vascular System," *Transactions of the American Society of Artificial Internal Organs* 17 (1971): 381–385.

12. Ivan Sutherland, Robert F. Sproul, and Robert A. Schumacker, "A Characterization of Ten Hidden Surface Algorithms," *ACM Computer Surveys* 6:1 (1974): 1–55.

13. John E. Warnock, "A Hidden Surface Algorithm for Computer Generated Half-Tone Pictures," Ph.D. thesis, University of Utah, 1969.

14. Garry S. Watkins, "A Real-Time Visible Surface Algorithm," Ph.D. thesis, University of Utah, 1970.

15. H. Gouraud, "Computer Display of Curved Surfaces," *IEEE Transactions in Computers* C-20:6 (1971): 623–629.

16. Other noteworthy graduates of the Utah program in the late seventies include Jim Kajiya, Ph.D. 1979, who developed the frame buffer concept for storing and displaying single-raster images; and Gary Demos, who started several major computer graphics production companies and had a big impact on the introduction of computer graphics technology in the film industry.

Table 1. Select alumni of the University of Utah's computer graphics program

Name/Affiliation	Accomplishments
Alan Kay Ph.D. 1969	Developed the notion of a graphical user interface at Xerox PARC, which led to the design of Apple MacIntosh computers. Developed Smalltalk. Director of Research, Disney Imagineering.
John Warnock Ph.D. 1969	Worked on the Illiac 4 Project, a NASA space-flight simulator, and airplane simulators at Evans & Sutherland. Developed the Warnock recursive subdivision algorithm for hidden-surface elimination. Founder of Adobe Systems, which developed the Postscript language for desktop publishing.
Chuck Seitz Faculty 1970–73	Pioneer in asynchronous circuits. Codesigner of the first graphics machine, LDS-1 (Line Drawing System). Designed the Cosmic Cube machine as a research prototype that led to the design of the Intel iPSC. Founder of Myricom Corp.
Nolan Bushnell B.S. 1969	Developed the table tennis game Pong in 1972, which launched the video game industry. Founder of Atari, which became the leading company in video games by 1982.
Henri Gouraud Ph.D. 1971	Developed the Gouraud shading method for polygon smoothing—a simple rendering method that dramatically improved the appearance of objects.
Ed Catmull Ph.D. 1974	Pioneer in computer animation. Developed the first computer animation course in the world. Cofounder of Pixar Animation Studios, a leading computer graphics company that has done work for LucasFilm and was recently involved in the production of the movie *Toy Story.* Received a technical Academy Award (with Tom Porter, Tom Duff, and Alvy Ray Smith) on March 2, 1996, in Beverly Hills from the Academy of Motion Picture Arts and Sciences (AMPAS) for "pioneering inventions in Digital Image Compositing."
Jim Clark Ph.D. 1974	Rebuilt the head-mounted display and 3-D wand to see and interact with three-dimensional graphic spaces. Former faculty at Stanford University. Founder of Silicon Graphics, Inc., Netscape Communications Corporation, and, most recently, Healtheon.
Bui Tuong-Phong Ph.D. 1975	Invented the Phong shading method for capturing highlights in graphical images by modeling specular reflection. Phong's lighting model is still one of the most widely used methods for illumination in computer graphics.
Henry Fuchs Ph.D. 1975	Federico Gil Professor, University of North Carolina at Chapel Hill. Research in high-performance graphics hardware, 3-D medical imaging, head-mounted display, and virtual environments. Founder of Pixel Planes.
Martin Newell Ph.D. 1975; Faculty 1977–79	Developed procedural modeling for object rendering. Codeveloped the Painter's algorithm for surface rendering. Founder of Ashlar, Inc., which develops computer-assisted design software.
James Blinn Ph.D. 1978	Invented the first method for representing surface textures in graphical images. Scientist at JPL, where he worked on computer animation of the Voyager fly-bys.

generated by the members of this group is astounding: no fewer than eleven commercial firms, several of which ship more than $100 million in product annually, were the offspring of the Utah program.

Sustaining the Graphics Revolution

Many of these firms have their own research divisions and have contributed importantly to the fundamental research base in computer graphics (both hardware and software) that has been essential to the take-off of VR. But here, once again, the importance of long-term government support, particularly by DARPA, to sustaining innovative research directions emerges as clearly as in our earlier example. The case of Atari illustrates this point dramatically. Founded in 1972 by a Utah graduate in computer science, Nolan Bushnell, Atari at one point in its history was the fastest-growing company in America. From an initial investment of $500, Atari reached sales of $536 million in 1980. During the late 1970s and early 1980s it hosted exciting developments in software and chip design for the home entertainment market, and its joint venture with LucasFilm in 1982, in which Atari licensed and manufactured games designed by LucasFilm, established cross-pollination between videogames and film studios. Atari was also a center of developments in VR, and several of the pioneering figures in the VR field got their start at Atari. For instance, Warren Robinett, who has directed the head-mounted display and nanomanipulator projects at the University of North Carolina, Chapel Hill (discussed below), developed the extremely popular videogame *Adventure* at Atari from June 1977 through November 1979. Jaron Lanier, who developed the DataGlove in 1985, got his start by creating the videogame *Moondust,* the profits from which he used to launch VPL-Research in 1984, the first commercial VR company.

In 1980 Atari created its own research center. It was directed by Alan Kay, who came over from Xerox PARC and assembled a stunning team of the best and brightest in the field of interface design and VR research—including Brenda Laurel (who had been at Atari since 1979), Scott Fisher (who had studied with Nicholas Negroponte at MIT before coming to Kay's laboratory to work on visual displays and virtual reality), and William Bricken (a recent Ph.D. from Stanford in computer science and educational psychology). But Atari fell on hard times: in 1983, it registered $512 million in losses.

The Atari Research Lab was, obviously, one of the casualties of the economic crash in the video game industry (and the computer industry more generally). Most of the people working in VR at Atari migrated to work in federally funded VR projects—like Jaron Lanier, who created VPL-Research in 1984 and landed a government contract to build the DataGlove for NASA. What emerges from this example is not that federal projects provided fortunate safety nets for failed industry initiatives, but more importantly, that centers such as NASA Ames and UNC had the right mix of basic research and long-term vision to move the technology forward. Thus, Scott Fisher moved from Atari to NASA Ames, where he directed the Virtual Environment Workstation Project and the VR project. Joining Fisher were Warren Robinett and Brenda Laurel. As noted above, Robinett eventually moved from NASA to Chapel Hill in 1989. William Bricken moved from Atari to Advanced Decision Systems, where he pioneered high-performance inference engines, visual programming systems, and instructable interfaces. He then went on to Autodesk Research Lab, where he developed the Cyberspace CAD (computer-assisted design) prototype of virtual reality. Bricken then moved from industry to the University of Washington's Human Interface Technology Laboratory, where he designed and implemented the Virtual Environment Operating System and interactive tools of the VR environment.[17]

There was little question that the continued development of virtual reality technology in the 1980s was not something that industry was prepared to do on its own; indeed, Lanier's failed efforts to market for Nintendo a consumer entertainment version of the DataGlove, called PowerGlove, demonstrated that the time was not yet right for a sustained industry push. Federal support was crucial to building the array of hardware and software necessary for industry to step in and move VR forward. The impressive synergism of federally funded projects and industry developments that today is bringing about the emergence of the new VR technologies in surgery and other fields would not have been possible without sustained federal funding in centers where the different components of VR work were developed in tandem. As several pioneers in the field observed in a 1991 Senate hearing, the merging of the substantially different technologies at stake in virtual worlds could not be undertaken by commercial interests whose horizon of return on investment is short, particularly while the technologies at issue remained in a precom-

17. W. Bricken, "Virtual Worlds: No Interface to Design," Technical Report R-90-2, Human Interface Technology Lab, University of Washington, 1990; idem, "Virtual Environment Operating System: Preliminary Functional Architecture," Technical Memorandum M-90-2, ibid., 1990; idem, "Coordination of Multiple Participants in Virtual Space," Technical Memorandum M-90-11, ibid., 1990.

petitive situation for so many years.[18] It is instructive to explore how a sustained mixture of government, industry, and university-based research and development turned the dim portrait of the future depicted in these 1991 Senate hearings into the extremely bright picture of the late 1990s.

By the mid-1980s it was universally acknowledged that the creation of virtual worlds technology depended upon developments in several fields, including computer architectures, processors, operating systems, and languages. DARPA funding played the crucial role in these initiatives. One critical turning point for enabling this next phase of development was the DARPA VLSI (very large systems integration) and reduced instruction set computing (RISC) programs begun in the late 1970s. For the first fifteen years of its life, the microprocessor improved its performance by an impressive 35% per year—but these performance gains began to slow down, and increasing chip-fabrication costs led DARPA program managers to be concerned about future growth. In 1976, they commissioned a RAND study on the problem.[19]

The study showed that the U.S. computer technology environment of the mid-1970s was characterized by (1) a tapering off in the rate of improvement in computer performance, as the marginal costs rose and the marginal gains from extending prevailing technologies declined; (2) extensive insulation of commercial microelectronics firms, concentrating on their own proprietary developments, from academic communities, which were limited in their access to advanced equipment and industry technologies; and (3) exponential growth in the cost of equipment and of implementing device design, as industry concentrated on incremental efforts to pack more gates and transistors into semiconductor devices. The authors of the study also realized that university engineering and computer science departments were being shut out of much of the microelectronics revolution because they could not afford the equipment necessary to manufacture silicon chips. Even those universities that could afford some equipment could never keep up with the rapidly advancing state of the art.[20]

18. Senate Committee on Commerce Science and Transportation, *New Developments in Computer Technology: Virtual Reality: Hearing before the Subcommittee on Science, Technology, and Space,* 102d Cong., 1st sess., May 8, 1991, esp. pp. 33–34, 42–49.

19. I. E. Sutherland, C. A. Mead, and T. E. Everhart, *Basic Limitations in Microcircuit Fabrication Technology,* RAND Corporation Report no. AD-A035149, Santa Monica, Calif., November 1976, prepared under DARPA Contract no. DAHC15-73-C-0181.

20. John Markoff, Phillip Robinson, and Donna Osgood, "Homebrew Chips," *BYTE,* May 1985, p. 363.

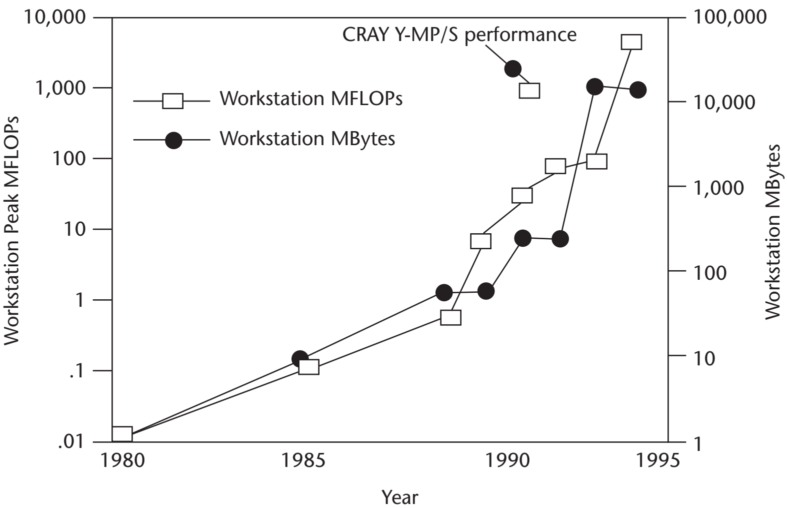

Figure 1. The development of processing power and memory

It was in this environment that DARPA originated the VLSI and RISC programs. Through his relations with the academic community going back to the early 1970s, Dr. Robert E. Kahn was aware both of the technology potentials of work being done at academic centers of excellence in computer science, and of the cost and limits placed on their ability to implement, validate, and demonstrate their work because of the proprietary practices of industry.[21] The VLSI and RISC programs were undertaken specifically to revitalize and tap creativity in the academic community. As a result of research at universities and industrial laboratories supported by the DARPA programs, performance gains began to increase by 1987 to about 55% per year—a doubling of performance every eighteen months (see Fig. 1).[22]

RISC processors have advanced the field of interactive graphics and contributed significantly to the development of VR. Silicon

21. During this period, Kahn advanced from chief scientist to deputy director of DARPA's Information Processing Techniques Office (IPTO) in 1976, and he became its director in November 1979.

22. See "Computer Hardware and Software for the Generation of Virtual Environments," in *Virtual Reality: Scientific and Technological Challenges*, ed. Nathaniel I. Durlach and Anne S. Mavor (Washington, D.C.: National Academy Press, 1995), pp. 247–303, esp. fig. 8-4, "The History of Workstation Computation and Memory," on p. 257.

Graphics, cofounded by Jim Clark in 1982, was an early adopter of RISC processors and has led in the recent development of high-end graphics, including virtual reality. Clark joined the Stanford engineering faculty in 1979, having done his Ph.D. with Ivan Sutherland on problems related to the head-mounted display. He worked with John Hennessy and Forrest Baskett on the Stanford VLSI program and was supported by DARPA for a project on the Geometry Engine, the goal of which was to harness the custom integrated-circuit technology of MIPS to create cost-effective, high-performance graphics systems. In 1981 Clark received a patent for his Geometry Engine, the 3-D algorithms built into the firmware that allow the unit to serve up real-time interactive 3-D. The patent on the Geometry Engine formed the basis of Silicon Graphics, Inc., founded in 1982 with Kurt Akeley (then a research assistant working with Clark at Stanford). Clark also invented the GraphicsLibrary, which is the graphics interface language used to program SGI's computers. These systems offered built-in 3-D graphics capabilities, high-speed RISC processors, and symmetrical (multiple-processor) architectures. In 1983 SGI marketed its first graphics terminal, the IRIS 1000.

The development of Silicon Graphics not only shows that federal funding initiatives have had major impacts on the economy, it also represents the contribution of commercial developments to the field of interactive graphics and VR. Silicon Graphics, Evans & Sutherland, HP, Sun Microsystems, DEC, and others have generated products enabling simulations of all sorts, scientific visualizations, and CAD programs for engineering. No less significant has been their contribution to the entertainment industry, particularly to the film and video game industries. Indeed, as I have noted above, the entertainment industry has been a major stimulus to graphics throughout its history, in providing not only sources of employment and markets for products, but also substantial research contributions.[23] The relationship between these different partners has been mutually enriching; the arrows of influence point in both directions.

Several spectacular examples of the contribution of the entertainment industry to graphics might be discussed here, but one of the most widely appreciated is RenderMan, developed by Pixar Animation Studios. Ed Catmull, another alumnus of the Utah graphics program in the 1970s, joined Alvy Ray Smith in the computer graphics

23. Discussed by Scott Fisher in his presentation to the Committee on Virtual Reality Research and Development, Woods Hole, Mass., August 1993; see Durlach and Mavor, *Virtual Reality* (above, n. 22), p. 508. Also see Frederick P. Brooks, "Project GROPE: Haptic Displays for Scientific Visualization," *ACM Computer Graphics* 24:4 (1990): 177–185, esp. p. 184.

laboratory at LucasFilm in 1979. In 1977 at the New York Institute of Technology, Catmull and Smith had collaborated on the integrated alpha channel, a fundamental technology in computer graphics.[24] Smith then went on to direct the genesis scene of LucasFilm's *Star Trek II*, a sequence several minutes long generated by computer graphics depicting the spread of life across a new world. In the view of George Lucas and his organization, such work signaled that computer animation was finally coming of age as a tool for building movies. To realize the dream of constructing an entire film from computer-generated material, Smith and Catmull recruited a number of young computer-graphics talents to LucasFilm—among them, Loren Carpenter from the Boeing Company in Seattle, Washington, who had studied Benoit B. Mandelbrot's research and then modified it to create realistic fractal images. At the 1980 SIGGRAPH conference Carpenter had presented a stunning film entitled *Vol Libre*, a computer-generated high-speed flight through rugged fractal mountains. In 1981 he wrote the first renderer for Lucasfilm, called REYES (Renders Everything You Ever Saw), which was the beginning of RenderMan.

In 1986 the computer graphics division of LucasFilm's Industrial Light and Magic was spun off as a separate company, Pixar, with Catmull as president and Smith as vice-president. Under their direction, work continued at Pixar on developing a rendering computer. Pat Hanrahan joined the REYES machine group at Pixar in 1986. At the University of Wisconsin and then at the New York Institute of Technology Computer Graphics Laboratory, where he was director of the 3-D Animation Systems Group, Hanrahan had published a number of pathbreaking papers on methods of volume rendering, including papers on ray-tracing algebraic surfaces and beam-tracing polygonal surfaces. He joined Robert Drebin and Loren Carpenter in developing the first volume-rendering algorithms for the Pixar image computer.[25] These algorithms were quite different from earlier approaches, in that they created images directly from three-dimensional arrays without the intermediate steps of converting to standard surface representations such as polygons. Hanrahan was responsible for the interface as well as the rendering software and the graphics architecture of RenderMan. The rendering interface of the system evolved into the RenderMan standard now widely used in the movie industry.

24 See Alvy Ray Smith's Academy Award citation: http://research.microsoft.com/research/graphics/alvy/memos/award.htm.

25. R. A. Drebin, L. Carpenter, and P. Hanrahan, "Volume Rendering," *SIGGRAPH 88*, Conference Proceedings, *Computer Graphics* 22:4 (1988): 65–74.

The RenderMan standard describes everything the computer needs to know—the objects, light sources, cameras, atmospheric effects, and so on—before rendering a 3-D scene. Once a scene is converted to a RenderMan file, it can be rendered on a variety of systems, from Macs to PCs to Silicon Graphics Workstations. This opened up many possibilities for 3-D computer-graphics software developers. With RenderMan, all the developer had to do was give the modeling system the capability of producing RenderMan-compatible scene descriptions; once it did this, then the developer could bundle a RenderMan rendering engine with the package, and not worry about writing a renderer. Another strength of RenderMan is its "shaders," pieces of programming code for describing surfaces, lighting, and atmospheric effects. The spatial texture of an object is generated by the computer in 3-D space. In contrast to most texture-mapping techniques, which map the texture to the outside surface of the object, Hanrahan's procedural textures run completely through the object in 3-D, so that if, for example, a cube of wood is sectioned, you see wood grain running through the whole cube. When the initial specification of RenderMan was announced, at least nineteen firms endorsed it, including Apollo, Autodesk, Sun Microsystems, NeXT, MIPS, Prime, and Walt Disney.

RenderMan was used in creating *Toy Story*, the first feature-length computer-animated film; the dinosaurs in *Jurassic Park*; the cyborg in *Terminator 2*; and numerous other major effects. But this powerful tool has not been limited to use in the film industry: it has also been important in recent work on scientific visualization and volume rendering in a number of fields in science, engineering, and medicine. Moreover, the hardware and software components are not the only things that have circulated between industry and academe—the people have circulated too. Thus Ed Catmull and Alvy Ray Smith moved from the academic environments of NYIT and Berkeley (in Smith's early career) to LucasFilms, and Pixar. Pat Hanrahan, after starting at NYIT and then Pixar, moved back to academe—first as an associate professor at Princeton, and more recently as professor at Stanford, where he has gone on to contribute to several areas of graphics, including the development of applications of the Responsive Workbench (a 3-D interactive virtual environment workspace) to areas of scientific visualization, architecture, and medicine. The work in Hanrahan's laboratory on the workbench has been a cooperative project between Stanford University and the GMD (the German Institute for Information Design), and has been supported by grants from Interval Research Corporation, DARPA (visualization of complex systems), and NASA Ames (virtual windtunnel). Equipment donations have been provided by Silicon Graphics and Fakespace, Inc.

Desire and the Cultural Imaginary

Through films such as *Jurassic Park* and *Toy Story,* media industries have created a desire for computer-generated imagery. Entertainment such as IMAX films, the *Star Tours* simulation ride at Disneyland, and, more recently, "Magic Edge" flight simulators all have whetted our appetite for sensory immersion experiences. The film *Titanic* is emblematic of this trend: James Cameron and his organization actually pursued digital effects as ends in themselves—indeed, they drew upon effects generated by nineteen different visual effects and graphics companies—stealing pride of place from older film techniques, stage effects, and models (which the film also employs to a limited extent). We have come to desire these effects even when the film could be made without them. The appetite for "realism" in visual effects forms a feedback loop with whatever technologies are currently available, being inspired in part by them at the same time that the imaginary inspires more extreme and exotic visions.

The science-fiction novel *Ender's Game* by Orson Scott Card provides an example of how this desire for the fusion of the digital and the real actually preceded the full availability of the technology. *Ender's Game* centers on a boy-ninja who saves the world from aliens in a war game where the video game simulation becomes not only the training ground for real world warriors, but the actual war itself. Originally written in 1977, years before flight simulators were invented, the training scenario in *Ender's Game* has nonetheless so inspired military training programs that it was adopted as required reading by the Marine University in Quantico, Virginia. Graphics designers and computer scientists frequently cite science fiction as a source of inspiration. For example, Ken Perlin and Athomas Goldberg of Disney Imagineering—the authors of Improv, a system for scripting autonomous interacting actors for virtual worlds—note the influence of Neil Stephenson's description of the problems in constructing authoring tools for avatars in the Metaverse in his novel *Snow Crash.* Numerous programmers of contemporary (1999) video games and military flight simulators report the inspiration they have derived from this novel.[26]

26. See, for example, Tony Parisi, "VRML: Low-Tech Illusion for the World Wide Web," in *Digital Illusion: Entertaining the Future with High Technology,* ed. Clark Dodsworth, Jr. (New York: ACM Press, 1998), pp. 129–136, esp. p. 134. Also see Ken Perlin and Athomas Goldberg, "IMPROV: A System for Scripting Interactive Actors in Virtual Worlds," *Proceedings of SIGGRAPH 96, Computer Graphics* (1996): 205–216, esp. pp. 205–206.

The desire for realistic computer-generated images has combined with the stimulus to the computer graphics and hardware markets provided by exponential improvements in processors (Moore's Law) and new chip architectures to fuel the growth of companies like Silicon Graphics, driving down the prices of machines equivalent to first-generation Onyx workstations (costing more than $20,000) to the price of powerful desktop computers, at around $5,000. The potential markets for multimedia have stimulated the search for new architectures for image caching and compression techniques that can greatly reduce bandwidth and the memory requirements of expensive high-end machines like the SGI InfiniteReality Engine, with its tens of megabytes of graphics memory and multiple memory buses hundreds of bits wide, in order to bring high-end multimedia performance to PC prices.[27] An example of how market forces are driving this convergence of high-end computer architectures, graphical rendering hardware, and software with low-end commercial markets for computer graphics, ultimately bringing VR to everyone, can be seen in Silicon Graphics' partnership with Nintendo to produce Nintendo64.

On August 23, 1993, Silicon Graphics, NEC, and Nintendo announced a partnership to build the world's most powerful game machine. Speaking to a crowd of analysts, news media representatives, and industry pundits, Silicon Graphics founder and then-CEO Jim Clark outlined an ambitious project, Project Reality, which he claimed would revolutionize the consumer electronics industry. Never one for understatement, he declared that Project Reality would harness the "combined computer power of hundreds of PCs" for less than $250. Clark's often-stated goal since he started the company, the plan called for Silicon Graphics to design two chips to form the heart of the system: the R4300i processor and the Reality CoProcessor (RCP). The R4300i processor, a low-cost, low-power MIPS RISC CPU, would handle the interaction with the game player and manage the game's control tasks; the RCP, a media-processing engine, would handle all the high-performance graphic and music-synthesis tasks. The R4300i processor team was already in place at MIPS, recently acquired by Silicon Graphics and staffed with experienced engineers. However, the Project Reality team, slated to design the RCP and write the software, had to be built from scratch. NEC manufactured the RCP chips on a totally new, state-of-the-art chip-fabrication line in Japan, built at a cost of more than one billion dollars. The chips in Nintendo64 were the first microchips produced in

27. Martin Randall, "Talisman: Multimedia for the PC," *IEEE Micro,* 17:2 (1997): 11–19.

volume using .35-micron semiconductor technology. Nintendo's partners, Silicon Graphics and NEC, succeeded in getting the world's most advanced semiconductor technology into a consumer product. Nintendo64, shipped in April 1996, has been one of the most successful entertainment products in history. By the end of 1997 SuperMario64 enabled Nintendo to capture a worldwide base of six million users, with video game revenues breaking the $2 billion mark.

In 1997, Silicon Graphics CEO Ed McCracken explained the importance of this development in his letter of introduction to the Silicon Graphics booth at the National Broadcasters convention:

> Through the years, many of you have asked why the entertainment market is critical to the success of Silicon Graphics. The answer is simple. Our entertainment customers drive our technological innovation. And technological innovation is the foundation of Silicon Graphics.[28]

Indeed, in the twelve months ending in March 1994, SGI reported revenues of $1.5 billion. In 1997, revenues were reported as $3.66 billion.[29] SuperMario was certainly super to SGI. Kurt Akeley, a cofounder of Silicon Graphics, echoed McCracken's sentiments to a group of SGI developers at a meeting in Munich in the spring of 1998:

> That's what Silicon Graphics has been about since 1982, when I was one of the people that started it. We've had a huge impact, with you, making that come true. We've done it in domains that seemed obvious at the time: computer-aided design scientific visualization, as well as domains that were not anticipated.
>
> It's easy to imagine that we've affected more people directly with the technology in the Nintendo64 than we have collectively with all of our other computers. We've certainly sold more of them—by far—than all of the rest of the workstations we've done. So we've had an effect, not just in the technical domain, not just in the places that would have been fairly obvious to applied

28. Edward McCracken, "Inspired by Vision: A Letter from Ed McCracken," in National Association of Broadcasters '97 and National Association of Broadcasters MultiMedia World, 1997: http://www.sgi.com/features/studio/nab/index.html. McCracken also noted: "While there have been incredible advances across many areas of science and technology, the new Craylink architecture for supercomputers, new improvements on the space shuttle, sheep cloning—no advance has been more prolific, more ubiquitous, more wide reaching than consumer oriented entertainment developments."

29. See Ed McCracken, *Strategic Computing: Defining the Workflow Across the Organization*, Silicon Graphics Computer Systems Summary Annual Report, 1997: http://www.sgi.com/company_info/investors/annual_report/97/ceo.html. Also see the comparative financial data reported for 1993–97 at http://www.sgi.com/company_info/investors/annual_report/97/fin_sel_info.html.

> 3-D technology, but across the board—in people's homes and in their lives, and we're going to continue doing that.[30]

By making the technology more affordable; by finding ways to scale it to large consumer markets; by aiming, in short, to make technologies like the RISC chip everywhere present, developments such as those illustrated by the research-entertainment nexus—including Pixar, Silicon Graphics, and Nintendo—have made the use of imaging technology in science and medicine possible on a scale and at a pace that would not otherwise be imaginable.

Distributed Networks: SIMNET

In addition to the central role of the research-entertainment complex, the examples discussed in the preceding sections point to the importance of federal funding of university research, as well as research in government-funded laboratories (primarily through DARPA contracts), in creating and sustaining the hardware developments that are critical to the fields of 3-D graphics, simulation technology, and virtual reality. But this is only half of the picture: although networks are usually thought of apart from computer graphics, network considerations are in fact crucial to large-scale interactive 3-D graphics. Graphics and networks have become two interlocking halves of a larger whole: distributed virtual environments. Central to this work have been DARPA funding and the U.S. Army's creation of SIMNET, the military's distributed SIMulator NETworking program.

Simulators developed prior to the 1980s were stand-alone systems designed for specific task-training purposes, such as docking a space capsule or landing on the deck of an aircraft carrier. Such systems were quite expensive—for example, more than \$30–\$35 million for an advanced pilot simulator system in the late 1970s, and \$18 million for a tank simulator, at a time when an advanced individual aircraft was priced at about \$18 million and a tank at considerably less. High-end simulators cost twice as much as the systems they were intended to simulate. Jack A. Thorpe was brought into DARPA to address this situation based on a proposal he had floated in September 1978. His idea was that aircraft simulators should be used to *augment* aircraft: they should be used to teach air-combat skills that pilots could not learn in peacetime flying, but that could be taught with simulators in large-scale battle-engagement interactions. Thorpe pro-

30. Kurt Akeley, "Riding the Wave," in *Silicon Graphics European Developers Forum*, Munich and Tel Aviv, 1998: http://www.sgi.com/developers/marketing/forums/akeley.html; see esp. slide 7: http://www.sgi.com/developers/marketing/forums/akeley7.html.

posed the construction of battle-engagement simulation technology as a twenty-five-year development goal.[31] Concerned about the costs for such a system, he actively pursued technologies developed outside the Department of Defense, such as video-game technology from the entertainment industries.[32] In 1982 he hired a team to develop a network of tank simulators suitable for collective training. The team that eventually guided SIMNET development consisted of retired Army Colonel Gary W. Bloedorn; Ulf Helgesson, an industrial designer; and a team of designers from Perceptronics of Woodland Hills, California, led by Robert S. Jacobs. Perceptronics had pioneered the first overlay of computer graphics on a display of images generated by a (analog) videodisc, as part of a tank gunnery project in 1979.

The SIMNET project was approved by DARPA in late 1982 and began early in the spring of 1983 with three essential component contracts. Perceptronics was to develop the training requirements and conceptual designs for the vehicle-simulator hardware and system integration; BBN Laboratories, Inc., of Boston, which had been the principal ARPANET developer, was to develop the networking and graphics technology; and the Science Applications International Corporation (SAIC) of La Jolla, California, was to conduct studies of field-training experiences at instrumented training ranges of the National Training Center in Fort Irwin, California.

Affordability was the chief requirement Thorpe placed on the development of SIMNET components, and sticking to this requirement led to the most highly innovative aspects of SIMNET. Prior to the late 1980s, simulators were typically designed to emulate the vehicles they represented as closely as engineering technology and the available funds permitted. The usual design goal was to reach the highest possible level of physical fidelity—to design "an airplane on a stick," as it were. The SIMNET design goal was different: it called for learning first what functions were needed to meet the training objectives, and only then specifying the needs for simulator hardware. *Selective functional fidelity,* rather than full physical fidelity, was SIMNET's aim, and as a result, many hardware items not regarded as relevant to combat operations were not included, or were designated

31. Jack A. Thorpe, "Future Views: Aircrew Training 1980–2000," concept paper at the Air Force Office of Scientific Research, September 15, 1978, discussed in Richard H. Van Atta, Sidney Reed, and Seymour J. Deitchman, *DARPA Technical Accomplishments: An Historical Overview of Selected DARPA Projects,* IDA P-2429, 3 vols. (Alexandria, Va.: Institute for Defense Analyses, 1991), vol. 2, chap. 16, p. 10.

32. Ibid., n. 50.

only by drawings or photographs in the simulator. Furthermore, the design did not concentrate on the armored vehicle per se. Rather, the vehicle simulator was viewed as a tool for the training of crews as a military unit. The major interest was in *collective,* not *individual,* training. The design goal was to make the crews and units, not the devices, the center of the simulations.[33] This approach helped minimize costs, thus making possible the design of a relatively low-cost device.[34]

An early snag that threatened to undo the project was the fact that the visual-display and networking architecture being developed by BBN would not support the SIMNET system concept within the limits of the low-cost constraints. Analyses and expert judgments, from both within and outside DARPA, indicated that the planned use of available off-the-shelf visual-display technology would not support the required scene complexity within the cost, computer, and communications constraints set by the SIMNET goals. However, a proposal from Boeing allowed Thorpe to take advantage of the new generation of DARPA-funded microprocessor advances in VLSI and RISC for the development of a new low-cost microprocessor-based computer image generating technology for visual displays. The technology proposed by M. Cyrus of Boeing met the scene complexity ("moving models") requirements at acceptably low dollar and computational costs. Also, it permitted the use of a simpler, less costly networking architecture: Microprocessors would be used in each tank simulator to compute the visual scene for that tank's own "virtual world," including the needed representations of other armored vehicles, both "friendly" and "enemy." The network would not have to carry all the information in the visual scenes (or potential visual scenes) of all simulators. Rather, the network transmission could be limited to a relatively small package of calibration and "status change" information.[35]

33. The training concept was to provide a means of cueing individual behavior, with the armored vehicle being part of the cueing. When individuals and crews reacted, they would provide additional cues to which others would react. Thus, the technology was to play a subservient role in the battle-engagement simulations, making no decisions for the crews, but simply and faithfully reproducing battlefield cues.

34. Van Atta, Reed, and Deitchman, *DARPA Technical Accomplishments* (above, n. 31), chap. 16, p. 13.

35. Once the decision had been made to remove BBN from the graphics portion of the project, Cyrus left Boeing and formed an independent company, Delta Graphics, in order to devote his full energies to developing the graphics technology for SIMNET. The initial contractor, BBN, continued with responsibility for the network technology, but with the needed change in architecture—i.e., with the use of microprocessor-based graphics generators.

With these architecture and design elements in place, SIMNET was constructed of local and long-haul nets of interactive simulators for maneuvering armored-vehicle combat elements (MI tanks and M2/3 fighting vehicles), combat-support elements (including artillery effects, and close air support with both rotary and fixed-wing aircraft), and all the necessary command-and-control, administrative, and logistics elements for both "friendly" and "enemy" forces. A distributed-net architecture was used, with no central computer exercising executive control or performing major computations, but rather with essentially similar (and all necessary) computation power resident in each vehicle simulator or center-nodal representation.[36]

The terrains for the battle engagements were simulations of actual places, 50 km by 50 km initially, but eventually expandable by an order of magnitude in depth and width. Battles were to be fought in real time, with each simulated element—vehicle, command post, administrative and logistics center, etc.—being operated by its assigned crew members. Scoring would be recorded on combat events such as movements, firings, hits, and outcomes, but actions during the simulated battle engagements would be completely under the control of the personnel who were fighting the battle. Training would occur as a function of the intrinsic feedback and lessons learned from the relevant battle-engagement experiences. Development would proceed in steps—first to demonstrate platoon-level networking, then on to company and battalion levels, and later, perhaps, to even higher levels.

Each simulator was developed as a self-contained stand-alone unit, with its own graphics and sound systems, host microprocessor, terrain database, cockpit with task-training-justified controls and displays only, and network plug-in capability (Fig. 2). Thus, each simulator generated the complete battle-engagement environment necessary for the combat-mission training of its crew. For example, each tank crew member could see a part of the virtual world created by the graphics generator using the terrain database and information arriving via the net regarding the movements and status of other simulated vehicles and battle effects. The precise part of the virtual world was defined by the crew member's line of sight—forward for the tank driver, or from any of three viewing ports in a rotatable turret for the tank commander.

The visual display depended primarily on the graphics generator resident in each simulator. This computer image generation (CIG)

36. See Jack A. Thorpe, "The New Technology of Large Scale Simulator Networking: Implications for Mastering the Art of Warfighting," in *Proceedings of the 9th Interservice Industry Training Systems Conference, November 30–December 2, 1987* (American Defense Preparedness Association, 1987), 492–501.

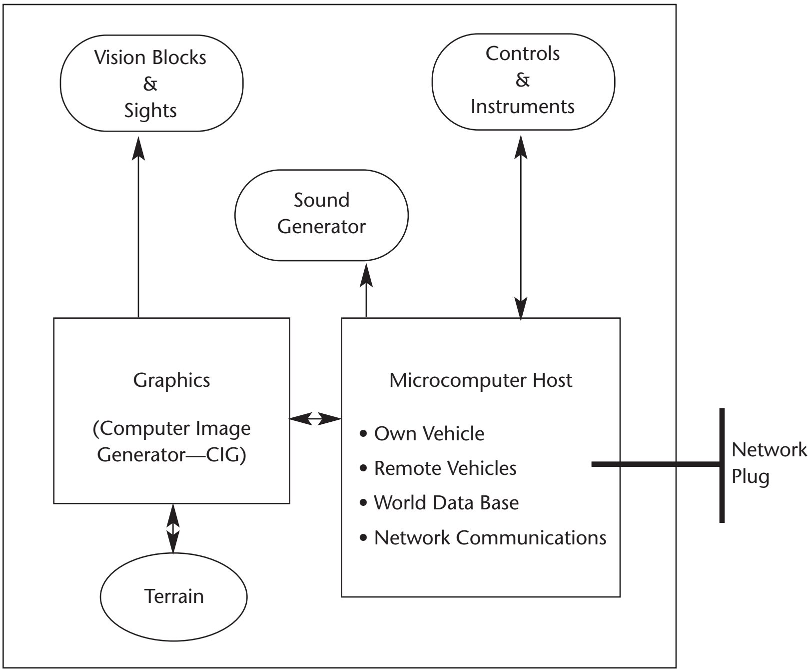

Figure 2. Architecture of a single M1 (Abrams tank) simulator in SIMNET. From J. A. Thorpe, "The New Technology of Large Scale Simulator Networking: Implications for Mastering the Art of Warfighting," in *Proceedings of the 9th Interservice/Industry Training Systems Conference, Nov. 30–Dec. 2, 1987* (Alexandria, Va.: American Defense Preparedness Association, 1987), p. 495.

system differed in several important characteristics from earlier CIG systems. First, it was microprocessor-based (vs. large-mainframe- or multiple-minicomputer-based), and therefore relatively low in cost (less than $100,000 per simulator visual-display subsystem, vs. more than $1 million per visual channel; typical flight simulators have at least five visual channels). Secondly, it was *high in environmental complexity,* with many moving models and special effects, but *low in display complexity,* with relatively few pixels, small viewing ports, and a relatively slow update rate of fifteen frames per second (vs. earlier CIG systems, and the technology being developed to improve and replace them). The development of the essentially unique graphics generator for SIMNET was a principal factor in permitting the system to meet the low-cost-per-unit constraint of the plan.

The architecture of the microprocessor-based graphics generator permits anyone or any simulator so equipped to connect to the net. This, combined with the distributed computing architecture of the net, provides an extremely powerful and robust system. New or additional elements can be included simply by "plugging into" the network. Once connected to the net, simulators transmit and receive data "packets" from other simulators or nodes (such as stations for combat-support or logistics elements), and compute their visual scenes and other cues (such as special effects produced by the sound system). Because the data packets need to convey only a relatively small amount of information (position coordinates, orientation, and unique events or changes in status), the communications load on the net and the increase in load with the addition of another simulator are both quite modest. Also, where updating information is slow in coming from another simulator, its state can be inferred, computed, and displayed. Then, when a new update is received, the actual-state data are used in the next frame, and any serious discontinuity is masked by the receiving simulator's automatic activation of a transition-smoothing algorithm. Should a simulator fail, the rest of the network continues without its contribution. Thus, network degradations are soft and graceful.

The prototypes and early experiments with SIMNET elements were carried out between 1987 and 1989, and the system was made operational in January 1990. The Army bought the first several hundred units for the Close Combat Tactical Trainer (CCTT) system, an application of the SIMNET concept—the first purchase of a system that would eventually contain several thousand units at a total cost of $850 million.[37]

From DARPA to Your Local Area Network

Throughout the period examined here, a key characteristic of federal funding of university research through agencies such as the NSF, NASA, and NIH, as well as through Defense Department agencies such as IPTO and DARPA, has been the interest in sustaining imaginative, exploratory, often "holy grail" research expanding the frontiers of knowledge. But as examples such as the VLSI program suggest, support from federal agencies has also been directed toward seeing that the products of federal research funding are transferred to technologies in service of both national defense and the commercial sector. For most of the period covered to this point (up to the end of the 1980s), policy discussions about these goals—of seeing

37. R. J. Lunsford, Jr., *US Army Training Systems Forecast, FY 1990–1994,* Project Manager for Training Devices (US Army Materiel Command), Orlando, Fla., October 1989, p. 14; cited in Van Atta, Reed, and Deitchman, *DARPA Technical Accomplishments* (above, n. 31), chap. 16, p. 31.

that research served national defense, and that it ultimately benefited the commercial sector—were either kept rigidly separate or delicately balanced in a complicated dance.

With the end of the Cold War, a stronger emphasis was placed during the 1990s on running a fiscally efficient military built on the practices of sound business, and of making military procurement practices interface seamlessly with commercial industrial manufacturing processes. With pressure to reduce military spending being applied by the Federal Acquisitions Streamlining Act of 1994, the Department of Defense (through DOD Directives 5000.1 and 5000.2) remodeled policies and procedures on procurement that had been in place for more than twenty-five years. Among the policies the new directives established was a move away from the historically based DOD reliance on contracting with segments of the U.S. technology and industrial base dedicated to DOD requirements—moving instead, by statutory preference, toward the acquisition of commercial items, components, processes, and practices. In the new mandated hierarchy of procurement acquisition, commercially available alternatives are to be considered first, and choice of a service-unique development program has the lowest priority. DOD components were directed to acquire systems, subsystems, equipment, supplies, and services in accordance with the statutory requirements for competition set out in directive 10 USC 2304. Organizational changes were necessary in order to implement these changes: adapting technology development and acquisition to the fast-paced high-technology sector of the U.S. economy meant adopting simplified, flexible management processes found in commercial industry—including the institutionalization of Integrated Product Teams, treating cost as an independent variable, and implementing a paperless procurement system of electronic commerce by the year 2000. Program managers were informed that this mandated change meant that military planners would work more closely with industrial partners in team fashion, sharing information on designs and specifications. In effect these changes, introduced by Secretary of Defense William Perry, have transformed military contracting units into business organizations. In keeping with this new shift in mentality, "Company" websites now routinely list their "product of the month."

As we have seen, the DOD has been the major source of long-term funding for 3-D graphics and work on VR throughout their thirty-year history. As a result of its changes in procurement, and indeed its entire culture for contracting, the DOD will continue to be a major force in developing these technologies in the near future, both through DARPA funding for the support of graphics laboratories at universities and through DOD funding of military projects. Directive 5000.1 on defense procurement acquisition mandated that models and simulations would be required of all proposed systems, and that "representations of proposed systems (virtual prototypes) shall be embedded in realistic, synthetic environments to support the various phases of the acquisition process, from requirements determination and initial concept exploration to the manufacturing and testing of new systems, and related training."[38] The total 1998 budget for programs for modeling and simulation exceeded $2.5 billion (see Table 2).[39] When such considerable resources are channeled through the new DOD procurement system intent upon seamless integration into the civilian high-tech industrial sector, a new and important role of federal funding in the post–Cold War era—as accelerator of the development and dissemination of modeling and simulation technologies—becomes evident.

An example suggesting the crucial role that federal funding will continue to play in the future of visualization and simulation technology is provided by the growing synergy between the U.S. Army's Simulation Training and Instrumentation Command (STRICOM) and the entertainment industry. For the last several years, the video game industry has been one of the fastest growing sectors of the entertainment business.[40] Physicians and computer scientists working on real-time volume rendering of medical imaging data are quick to point out that the systems they are developing depend on the ability to deliver live 3-D images on a desktop computer in a physician's office.[41] This will require improved graphics capabilities in PCs and higher-bandwidth networking technologies; developments in the entertainment industry, such as those emerging from the partnership between Nintendo and Silicon Graphics, produce such capabil-

38. DOD Directive 5000.1, March 15, 1996, section D: Policy, para 2: Acquiring Quality Products, item (f): Modeling and Simulation.

39. U.S. Department of Defense, Office of the Inspector General, 1997, *Requirements Planning for Development, Test, Evaluation, and Impact on Readiness of Training Simulators and Devices*, cited by Committee on Modeling and Simulation, *Modeling and Simulation: Linking Entertainment and Defense* (Washington, D.C.: National Academy Press, 1997), table 1.1, p. 17: http://www.nap.edu/readingroom/books/modeling/table1.1.html; http://www.nap.edu/readingroom/books/modeling/ (main url).

40. In 1999, video games alone grossed $6 billion. According to a recent survey by *Entertainment Weekly* of entertainment preferences in American households, 35% listed reading books as their favorite entertainment; in second place was playing video games, at 30%, while watching a video ranked 17%.

41. According to responses in interviews I have done for a project on the development of computers in medicine, and frequently mentioned in articles for the popular press.

Table 2. Large DOD development programs in modeling and simulation

Project name	Description	Estimated program cost ($millions)
Close Combat Tactical Trainer	Networked simulation system for training army mechanized infantry and armor units. It is composed of various simulators that replicate combat vehicles, tactical vehicles, and weapons systems interacting in real time with each other and semiautonomous opposing forces.	846
Battle Force Tactical Training	Tactical training system for maintaining and assessing fleet combat proficiency in all warfare areas, including joint operations. It will train at both the single-platform and battle-group levels.	165
Warfighter's Simulation 2000	Next-generation battle simulation for training Army commanders and battle staffs at the battalion through theater levels. It has a computer-assisted exercise system that links virtual, live, and constructed environments.	172
Joint Tactical Combat Training System	Joint effort by the Navy and Air Force to create a virtual simulation at the battle-group level in which combat participants will interact with live and simulated targets that are detected and displayed by platform sensors.	270
Synthetic Theater of War (STOW) Advanced Concept Technology Demonstration	A program to construct synthetic environments for numerous defense functions. Its primary objective is to integrate virtual simulation (troops in simulators fighting on a synthetic battlefield), constructive simulation (war games), and live maneuvers to provide a training environment for various levels of exercise. The demonstration program will construct a prototype system to allow the U.S. Atlantic Command to quickly create, execute, and assess realistic joint training exercises.	442
Joint Simulation System (core)	A set of common core representations to allow the simulation of actions and interactions of platforms, weapons, sensors, units, command, control, communications, computers, and intelligence systems, etc., within a designated area of operations, as influenced by environment, system capability, and human and organizational behavior.	154
Distributed Interactive Simulation	A virtual environment within which humans may interact through simulation at multiple sites that are networked using compliant architecture, modeling, protocols, standards, and databases.	500
TOTAL		$2,549

Source: U.S. Department of Defense, Office of the Inspector General, *Requirements Planning for Development, Test, Evaluation, and Impact on Readiness of Training Simulators and Devices* (a draft proposed audit report), Project No. 5AB-0070.00, January 10. 1997, Appendix D.

ities. In a similar fashion, those engaged in the VR field have argued that VR's breakthrough to acceptance has depended on the dissemination of VR technologies in the entertainment market for video games and video arcades. One of the brightest new players in that industry is Real3D of Orlando, Florida.

While its present incarnation is new, Real3D has a venerable history, tracing its origins back to the first GE Aerospace Visual Docking Simulator for the Apollo lunar landings. In 1991, GE Aerospace began exploring commercial applications of its real-time 3-D graphics technology, which led to a contract with Sega Enterprises Ltd. of Japan, the largest manufacturer of arcade systems in the world. Sega was interested in improving its arcade graphics hardware so their games would present more realistic images. GE Aerospace adapted a miniaturized version of their real-time 3-D graphics technology specifically for Sega's Model 2 and Model 3 arcade systems, which incorporated new algorithms for features such as antialiasing and was able to provide a visual experience far exceeding expectations.[42] To date, Sega has shipped more than 200,000 systems that include what is today Real3D technology.

This spinoff of technology originally developed for defense contracts is not in itself new, but the next phase of the story points to the impact of the procurement reforms in creating a synergy between government and industry sectors that is of potential benefit to both the research and the industrial communities. In the newly streamlined, flexibly managed military of the nineties, STRICOM is the DOD's executive agent in charge of developing the Advanced Distributed Simulation Technology Program behind much of the military's simulator training efforts. STRICOM has an interesting web presence: On one side of its spinning Weblogo is a figure in what might be either a space suit or a cleanroom suit worn by a chip worker. In the background are objects that could be tanks or chips on a board. The figure holds what could be a laser gun. Just when the viewer begins to wonder whether this is a video game, the reverse side of the spinning logo dispels that illusion: the figure there holds a lightning bolt as a weapon, but is otherwise a traditional helmet-clad soldier. The rim of the logo reads, "All But War Is Simulation."

In its capacity as manager of the military simulation training effort, STRICOM arranged a partnership of the San Diego–based Science Applications International Corporation (SAIC) and Lockheed Martin to develop hardware, software, and simulation systems for,

42. See the discussion by Jeffrey Potter of Real3D in *Modeling and Simulation* (above, n. 39), pp. 164–165. Also see http://www.real3d.com/sega.html.

among other things, networking simulations in live simulation environments such as SIMNET. Given the new imperative to build on products supplied by commercial industry, one key to success in this program of "integrated product development" is the development of standards for distributed interactive simulations (DIS) and the high-level software architecture (HLA) that sets specifications, interfaces, and standards for a wide range of simulations.[43] The adoption of these standards across the board by industry and by the American National Standards Institute prepares the ground for assimilating networked videogaming and more robust military simulations.

Developments connected with companies like Real3D can be seen as seminal in the historical evolution of the post–Cold War effort to create a seamless environment in which research work carried out for high-end military projects can be integrated with systems in the commercial sector. In 1993, GE Aerospace was acquired by Martin Marietta, another leader in the field of visual simulation. Martin Marietta not only advocated expansion of the relationship with Sega, but also encouraged further research and analysis to look at other commercial markets, such as personal computers and graphics workstations. In 1995, Martin Marietta merged with Lockheed Corporation to form Lockheed Martin, and shortly thereafter launched Real3D to focus solely on developing and producing 3-D graphics products for commercial markets. To that end, in November 1996 a strategic alliance was formed between Real3D and Chips and Technologies, Inc., of San Jose, California, aimed at selling and distributing Real3D®'s R3D/100 two-chip graphics accelerator exclusively to the PC industry, and bringing world-class 3-D applications in the PC environment to professionals who use 3-D graphics acceleration on Windows® NT machines.[44] Finally, in December 1997, Lockheed Martin established Real3D, Inc., as an independent company, and at the same time announced that Intel had purchased a 20% stake in the firm. Real3D thus builds on more than three decades of experience in real-time 3-D graphics hardware and software, going back to the Apollo Visual Docking Simulator—experience in a variety of projects related to the construction of real-time distributed simulations, and considerable intellectual property, consisting of more than forty key patents on 3-D graphics hardware and software. These assets, together with its strategic relationships to Lockheed Martin,

43. For the program description, see http://www.stricom.army.mil/STRICOM/PM-ADS/ADSTII/.

44. The R3D/100 chipset directly interfaces with Microsoft®-compliant APIs (application programming interfaces), such as OpenGL[a].

Intel, and Chips, position the company well for getting high-end graphics from leading-edge research environments onto the desktops of physicians, engineers, and scientists. The company profits from its role as a supplier of commercial video game technologies, developed by companies like Sega, to the research community developing military training simulators.

But it is not just the 3-D graphics capabilities that are being made more widely accessible through such developments. High-level research on distributed simulation environments such as SIMNET, and on the use of artificial intelligence in generating synthetic agents—both high-priority research problems in computer science—are other examples of federally funded research work being more rapidly disseminated through the military's new integrated product teams. Once again, Real3D's relation to Intel and the entertainment industry is thought-provoking. Intel is committed to advancing the capabilities of the PC platform; with its Pentium II processor with MMX technology, the corporation has launched an all-out campaign focused on bringing 3-D technology to mainstream PCs. In July 1997 Intel plus sixty hardware and software manufacturers in the arcade industry—including Real3D, Evans & Sutherland, 3Dfx Interactive, and Quantum 3D—joined in the Open Arcade Architecture Forum to encourage the development of hardware and software for open arcade systems through proactive market development efforts that ensure systems and software compatibility, while delivering arcade-game performance equaling or exceeding proprietary systems. The Open Arcade Architecture (OAA) specification, which Intel announced in April 1997, supports dual-processor-based arcade systems, which allow for faster, richer games and provide additional processing power for networking, video, and voice conferencing.[45]

An examination of the work and careers of individuals who have participated in both the military simulation community and the entertainment industry suggests paths through which the dissemination of research ideas across these seemingly different fields takes place. For example, prior to joining Walt Disney Imagineering in 1992, Dr. Eric Haseltine was an executive at Hughes Aircraft Co., where he held a series of posts in the Human Factors, Flight Simulation, and Display System areas. He joined Hughes in 1979 after completing a Ph.D. in physiological psychology at Indiana University

45. See the press release on the Open Arcade Architecture forum: http://www.intel.com/pressroom/archive/releases/CN71497B.htm. Also see the speech by Andy Grove at the June 20, 1997, Atlanta Entertainment Expo, "The PC Is Where the Fun Is": http://www.intel.com/pressroom/archive/speeches/asg62097.htm.

and a postdoctoral fellowship in neuroanatomy at Vanderbilt University School of Medicine. He has published in the fields of sensory physiology, neuroanatomy, flight simulation, training systems development, and display systems engineering; he also holds a number of patents in laser projection and electro-optical imaging. At Disney Imagineering, Haseltine is vice-president and chief scientist of research and development of projects including advanced head-mounted displays, optical systems, wireless communications, user interfaces, paperless animation systems, data security, and biomedical imaging.

Dr. Robert S. Jacobs, currently director and president of Illusion, Incorporated, offers a similarly illustrative profile. He has a B.S.E. in systems engineering from the University of California, Los Angeles; an M.S. in management science from the University of Southern California; and a Ph.D. in engineering psychology from the University of Illinois, Urbana-Champaign. Having headed up the design team at Perceptronics that worked on the original design of SIMNET, he has been a technical contributor to the majority of later, related training programs. At Illusion Jacobs has directed the definition, development, and manufacturing of advanced technology training and simulation products, including analytical studies, hardware design, software development, and courseware production.

SIMNET has been an incubator for the ideas and technology behind many current-generation video games. Consider the company description of WizBang! Software Productions, Inc., which created the 3-D environments for *Hyperblade* and Microsoft *Baseball:*

> [“WizBang!”] is a 3D computer games company founded in 1994. WizBang!’s founders and staff combine expertise and years of experience in military simulation, artificial intelligence, traditional gaming, music composition and theater production, as well as game development. With this unique perspective, they continue to be at the forefront of the ever-evolving high-tech game industry.[46]

Indeed, among WizBang!’s illustrious team members is company founder Stuart Rosen, with experience in both the development of computer games and military simulations. His computer game development experience began at Atari, where he managed the *PAC MAN* project for Atari’s home-computer and advanced video game. He also headed the design team for one of the first movie-to-computer-game spin-offs: Stephen Spielberg’s *E.T.* Rosen left Atari to manage the Image Generation Department at Singer-Link Flight

46. See “Company” at http://www.wizbang.com/.

Simulation, one of the early companies in the flight simulator business, which built such systems as the Apollo Docking Station and the DC8 flight simulator used in airlines around the world, and many others. For Singer-Link Rosen developed virtual reality databases and advanced modeling tools for pilot training simulators. He then moved to Bolt Beranek & Newman Advanced Simulation, where he led the design, development, and integration of networked interactive simulation systems for U.S., British, and Japanese forces. This included extensive work on the SIMNET project.[47]

Andrew Johnston, WizBang!'s other founder and president, was also a key contributor to SIMNET. Along with M. Cyrus from Boeing, Johnston was the cofounder, vice-president, and director of engineering of Delta Graphics (later acquired by Bolt Beranek & Newman), and he directed the software development effort for the computer image generator (CIG) I have described above, the CAD modeling system for the CIG database, and commercial computer animation software. Prior to that, while at the Boeing Aerospace Company in Seattle, he managed a group of forty-five engineers involved in research and development in advanced computer-image generation and was a key architect of a real-time 3-D computer-image generation system under contract with DARPA. This system was the basis of the Boeing B1-B Weapons System Trainer, a large-scale computer-image generation system.[48]

For my purposes, an example of how such career trajectories can work in disseminating research ideas is provided by the work and career of Steven Woodcock, who has been lead software engineer for Gameware Development at Lockheed-Martin Real3D since January 1995. Woodcock began his career in the development of game simulations for Martin Marietta. From October 1989 to January 1992 he was senior software engineer, and from 1992 to 1995 lead software and technical engineer, for Martin Marietta Information Group, National Test Bed (NTB), where he was responsible for all weapons code development, testing, integration, and documentation for ARGUS, the Advanced Real-time Gaming Universal Simulation.[49] ARGUS is a

47. Ibid.

48. Ibid.

49. For Steven Woodcock's biography, see: http://www.cris.com/~swoodcoc/stevegameresume.html. Also see Steven Woodcock, "Interview on the Future of AI Technology and the Impact of Multiplayer Network-Capable Games," in *Wall Street Journal Interactive Edition* (May 19, 1997); Donna Coco, "Creating Intelligent Creatures: Game Developers Are Turning to AI to Give Their Characters Personalities and to Distinguish Their Titles from the Pack," *Computer Graphics World* 20:7 (1997): 22–28: http://www.cgw.com/cgw/Archives/1997/07/07story1.html.

real-time, distributed, interactive command-and-control simulation focusing on ballistic missile defense (BMD) and theater missile defense (TMD), running on a TCP/IP network consisting of a Cray-2 supercomputer and more than fifty Silicon Graphics workstations. As noted above, Martin Marietta contracted with Sega to build the Model 2 arcade platform, and Woodcock contributed to this effort. From March 1995 to March 1997 he shifted his venue from military network simulations to the interactive game industry, where he was lead programmer and oversaw all aspects of game development on the Sega-produced Model 2 arcade game *Behind Enemy Lines,* featuring a true 3-D environment and the use of AI. He has noted that his previous experience at Martin Marietta on the NTB and ARGUS in distributed applications, real-time simulations, and artificial intelligence has proved invaluable in designing the real-time, 3-D, multiplayer environments of games he has been working on since 1995. During the same period, from September through October 1996 he worked with another of the companies in the Intel-initiated Open Arcade Architecture Forum, Dreamality Technologies, on the location-based entertainment (LBE) simulator *DreamGlider.* For that project he integrated a message layer based on the military distributed interactive simulation (DIS) protocols, designed to support large-scale, many-machine, network connectivity. From January to June 1996 he was AI and game-engine developer for a Sony PlayStation project named *Thundering Death.* On this project Woodcock implemented the first goal-based AI on the PlayStation, using neural networks to provide an ever-learning opponent.

If the career of Steven Woodcock illustrates the ways in which ideas, technologies, and personnel have flowed from military simulation efforts to the entertainment industries, *DOOM II* produced by Id Software, and *FALCON 4.0,* one of Spectrum Holobyte's video games, provide glimpses into how the exchange is being accelerated in the opposite direction at the present time.

The shift in culture of the military reflected in procurement policies discussed above is also evident in new military approaches to developing critical thinking. Emblematic of this shift is Marine Corps Commandant Gen. Charles C. Krulak's directive 1500.55, issued in 1996, aimed at implementing improvements in what he termed "Military Thinking and Decision Making Exercises." In his comments on the planning guidance he wrote: "It is my intent that we reach the stage where Marines come to work and spend part of each day talking about warfighting: learning to think, making decisions, and being exposed to tactical and operational issues." He identified an important way to exercise these skills:

> The use of technological innovations, such as personal computer (PC)-based wargames, provide great potential for Marines to develop decision making skills, particularly when live training time and opportunities are limited. Policy contained herein authorizes Marines to use Government computers for approved PC-based wargames.[50]

General Krulak directed, furthermore, that the Marine Combat Development Command assume responsibility for the development, exploitation, and approval of PC-based war games. In addition, they were to maintain the *PC-based Wargames Catalog* on the Internet.[51]

With this incentive, some Marine simulation experts from the Marine Corps Modeling and Simulation Management Office in the training and education division at Quantico, Virginia, tracked down a shareware copy of the commercial game *DOOM* produced by Id Software, Inc., and began experimenting with it. This led to the adaptation of this game as a fire-team simulation, with some of the input for the Marine version coming from Internet *DOOM* gamers employing shareware software tools.[52] They then rewrote the code for the commercial game *DOOM II.* Instead of employing fantasy weapons to face down monster-like characters in a labyrinthine castle, real-world images were scanned into WAD files along with images of weapons such as the M16(a1) rifle, the M-249 squad automatic weapon, and M-67 fragmentation grenades. The game was also modified from its original version to include fighting holes, bunkers, tactical wire, "the fog of war," and friendly fire. *MARINE DOOM* trainees use Marine-issue assault rifles to shoot it out with enemy combat troops in a variety of terrain and building configurations. In addition to training fire teams in various combat scenarios, the simulation can be configured for a specific mission immediately prior to engagement. For example, Marines tasked with rescuing a group of Americans held hostage in an overseas embassy could rehearse in a virtual building constructed from the actual floor plans of the structure. Users needed only to purchase version 1.9 of the commercial game and add the Marine rewrite code to run the new tactical simulation. The Quantico-based software could not run without the original commercial package, so no licensing violations occurred. Indeed,

50. General Charles C. Krulak, Marine Corps Order 1500.55, "Military Thinking and Decision Making Exercises," online at http://www.tediv.usmc.mil/dlb/milthink/.

51. For the *PC-Wargames Catalog,* see http://www.tediv.usmc.mil/dlb/milthink/catalog/title.html.

52. For an interesting discussion of *Marine Doom,* see Rob Riddell, "Doom Goes to War: The Marines Are Looking for a Few Good Games," in *Wired Magazine* 5:4 (1997), online at http://www.wired.com/wired/archive/5.04/ff_doom.html?topic=&topic_set=.

any personal computer owner with *DOOM II* can download the code for *MARINE DOOM* from the Modeling and Simulation Management Office's web page. You too can become a military assault commando.

The success of the *DOOM II* simulation rewrite led the Marines to look ahead to the next step in commercial war-gaming. Discussions with MÄK (pronounced "mock") Technologies (Cambridge, Mass.), a commercial game manufacturer specializing in network simulation tools for distributed interactive simulations, led to the design of a tactical operations game built to Marine specifications. According to the contract, the Marine Corps would help develop the software code and in turn would receive a site license to train on this game, while MÄK would sell it commercially as an official Marine Corps tactical training game. This from-the-ground-up development would eliminate all of the nuances of the other adapted games that are not particular to Marine combat.

MÄK was founded in 1990 by two MIT engineering graduates, Warren Katz and John Morrison. After graduation both were original members of Bolt Beranek & Newman's SIMNET project team from 1987 to 1990, which developed low-cost, networkable 3-D simulators for the Department of Defense. MÄK's corporate goal is to provide cutting-edge research and development services to the DOD in the areas of distributed interactive simulation and networked virtual reality systems, and to convert the results of this research into commercial products for the entertainment and industrial markets. MÄK's first commercial product, the VR-Link™ developer's toolkit, is the most widely used commercial DIS interface in the world. It is an application programmer's toolkit that makes possible the networking of distributed simulations and VR systems. The toolkit complies with the Defense Department's DIS protocol, enabling multiple participants to interact in real time via low-bandwidth network connections. VR-Link is designed for easy integration with existing and new simulations, VR systems, and games. Thanks to such products, MÄK was ranked 36th in the 1997 New England Technology Fast 50, and 380th in the 1997 National Technology Fast 500, based on revenue growth between 1992 and 1996.

In addition to its work in the defense community, MÄK's software has been licensed for use by several entertainment firms, such as Total Entertainment Network and Zombie Virtual Reality Entertainment, to serve as the launching pad for real-time, 3-D, multiuser video games. One such game, *Spearhead,* a multiuser tank-simulation game released in mid-1998, was written by MÄK and published by Interactive Magic. *Spearhead* can be played over the Internet and incorporates networking technology similar to that used in military simulations.

Both distributed interactive simulation and high level architecture efficiently connect thousands of 3-D simulations together on a computer network. Replacing the DIS standard for net-based simulations, HLA has been designated as the new standard technical architecture for all Department of Defense simulations, part of a DOD-wide effort to establish a common technical framework to facilitate the interoperability of all types of models and simulations, as well as the reuse of modeling and simulation components. MÄK intends to leverage its technology for both the military and commercial markets by taking advantage of the nearly $500 million a year spent by the U.S. government on optimizing the speed and capabilities of DIS and HLA. State-of-the-art military DIS systems are now capable of running more than ten thousand simulations simultaneously, networked together across far-ranging geographies. With low-cost commercial data services (bidirectional cable TV, ADSL [Advanced Distributed Simulation Network], etc.) becoming more widely available to consumers, industry analysts projected the market for online, 3-D, multiuser simulations to reach $2 billion in the year 2000. The networking capabilities of distributed simulation technology developed by MÄK and other government suppliers will enable entertainment providers to create platforms for 3-D worlds supporting up to 100,000 participants simultaneously. Katz has described his vision provocatively in a chapter for the book *Digital Illusion: Entertaining the Future with High Technology,* titled "Networked Synthetic Environments: From DARPA to Your Virtual Neighborhood."[53] MÄK cofounders Katz and Johnson are betting that in the near future Internet-based populations the size of a mid-sized U.S. city will be able to stroll through an electronic shopping mall, explore and colonize a virtual universe, or race for prizes in cyberspace's largest 3-D road rally.

The contract awarded by the U.S. Marine Corps to MÄK in 1997 will assist this vision of vastly shared virtual reality; it further erodes the distinction between military simulation technology and the technology available to ordinary users. The contract is for *MEU 2000,* a computer-based tactical decision-making game for the Marine Corps that will also be released simultaneously as a commercial computer game. The player of *MEU 2000* assumes the role of a Marine of-

53. The book is published by Addison-Wesley. For more information, visit http://www.aw.com/cseng/.

ficer coordinating the actions of a "Marine Expeditionary Unit—Special Operations Capable [MEU (SOC)]." The player will see the battle from a 3-D tactical view, enabling him to select units, issue orders, and monitor the progress of his forces. *MEU 2000* will be a multiplayer game. Each player may assume a position in the command hierarchy of either U.S. or opposing forces (players will be able to command only U.S. equipment). Additionally, players of platform-level simulations will be able to assume their appropriate positions in the hierarchy. *MEU 2000* will be a real-time, networkable, 3-D strategy game, developed in cooperation with the Marine Corps in order to ensure that a high level of realism is incorporated into the simulation. MÄK will use the same game engine in both its military and civilian versions. The military version will add more accurate details about tactics and weapons, while the civilian game will be less demanding, but both versions will allow multiple players to compete against each other over a local-area network or the Internet.

While a number of military simulations and commercial airline flight simulators have been adapted to the commercial game market, *FALCON 4.0* is the first flight-simulation video game to be adapted to military training. *FALCON 4.0* is a network-based game that supports both single-player and multiplayer modes. The multiplayer mode supports dogfights with up to four squadrons of four F-16s each. The game's whopping six-hundred-page manual suggests the seriousness of play involved and indicates why the military finds it attractive for its own training purposes. As producer Gilman Louie explains, the *FALCON 4.0* is a detailed simulation re-creating the feel of being an F-16 pilot operating over a modern battlefield. The simulation has a highly accurate flight model and avionics suite that incorporates flight parameters conforming to real-world specifications. It accurately re-creates such effects as deep stall (to escape, the player must use the real-world procedure of flipping the manual pitch override switch and "rocking" the aircraft out—the standard game trick of simply lighting the afterburners will not restore normal flight in this simulation). Weapon modeling is equally realistic and, except for omitting a few classified details, provides an amazingly accurate representation of weapons deployment. The simulation is so detailed, in fact, that reviewers of the game report consulting a real-world "Dash 1" manual for the F-16 when playing the game. The realism of *FALCON 4.0* is further enhanced by graphics generated from actual aerial photographs and map data from the Korean peninsula. In its current version, the game plays best on a computer with a processor of 400 MHz or higher.

The extreme realism in this video game led Peter Bonanni, a graduate of the F-16 Fighter Weapons School and pilot instructor of the Virginia Air National Guard, to work with Spectrum HoloByte, Inc., to modify the game for military training. According to Bonanni, *FALCON 4.0* mimics the look and feel of real military aircraft and allows users to play against computer-generated forces or, in a networked fashion, against other pilots, which facilitates team-training opportunities. Another reason for Bonanni's enthusiasm is the virtual world around the player. Although the product features scripted tactical engagement missions as well as an instant action mode for newcomers, the heart and soul of the product is the dynamic campaign mode, where the player assumes the role of a pilot in an F-16 squadron during a conflict on the Korean peninsula. The campaign engine runs an entire war, assigning missions to units throughout the theater. A list (displayed either by priority to the war effort or by launch time) shows the missions available to the player's squadron. The player can fly any of these missions, with the freedom to choose air-to-air or air-to-ground sorties. Unlike games with pre-scripted outcomes, the campaign engine allows story lines, missions, and outcomes to be dynamically generated. Each play of the game influences the next. If a player is first assigned a mission to destroy a bridge but fails, the next mission may be to provide support to friendly tanks engaged by an enemy that has just crossed the bridge.

Networked video games such as *FALCON 4.0* are emblematic of the calculated emergence of a military-entertainment complex, but also of the fusion of the digital and the real happening around us. It is hardly surprising that Bonanni not only helps adapt the video game to military training needs but also writes a regular column for the www.falcon4.com Web site on tactics, and has designed several of the thirty-one prebuilt training missions included with the game. He is coauthor of two best-selling books on the game—one with colleague James Reiner, also an F-16 instructor pilot and graduate of the F-16 Fighter Weapons School, and, like Bonanni, a consultant on the game. Beginning with some basics on the game and the various gameplay options, *FALCON 4.0: Prima's Official Strategy Guide* gives readers a guide to instant action missions, multiplayer dogfights, and full-fledged campaigns. The book is a serious, no-nonsense manual, devoting separate chapters to laser-guided bombs and even the AGM-65 Maverick missile. Bonanni's second book, *FALCON 4.0 Checklist,* is scheduled to appear soon and is already high on the Amazon.com sales list before it has even hit the bookstores. Recalling that *Ender's Game* has been taught in flight schools, would-be Falcon pilots will probably want to add a copy to their Amazon.com shopping cart for inspirational reading.

Until the last two or three years, these crossovers between military simulations and the entertainment industries have been unplanned and opportunistic. In December 1996 the National Academy of Sciences hosted a workshop on modeling and simulation aimed at exploring mutual ground for organized cooperation between the entertainment industries and defense.[54] The report stimulated the Army in August 1999 to give $45 million to the University of Southern California over the next five years to create a research center to develop advanced military simulations. The research center will enlist film studios and video game designers in the effort, with the promise that any technological advances can also be applied to creating more compelling video games and theme park rides. The idea for the new center, called the Institute for Creative Technologies, reflects the fact that although Hollywood and the Pentagon may differ markedly in culture, they now overlap in technology. Moreover, as we have seen, military technology, which once trickled down to civilian use, now often lags behind what is available in games, rides, and movie special effects. STRICOM chief scientist and acting technical director Dr. Michael Macedonia wrote in a recent article in *Computer:*

> As SIGGRAPH—the computer-graphics community's showcase—has demonstrated over the past several years, the demands of digital film development are making way for computer games' even more demanding real-time simulation requirements. As a mass market, games now drive the development of graphics and processor hardware. Intel and AMD have added specialized multimedia and graphics instructions to their line of processors in their battle to counter companies such as Nvidia, whose computer graphics chips continue breaking new performance boundaries. . . .
>
> By aggressively maneuvering to seize and expand their market share, the entertainment industry's biggest players are shaping a 21st century in which consumer demand for entertainment—not grand science projects or military research—will drive computing innovation. Private-sector research-and-development spending, which now accounts for 75 percent of total US R&D, will increase to about $187.2 billion in 2000, up from an estimated $169.3 billion in 1999, according to Battelle Memorial Institute's annual R&D forecast.[55]

54. Cited in Committee on Modeling and Simulation, *Modeling and Simulation* (above, n. 39).

55. Michael Macedonia, "Why Digital Entertainment Drives the Need for Speed," *Computer* 33:2 (2000): 124–127. Online at http://www.computer.org/computer/co2000/r3toc.htm.

In opening the Institute for Creative Technologies, Secretary of the Army Louis Caldera said: "We could never hope to get the expertise of a Steven Spielberg or some of the other film industry people working just on Army projects"; but the new institute, he said, will be "a win-win for everyone."[56]

While putting more polygons on the screen for less cost is certainly one of the military's objectives at the Institute for Creative Technologies and in similar alliances, other dimensions of simulated worlds are equally important for their agenda. Military simulations have been extremely good at modeling hardware components of military systems. Flight and tank simulators are excellent tools for learning and practicing the use of complex, expensive equipment. However, movies, theme park rides, and (increasingly) even video games are driven by stories with plot, feeling, tension, and emotion. To train for real-world military engagements is to train not just on how to use the equipment, but on how to cope with the implementation of strategy in an environment with uncertainties, surprises, and participants with actual fears. As Gen. Krulak's directive on "Military Thinking and Decision Making Exercises" emphasized, decisions made in war must frequently be made under physical and emotional duress. The directive stated that the PC-based wargame exercises in peacetime should replicate some of the same conditions: "Imaginative combinations of physical and mental activities provide Marines the opportunity to make decisions under conditions of physical stress and fatigue, thereby more closely approximating combat."[57]

Early military simulations incorporated very rote behaviors; they did not capture "soft" characteristics well. An effort to go beyond this was launched in 1991 by the Institute for Defense Analyses (IDA) in their project to construct a computer-generated "magic carpet" simulation/re-creation of the Battle of 73 Easting, based on in-depth debriefings of 150 survivors of a key battle that had taken place during the Gulf War.[58] The goal of the project was to get

56. Andrew Pollack, "Trying to Improve Training, Army Turns to Hollywood," *New York Times* August 18, 1999. Online at http://www.isi.edu/nyt_uarc.html.

57. Krulak, "Military Thinking" (above, n. 50).

58. For interesting discussions of the Battle of 73 Easting, see Sterling, "War Is Virtual Hell" (above, n. 4), esp. pp. 6–7 of the online article. An important discussion of the place of the 73 Easting Simulation in military strategic planning is to be found in Stephen Biddle, "Victory Misunderstood: What the Gulf War Tells Us about the Future of Conflict," *International Security* 21:2 (1996): 139–179. For details on the construction of the simulation, see Jesse Orlansky and Colonel Jack Thorpe, eds., *73 Easting: Lessons Learned from Desert Storm via Advanced Distributed Simulation Technology,* IDA D-1110

timeline-based experiences of how individuals felt, thought, and reacted to the dynamic unfolding of the events—their fears and emotions as well as actions—and to render the events as a fully three-dimensional simulated reality that any future cadet could enter and relive. Going a step beyond the traditional "staff ride"—a face-to-face postbattle tutorial at the site itself, in which a commander leads his staff in a verbal re-creation of the skirmish—this tour of a battle site was a simulacrum of the war itself. Work on data-gathering for the simulation began one month after the battle had taken place. The IDA brought the soldiers who had actually taken part and had them sketch out the battle. They walked over the battlefield amid the twisted wreckage of Iraqi tanks, recalling the action as best they could. A few soldiers supplied diaries to reconstruct their actions; some were even able to consult personal tape recordings taken during the chaos. Tracks in the sand gave the simulators precise traces of movement. A black box in each tank, programmed to track three satellites, confirmed its exact position on the ground to eight digits. Every missile shot left a thin wire trail that lay undisturbed in the sand. Headquarters had a tape recording of radio-voice communications from the field. Sequenced overhead photos from satellite cameras gave the big view. A digital map of the terrain was captured by lasers and radar.[59]

With these data a team at the IDA Simulation Center spent nine months constructing a simulation of the battle. A few months into the project, they had the actual desert troops, then stationed in Germany, review a preliminary version of the re-creation. The simulacra were sufficiently fleshed out that the soldiers could sit in tank simulators and enter the virtual battle. They reported corrections of the simulated event to the technicians, who modified the model. One year after the confrontation, the re-created Battle of 73 Easting was demonstrated for high-ranking military in a facility with panoramic views on three 50-inch TV screens at the resolution of a very good video game.

(Alexandria, Va.: Institute for Defense Analyses, 1992); Colonel Michael D. Krause, *The Battle of 73 Easting, 26 February 1991: A Historical Introduction to a Simulation* (Washington, D.C.: U.S. Army Center for Military History and the Defense Advanced Research Projects Agency [DARPA], 1991); J. R. Crooks et al., *73 Easting Re-Creation Data Book,* IEI report no. DA-MDA972-1-92 (Westlake, Calif.: Illusion Engineering, 1992); W. M. Christenson and Robert Zirkle, *73 Easting Battle Replicaton,* IDA P-2770 (Alexandria, Va.: Institute for Defense Analyses, 1992).

59. See Kevin Kelly, "God Games: Memorex Warfare," from *Out of Control* (New York: Addison Wesley, 1994): http://panushka.absolutvodka.com/kelly/ch13-e.html.

The Battle of 73 Easting is an extremely accurate historical reconstruction of a battle whose outcome is known. It set the standard for a future genre of training simulations, something like the *Saving Private Ryan* of staff rides. Although the cost of creating the simulation is not available, it was undoubtedly expensive. As a computer simulation with programmable variables, however, the scenario could be replayed with different endings. Indeed, the next logical step after creating this fantastically accurate simulation would be to use the data and behaviors of the simulation as inputs to a game engine, like *MARINE DOOM*, or a more current best-seller, *QUAKE*. By making the simulation reprogrammable, the staff ride could become an adaptable tool for battle training. Embedded simulations involving real global-positional data, and information on opposing forces and their capabilities, could be built into the M1 tank units, attack helicopters, or F-16s themselves as real soldiers train for an impending mission right up to the hour of the engagement.

How might the interest in pursuing this line of development in new settings like the Institute for Creative Technologies (ICT) proceed? At this early date we can only speculate. In light of the new military practice of forming product-development teams consisting of military, industry, and possibly academic partners, and in light of efforts to merge military and entertainment projects for their mutual benefit, I would like to propose an imaginary scenario of teamwork involving elements from each of these sectors. Several of the members of the new ICT work on constructing semiautomated forces and multiple distributed agents for virtual environments, such as training programs; others work on building models of emotion for use in synthetic training environments. The work of professors Jonathan Gratch and Jeff Rickel is prototypical. Prior to the formation of the ICT, these researchers had been working on the construction of intelligent agent technology for incorporation into state-of-the-art military simulation systems. They are more interested in modeling training behaviors than in developing "believable agents" for video games or film. The goal of one of their projects is to develop command-and-control agents that can model the capabilities of a human military commander, where command agents must plan, monitor their execution, and replan when necessary.

I can imagine many potential collaborations with commercial video-game companies that would leverage the skills and knowledge of both commercial and academic partners interested in artificial agents and historically accurate "staff ride" training scenarios that build in uncertainty, fear, emotion, and a gripping sense of story and narrative. I find Atomic Games an interesting candidate: its personnel and company history map the trajectory from military to commercial applications that I have explored above. Atomic Games is a company of ten persons founded in 1991 by Keith Zabalaoui; today it is a subsidiary of Microsoft Games. Before entering the video game business, Zabalaoui and his colleagues worked for Rockwell International at the Johnson Space Center in Houston, Texas. Zabalaoui worked on a space-based robotic retriever for recapturing astronauts, tools, or anything else that might become detached from the space shuttle. After the retriever project was canceled, he shifted his activities full-time to what had been until then his recreation during breaks at the Center: a board game called *Atlantic Wall,* with three boards set up in different rooms for the Allies, Axis, and referees. He started bringing his Macintosh computer with him to the game, and between moves he began writing the first *V for Victory* game that has become the trademark of Atomic Games: *V for Victory, Utah Beach,* which was selected as Game of the Year by Strategy Plus in 1992.

Atomic Games' most successful attempt to build a historically accurate game is *Close Combat 2: A Bridge too Far.* It is based on a rendering of a World War II German-American tank battle, and it has won many awards for its realism. In part this is achieved by the addition of sound and movie-like visual effects, but a key element is its models of the behavior of men under fire. This human aspect of combat has been provided by advisors such as Dr. Steven Silver, who is a combat psychologist.

Whether or not this imaginary alliance between Atomic Games and AI researchers in the ITC is ever realized, my point is to illustrate how the Army's goals of leveraging technology for its own purposes from the film and video-game industries at sites like this incubator institute might be achieved. The military has contributed enormously to the development of the digital technologies that are transforming our world, but they have become a backseat player in the new digital economy.[60] According to the Interactive Digital Software Association (IDSA), in 1998 the sale of game and edutainment software for computers, video consoles, and the Internet generated revenues of $5.5 billion in the United States alone, making it the fastest-growing entertainment industry in the world; video-game rentals accounted for a further $800 million. The interactive entertainment software industry that created these products did so with

60. On the role of the military in creating and sustaining the computer revolution, see Thomas P. Hughes, ed., *Funding a Revolution: Government Support for Computing Research* (Washington, D.C.: National Academy Press, 1999); idem, *Rescuing Prometheus* (New York: Pantheon Books, 1998).

only about seventy thousand employees. Compare these figures with the motion picture business, which generated $6.9 billion, but employed more than 240,000 people in doing so.[61] Software sales continued to skyrocket, increasing by 22% on a dollar basis, making 1998 the third consecutive year in which the industry experienced double-digit growth. Video-game sales racked up more than $3.7 billion, and computer-game sales topped $1.8 billion. Retail sales remained strong throughout the year, with each month outperforming the same month of the previous year. In addition, unit sales increased by 33%: 181 million units of PC and video games in the United States alone, or almost two per household. Through the first three-quarters of 1999, video-game unit sales were up 31%, and dollar sales were up 21%. Unit growth for computer games increased 22%, and dollar sales increased almost 20%. Total sales reached $3.3 billion, a 19% increase compared to the same period in 1998.

What these figures suggest is that sufficient economic incentives exist alongside the policy and organizational structures I have been describing to fuel the continued rapid diffusion and improvement of military SIMNET technology through its fusion with video game and film. Perceptronics, for example, one of the original contractors for SIMNET, has been committed to the redeployment and further development of that technology into its Internet Collaborative 3D™ Framework (IC3D™) for mass-market, people-oriented 3-D experiences on the Web in which multiple users can interact fully, naturally, collaboratively, and in real time within virtual environments.[62] For those who see such developments as contributing to the fusion of the digital and the real and, as I have argued, creating the precondition for a "posthuman" future, the ride is not over yet.

Conclusion: *Ender's Game* Redux

The Institute for Creative Technologies seeks to merge the military's interests in interactive simulation technology with similar interests of academics and the film industry. Such incubators of mutual interests in computing and communications technologies have been launched in other domains as well. A few days following the Army's announcement of its investment in Creative Technologies, the CIA announced that it was investing $28 million in a venture capital firm, In-Q-It, headed by thirty-nine-year-old Gilman Louie, the former head of game company Spectrum Holobyte, now Hasbro,

61. See the Interactive Digital Software Association's *1999 State of the Industry Report*: http://www.idsa.com/.

62. See descriptions of Perceptronics' recent work at http://www.perceptronics.com.

which produces *FALCON 4.0* among other leading games.[63] Just exactly what the CIA hopes to gain from this arrangement was unclear, but Louie said that the new company is designed to move information technology to the agency more quickly than traditional governmental procurement processes allow. Among the new company's board members are John Seeley Brown, director of the Xerox Corporation's Palo Alto Research Center; Lee Ault, director of Equifax Alex Brown; Stephen Friedman of Goldman Sachs; Norm Augustine, chairman of Lockheed Martin; and William Perry, former secretary of defense, the person who, I have argued, contributed enormously to transforming the military into a commercially efficient engine.[64]

At the outset I discussed developments related to ubiquitous computing, MEMS, and smart matter supported by a consortium of private companies and government-funded research, particularly DARPA. To some, the remaking of the world suggested by proponents of those projects has more the chilling fantastic character of science fiction depicted in *The Matrix* or in Stephenson's *Snow Crash* than of warm-blooded reality. Earlier audiences no doubt voiced similar reactions to *Ender's Game,* and even *2001,* as unrealizable, paranoid figments of the cultural imagination (indeed, the introduction to the 1988 edition of *Enders Game* claims that any such realization on the Internet will be far in the distant future). As an exercise in thinking about how such a world might develop, given events and programs currently in place, I have drawn an analogy to a parallel but closely related development within the military-entertainment complex. I have attempted to show how the boundaries between exotic graphics and computer simulations for military purposes, on the one hand, and video games and entertainment graphics on the other, have dissolved into bonds of mutual cooperation symbolized powerfully by the creation of the joint military/film industry–funded Institute for Creative Technologies.

I have also argued that in the course of that development a fusion of the digital and the real has taken place, and with it the disappearance of the boundary between fantasy and reality. The fact that the campaign engine driving preparations for F-16 missions and tank maneuvers in future Bosnias and Serbias is the very same technology we use to engage our skills in Internet gaming is certainly suggestive. That it represents a fusion of the digital and the real is perhaps even

63. CIA Press Release, September 29, 1999: http://www.odci.gov/cia/public_affairs/press_release/index.html.

64. See John Markoff, "High-Tech Advances Push C.I.A. into New Company," *New York Times,* September 29, 1999.

more strongly indicated by the midterm report filed in August 1999 by Colonel Mark E. Smith, the director of the Joint Advanced Distributed Simulation Joint Test Force (JADS JTF), responsible for monitoring progress in implementation of the simulation projects discussed above. Among the successful tests of the ADS system reported was a "live fly phase" (LFP) conducted in October 1997 in which live units were interconnected with simulation units in a training scenario. Distributed simulation techniques were used to link two live F-16 aircraft (flying on the Gulf Test Range at Eglin Air Force Base, Florida), representing the shooter and the target, to a simulated air-to-air missile in the "hardware-in-the-loop" (HWIL) laboratory (also at Eglin). The shooter aircraft "fired" the air-to-air missile in the missile laboratory at the F-16 target and provided data-link updates of the target position and velocity to the missile during its flyout. Other combinations of simulation–live unit fusion are being tested as well. Smith's report pronounced the tests a surprising success, the only downside being a 3.1-second latency in one of the data links.

On September 1, 1999, Intel Corporation announced the first of a new series of network processors designed to solve bandwidth problems of the sort encountered in the LFP test. The new processors comprise programmable, scalable switching and formatting engines and physical layer devices. In all, thirteen different components of the new processors can be used to develop network devices for local and wide area networks (LAN and WAN) as well as Internet-based networks. Such technologies are aimed at delivering real-time voice and video transmission over the Internet, thus resolving the discrepancy between real-world and simulated experience. Orson Scott Card's vision of a young squadron of Enders switching between live and simulated versions of a military engagement may not be that far off.