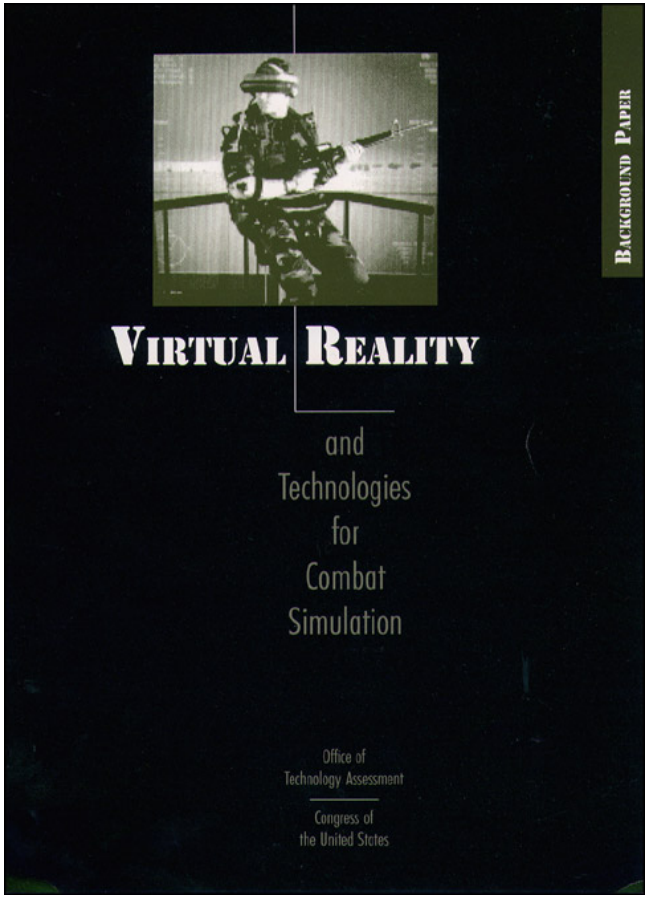
Virtual Reality and Technologies for Combat Simulation

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Foreword

Virtual reality (VR) is the popular name for an absorbing, interactive, computer-mediated experience in which a person perceives a synthetic (i.e., simulated) environment by means of special human-computer interface equipment and interacts with simulated objects in that environment as if they were real. Several persons can see one another and interact in a shared synthetic environment, such as a synthetic battlefield. For over a decade the Department of Defense (DOD) has been developing and expanding virtual battlefields to be used both for training and to develop combat systems and doctrine. This background paper describes applications of synthetic-environment technologies in simulating combat. It traces technology development from the 1929 Link Trainer through the SAGE air defense system, the first head-mounted display, and the Defense Advanced Research Projects Agency's SIMNET simulator networking project.

Synthetic-environment technology is dual-use. Research funded by DOD seeded the field; now there is a large commercial market, and DOD is actively exploiting the dynamism and efficiency of that market. Advances in synthetic-environment technologies such as computer image generation are reducing the costs of cockpit simulators and facilitating other applications. This paper describes technical challenges and discusses issues of validation, standardization, scalability, flexibility, effectiveness, cost-effectiveness, and infrastructure.

This background paper is the first of several publications of the Office of Technology Assessment's (OTA'S) assessment of combat modeling and simulation, which was requested by Representatives Ronald V. Dellums (Chairman) and Floyd Spence (Ranking Minority Member) of the House Committee on Armed Services, Senators Sam Nunn (Chairman) and Strom Thurmond (Ranking Minority Member) of the Senate Committee on Armed Services, and Senators Jeff Bingaman (Chairman) and Bob Smith (Ranking Minority Member) of its Subcommittee on Defense Technology, Acquisition, and Industrial Base.

In undertaking this assessment, OTA sought the contributions of a wide spectrum of knowledgeable individuals and organizations. OTA gratefully acknowledges their contributions of time and intellectual effort. OTA also appreciates the help and cooperation of officials of the Department of Defense and the Department of Energy. As with all OTA publications, the content of this background paper is the sole responsibility of the Office of Technology Assessment and does not necessarily represent the views of our advisors or reviewers.



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Contents

Focus: High-Tech Combat Simulation 2

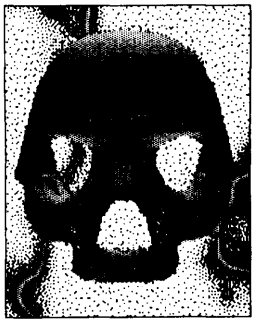
Why Congress Cares 4

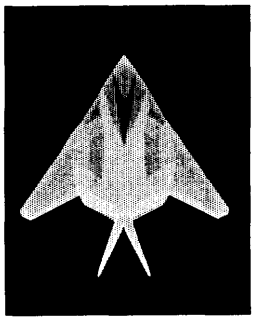
Milestones in Simulation Technology 5
Link Trainers (1929) 7
The Whirlwind Computer (1946) and the SAGE Air Defense System (1958) **9**
The ''Sword of Damocles'' Head-Mounteded Display (1966) 10

Virtual Reality 11
Types of VR Systems 12
Cockpit Simulators 13
Image Generators 14
Manipulation and Control Devices 15
Position Tracking **16**
Stereo Vision 17
Head-Mounted Displays 18
Haptic Transducers 20
Degrees of Virtual Reality 22
Shared Virtual Reality **23**

Observations 24
Synthetic Environment Technology Is Dual-Use **24**
Cost-Effectiveness Is Increasing **25**

Challenges 26
High-Density, Color Flat-Panel Displays **26**
Fast Head Tracking **26**
Wideband Networks With Low Latency **27**
Multilevel Network Security **27**
Automating Object and World Description for Scene Generators **27**
Simulating Infantry and Noncombatants **28**







Issues 30
Validation **30**
Standardization **31**
Scalability **32**
Flexibility **33**
Effectiveness 34
Cost-Effectiveness 34
Infrastructure 34

References and Bibliography 37

APPENDICES

A Acknowledgments 47

B Glossary of Acronyms 49

Virtual Reality and Technologies for Combat Simulation

Virtual reality (VR) is the popular name for an absorbing, interactive, computer-mediated experience in which a person, or persons, perceives and interacts through sensors and effecters with a synthetic (i.e., simulated) environment, and with simulated objects in it, as if it were real. The experience is characterized by inattention to the artificiality of the experience. The experience is provided by sensory stimuli generated by special human-computer interface (HCI) systems in response to the user's movements or speech, which are detected by other interface systems and interpreted by computer.

HCI systems have become the visible symbols of VR. The most distinctive system is the head-mounted display (HMD), which monitors the position and orientation of the wearer's head and displays a view (and might generate sounds) of an artificial world from that perspective. Another distinctive system is the glove-input device, which monitors the position and orientation of the wearer's hand and the flexure of each joint, so that the display can show the wearer's hand, and the computer can interpret hand gestures as commands[1] or sense whether the wearer is attempting to push a button or flip a switch on a control panel that the wearer sees in a display. An advantage of these HCI devices is their versatility. In principle, a simulator equipped with an HMD and a glove-input device could serve, in successive sessions, as a fighter cockpit simulator, a ship's bridge simulator, and a tank turret simulator—if appropriate software and databases were available.



[1] For example, a pointing gesture may mean "fly in this direction!"

However, in none of these applications does the combination of an HMD and a glove-input device yet offer the realism provided by the best instrumented cockpit mock-up with out-the-window computer image generation. Virtual (or synthetic) environment technology-the technology of VR-evolved from aircrew training devices (ATDs) such as the Link Trainer, which was introduced in 1929. Cockpit and cab simulators still provide the most realistic, absorbing experiences and are used for entertainment as well as training and research-just as Link Trainers were.

"Desktop VR" systems use more familiar HCI equipment—a monitor, a keyboard, and a mouse. These HCI systems are important because they are so pervasive—not only in the civil sector (homes, schools, business, government), but also in the military. Desktop VR may have the greatest near-term impact on improving American education and productivity through VR. It may enable most Americans to visualize, manipulate, and interact with computers and extremely complex data in a simple, natural way. This could be useful in military applications such as acquisition management and intelligence analysis.

In opening the 1991 Senate hearing on VR, Senator Albert Gore said "virtual reality promises to revolutionize the way we use computers. . . . It has the potential to change our lives in dozens of ways [70]."[2] A witness, Thomas A. Furness, III, a pioneer of military applications of VR, testified:

> Instead of using highly coded, highly complex interfaces like you have to program a VCR, or the old type of fighter cockpit, we want to go back to the basics of how humans work, realizing that we are three-dimensional beings. We see things and hear things and touch things in three dimensions [65].

This background paper describes demonstrated and potential applications of VR technologies to combat simulation for training and for development of combat systems and doctrine. It traces the development of VR technology from the 1929 Link Trainer, an aircrew training device ("flight simulator"); through digital flight simulation; through the Semi-Automatic Ground Environment (SAGE) air defense system, which immersed radar operators and weapon controllers in virtual air combat; to the first HMD, begun in 1966 with the aim of immersing the wearer in a virtual *visual* environment.

VR technology is dual-use. Research funded by the Department of Defense (DOD) seeded the field; now there is a large commercial market, and DOD is actively exploiting its dynamism and efficiency. As system performance improves and prices decline, many new military and commercial applications are becoming cost-effective. Advances in particular VR technologies, such as computer image generation, are applicable in cockpit simulators and other applications that purists do not call "VR."

Hardware challenges include the development of high-density, high-brightness, high-contrast color displays (especially lightweight flat-panel displays); fast head trackers; and wideband networks with high availability and multilevel security. Automating object and world description for scene generators and simulating infantry and noncombatants are also technical challenges. This paper describes these challenges and discusses issues of validation, standardization, scalability, flexibility, effectiveness, cost-effectiveness, and infrastructure.

FOCUS: HIGH-TECH COMBAT SIMULATION

This background paper is the first of several publications planned to document the results of the Office of Technology Assessment's (OTA's) assessment of combat modeling and simulation. Only incidentally does OTA's assessment consider simulation of military activities other than combat, such as logistics, nor does it investigate engineering simulations used in the development

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of military equipment or simulations used in scientific research for military applications. Such simulations are important, and their results are used in the design, acquisition, and operation of combat simulations. However, they are beyond the scope of OTA's assessment. This white paper focuses on *high-tech* human-machine simulation—i.e., simulation using computer hardware, software, and human-computer interface technologies that provide qualitatively new capabilities or improvements in quantitative measures of performance. It focuses particularly on their application to virtual reality, which poses the greatest demands on performance.

DOD Directive 5000.59 defines *simulation* as:

> . . . a method for implementing a model over time. Also, a technique for testing, analysis, or training in which real-world systems are used, or where real-world and conceptual systems are reproduced by a model.

The directive defines *model* as:

> . . . a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process [191].

The phrase "over time" in the definition of simulation is important: a simulation represents a system, entity, phenomenon, or process that changes with time; it implements a dynamic model and predicts (although it may not display) a history of intermediate conditions ("states") that are expected to occur over the span of time between the initial condition and the final time. Not all models are dynamic; some combat models predict which side will win a battle, or how many soldiers and vehicles will survive, based on the numbers and types of units committed to battle when it begins, without predicting how the situation will change during the battle. Simulations, in contrast, predict how an initial situation will change during a battle. Some simulations do this automatically. Others use human participants to make decisions and plans, issue orders, operate sensors, or pull triggers; these were formerly called *man-in-the-loop* simulations and are now called *human-machine* simulation or, if no computer is involved, *human-centered* simulations in accordance with Institute of Electrical and Electronic Engineers (IEEE) Standard 610.3 [96]. Human-machine or human-centered simulations of combat are sometimes called *wargames.*

Simulation of combat by moving paper counters (or more elaborate models) representing soldiers, companies, or battalions over map boards or sand tables is still done for recreation, but in professional military education such games have been largely superseded by computer-mediated wargames, in which computers act as fast, reliable data banks and as referees.[3] Current trends include:

1. the networking of such computers in growing numbers to simulate—and to involve as participants—larger forces over larger areas in greater detail;
2. continued growth in the information storage capacity and processing speed per processor, per computer, and per dollar; and
3. the use of ever more sophisticated HCI technology, such as HMDs with head trackers and digital three-dimensional (3-D) sound synthesizers.

The newest of these technologies were introduced almost three decades ago, but continuing advances in microelectronics and other technologies have made them useful, affordable, and cost-effective for some training tasks. Further advances promise to make computer-mediated simulation cost-effective for additional training tasks.

Human-machine simulation of combat is used not only for training but also for research-+. g., to assess the effectiveness of proposed tactics or weapons. However, it would be prohibitively expensive to assess the effect of, say, a proposed corps surveillance system under 1,000 different conditions by putting a corps's personnel in simulators for 1,000 exercises. Such analytical tasks

[3] Cf. [153], p. 152, which shows U.S. Army forces engaged in a sand-table exercise during Operation Desert Stem.

are usually accomplished by *computer-based* (or, synonymously, *machine-centered)* simulation, which simulates human behavior along with other dynamic processes. This allows the simulation to run much faster than real time, so the research may be completed quickly and inexpensively; it requires neither human participants nor HCI systems. However, the validity of the results depends on the validity of the model of human behavior that is implemented by the simulation. This is not anew issue [161], and it is not a hardware issue; it will be treated in depth in the final report of this assessment.

WHY CONGRESS CARES

Congress authorizes and appropriates funds for development, testing, evaluation, procurement, operation, and maintenance of simulation equipment and therefore has a direct interest in how those funds are spent. In addition to the funds authorized and appropriated specifically for simulation technology development programs and procurement of simulators, an indeterminate fraction of what DOD spends for operations and maintenance is spent on combat simulation, as is an indeterminate fraction of what DOD spends for research, development, testing, and evaluation (RDT&E). How much is spent depends partly on the expansiveness of the definition one uses. For example, General Paul Gorman, USA-Ret., Chairman of DOD's Simulation Policy Study, testified in 1992 that "all tactical training short of combat itself is a simulation" [72]. The 1993 report of the Defense Science Board Task Force on Simulation, Readiness, and Prototyping went a step further by stating "everything is simulation except combat" [196]. However, these expansive definitions are not used in most estimates of spending. According to one estimate, DOD spends about $2.5 billion per year on simulation equipment and services [170], to say nothing of the pro rata share of the pay of military and other federal employees engaged in simulation activities.

The widespread and increasing use of simulation to evaluate developmental systems at acquisition milestones is of potentially greater significance. Decisions for all acquisition category I programs are based partly on cost and operational effectiveness analyses (COEAs), which use models, and often simulations, to predict how candidate systems would perform in service—e.g., combat. Much is staked on the validity of those models and simulations. Some force employment decisions are also informed by simulation results.

DOD's Advanced Research Projects Agency (ARPA) is undertaking to allow simulation and virtual reality to play an even greater role in system acquisition (as well as training, logistics, and operations) with its Simulation-Based Design (SBD) program:

> SBD will integrate computer and information science technology developments such as advanced visualization techniques, high bandwidth networks, human/computer interaction, and massive database management to develop a revolutionary design environment for the acquisition of complex systems [181].

In 1993 ARPA awarded a $1 .4-million contract for research on a Simulation-Based Design System (SBDS) [175] and later solicited proposals to develop specific technologies (including virtual environment technologies) required for an SBD system to completely integrate ship design, acquisition, and support processes [178]. This year (1994), ARPA solicited proposals to "develop and demonstrate a Simulation-Based Design . . . system." ARPA anticipates that:

> . . . the requirements for a SBD system, having the capabilities stated above, would include: . . . an open, scalable architecture with a distributed computing structure; . . . multilevel security; . . . multiple personnel immersion capability in the synthetic environment, where participants may be physically remote; . . . synthetic environment graphical display rates of 30 frames per second and polygonal representations of models as large as 10 million polygons displayed from a database of greater than 10 billion polygon models; . . . network capable of greater than 1 gigabit/see; . . . Analysis capabilities including

models with as many as one million degrees of freedom [18 1].

If the effort succeeds in revolutionizing the design and acquisition of complex military systems such as ships, its fiscal impact could overshadow its direct cost.[4]

Members and committees of Congress, including the requesters of this assessment, have shown persistent keen interest in the potential of advanced simulation technology, not only for combat simulation but for other purposes as well. At a 1992 hearing on advanced simulation technology [173], members of the Senate Committee on Armed Services questioned DOD witnesses about:

- the limits of substitutability of virtual simulation for live simulation (e.g., training exercises),
- the prospect for modeling political and economic processes to make simulators for crisis management training,
- the use of simulators for command and staff training and for better training of National Guard units,
- the funding requirements for a rational investment strategy, and
- the potential for technology transfer to the civil sector, particularly the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), and education.

Similar questions were raised at the 1991 hearing on virtual reality before the Subcommittee on Science, Technology, and Space of the Senate Committee on Commerce, Science, and Transportation [172]. Questions and testimony concerned the dual-use applications and benefits of this very rapidly developing technology, requirements for U.S. competitiveness in the virtual reality marketplace, and potential benefits of applications of the technology in other sectors such as manufacturing, medicine, education, and entertainment, as well as defense.

Human-computer interaction is one of six "priorities . . . identified by the NSTC (National Science and Technology Council) Committees as needing new or additional emphasis in FY 1996" to help achieve the Administration's goal of harnessing information technology-one of the six FY 1996 research and development goals articulated by the President's Science Advisor and the Director of the Office of Management and Budget in their May 6, 1994, Memorandum for the Heads of Executive Departments and Agencies [69]. It said, "Development and use of the following should be advanced: virtual reality; simulation; flat-panel displays; video and high-definition systems; 3-D sound, speech interfaces, and vision."

MILESTONES IN SIMULATION TECHNOLOGY

Many techniques and technologies used in state-of-the-art computer-based simulation and human-computer simulation have been around for decades (see table l-l). In this section we review Link Trainers, introduced in 1929; the Whirlwind computer, begun in 1946 for digital flight simulation and eventually used as a technology demonstrator for the SAGE air defense system; and the first head-mounted display (HMD) for computer-generated imagery, begun in 1966. Many new technologies have been introduced since then, but the most obvious novelty is the detail and speed with which virtual visual scenes may be synthesized digitally and displayed. The use of digital, rather than analog, optical, or mechanical, techniques facilitates the networking of simulators, which is very recent and significant.

4 The program was funded for $3 million in FY 93 and for $9.074 million in FY 94. The President's Budget Contains funding for the Program through FY 98: $15.77 million in FY 95,$15.28 millioninFY96,$16.11 million in FY 97, and $20.15 million in FY 98 [182].

TABLE 1-1: Milestones in Technology for Combat Simulation

1929	First Link Trainer,
1931	Navy buys a fully instrumented Link Trainer for $1,500.
1934	Army buys six Model A Link Trainers for $3,400 each.
1943	Development of the Electronic Numerical Integrator and Calculator (ENIAC) is begun at the University of Pennsylvania to calculate artillery range tables by simulating the flight of artillery shells.
1945	ENIAC performs calculations for hydrogen bomb development.
WW II	Airplane Stability Control Analyzer (ASCA) is begun at Massachusetts Institute of Technology (MIT) for the Navy, intended for engineering simulation, experiential prototyping, and training,
1946	Jay Forrester begins building a digital computer, later named Whirlwind, for ASCA, Whirlwind was later used for the Air Force's Cape Cod System, a technology demonstrator for the Semi-Automatic Ground Environment (SAGE) air-defense system.
1946	ENIAC is publicly announced.
1949	Link Co. presents the Air Force with a sales brochure citing experiments comparing effectiveness of flight simulation to flight training and estimating savings in dollars, man-hours, and lives.
1949	Link Co. wins an Air Force contract to develop first simulator for a jet, the F-80.
1949	Digital Radar Relay (DRR) transmits data from Microwave Early Warning (MEW) radar at Hanscom Field to the Air Force Cambridge Research Center by telephone line using modems at 1,300 bits per second.
1950	MEW radar sends data to Whirlwind computer using DRR.
1953	Cape Cod System is used in live simulations, directing Air Defense Command and Air Research and Development Command interceptors against Strategic Air Command bombers acting as hostile aircraft. Cape Cod System is also used in virtual simulations, with computer-generated simulated targets presented to surveillance operators and weapon controllers.
1958	First Air Force SAGE center is operational.
1950s	SAGE air defense system is used for mixed live and virtual simulation,
1965	Ivan Sutherland presents his seminal conference paper, "The Ultimate Display, " articulating the vision of virtual reality.
1966	Ivan Sutherland begins developing the first head-mounted display (the "sword of Damocles") at MIT's Lincoln Laboratory and continues at the University of Utah.
1968	Evans and Sutherland, Inc., is founded to create electronic "scene generators, "
1972	General Electric builds the Advanced Development Model (ADM) for the U.S. Navy to measure the effectiveness of computer image generation for pilot training,
ca. 1973	Computers rendered scenes composed of 200 to 400 polygons at 20 frames persecond. This was adequate for pilot training-e.g., simulating night approaches to landing on an aircraft carrier. Studies showed that pilot performance suffered at slower frame rates.
1976	Myron Krueger demonstrates VI DEOPLAC E (two-dimensonal) and coins term "artificial reality. "

TABLE 1-1 continued: Milestones in Technology for Combat Simulation

1980	McDonnell-Douglas Aircraft Corp. develops a helmet with magnetic head tracking and see-through HMD for its Virtual Image Takeoff and Landing (VITAL) F-18 aircraft cockpit simulator.
1982	Thomas Furness III demonstrates Visually Coupled Airborne Systems Simulator (VCASS) at the Air Force's Wright Laboratories. The HMD used a Polhemus six-dimensional magnetic tracker and custom 1-in, diameter monochrome cathode-ray tubes (CRTs) with 2000 scan lines, which provided more detail than anything commercially available even today.
1983	Defense Advanced Research Projects Agency (DARPA) begins Simulator Network (SIMNET) project.
1984	Michael MacGreevy and Stephen Ellis of NASA's Ames Research Center build the Virtual Visual Environment Display (ViVED, pronounced vivid), the first $2,000 head-mounted display.
1986	The Air Force funds phase 2 of VCASS: "Super Cockpit. " Voice command recognition and voice response plus three-dimensional synthetic audio environment added.
1987	SIMNET has about 250 simulators fielded.
1991	University of North Carolina computer renders scenes at 1 million untextured polygons per second or 200,000 textured polygons per second.
1992	Virtual Cockpit project begins at the U.S. Air Force Wright Laboratories.
1993	Institute of Electrical and Electronic Engineers issues IEEE Standard 1278-1993 (DIS protocol).
1994	Kaiser Electro-Optics, Inc., offers the SIMEYE ™60 HMD, providing 1,024 interlaced color scan lines, for $165,000.
1994	1,000 entities (vehicle simulators, etc.) are netted for Synthetic Theater of War (STOW) exercise.
1997	Synthetic Theater of War goal is 100,000 entities.

I Link Trainers (1929)

The development of Link Trainers led to digital flight simulation and then to distributed human-computer digital combat simulation. The marketing of Link Trainers is also of interest, because it used cost-effectiveness analyses based on experiments to gauge the transfer of learning in aircrew training devices (ATDs) to proficiency in the cockpit.

Lloyd Kelly's book, *The Pilot Maker* [1 10], contains many passages about the substitutability of Link Trainer time for flight time, for example:

> Ed [Edwin A. Link] taught his brother George to fly with only forty-two minutes of actual flight time, after George had taken a concentrated six-hour course in the trainer.
>
> .Casey [Charles S. Jones] was deeply impressed with the young man (Edwin A. Link) from Binghamton, who would teach people to fly up to first solo for eighty-five dollars. It was costing Casey at that time over two hundred dollars to accomplish the same task.

Kelly also quotes the New York *Herald Tribune* as printing in 1933:

> This system [the Link Trainer] does not purport to turn out a finished "blind" flier without the necessity of actual time in the air at the controls and behind the instrument board of a real airplane, but its sponsors do claim that it will shorten the essential air training by more than 50 per cent. They maintain that 15 hours of the new style "hangar flying" and five hours in the

> school's blind flying training plane will result in a proficiency equivalent to that obtained by 25 hours' blind flying instruction on an all-airplane basis, which has been the average time required to qualify America's airline pilots in this highly specialized field.

The first fully instrumented Link Trainer was sold to the Navy in 1931 for $1,500. By mid-1932 it was still the only fully instrumented trainer that had been sold, still the only one sold to the military, and one of only three sold to the "aviation industry": one had been sold to the Pioneer Instrument company to demonstrate the turn and bank indicator, the airspeed indicator, and the magnetic compass; another had been sold to a museum. But by mid-1932, almost 50 had been sold, at cost ($300 to $500), for use in amusement parks. This demand trend contrasts with that for non-cockpit "virtual reality" systems (described below), which were first developed largely by the government for military and space-related use, with entertainment-related demand now growing rapidly, about three decades later.[5]

When the Post Office canceled all airmail contracts in 1934 and asked the Army Air Corps to fly the mail, the Army soon discovered it would need to train its pilots to fly on instruments and recognized the value of the Link Trainer as a training aid, but had no money to purchase them. Edwin Link and "Casey" Jones lobbied Congressman Howard McSwain, Chairman of the House Military Affairs Committee, who promised cooperation, with the result that an emergency appropriation was passed by both houses of Congress and signed by the President on March 28, 1934. Less than three months later, on June 23, the Army took delivery of its first six Link Trainers, Model A's, for which it paid $3,400 each. Sales to Japan, the Soviet Union, and other countries followed, and many new types of trainers were developed and sold to the Army and the Navy during World War II.

These were later estimated to have saved the Army Air Force "at least 524 lives, $129,613,105, and 30,692,263 man-hours. . . in one year," and to have saved the Navy "a potential total savings of $1,241,281,400 in one year," according to "a report . . . to the Subcommittee of the Committee on Appropriations of the United States House of Representatives" quoted by Kelly.

Nevertheless, there was a postwar slump in ATD sales, as well as competition. Researcher Stanley Roscoe later wrote that "in 1949 Edwin A. Link was building more canoes than flight trainers" [58]. The fortunes of the company turned around in 1949, when the Link Co. won the Air Force contract to build a simulator[6] (the C- 11) for the F-80 jet fighter. Not only was this the first simulator of a jet airplane, it also used analogue electronic computer technology.[7] Roscoe attributed the company's success to a sales brochure written by Paul Dittman, a graduate student, summarizing the results of experiments in the effectiveness of transfer of training from simulator to airplane.

Details of these experiments, which were conducted by Ralph Flexman, were not published until 1972. Flexman wrote: "On all exercises an hour

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[5] The Department of Commerce's *Industrial Outlook* 1994 states that, as of 1993, most virtual reality applications were entertainment-oriented [174]. However, this accounting counts *applications* (i.e., types of computer programs), not sales volume in dollars, and it appears to exclude cockpit simulator applications, for which there is a large non-entertainment demand from the military and the airlines.

A recent forecast by 4th Wave, Inc., projects worldwide nongovernmental demand for virtual reality hardware, software, and services to grow from $115.8 million in 1994 to $569.9 million in 1998. Consumer sales, public play, and entertainment equipment purchases by operators of public play installations are expected to amount to 57.2% of the 1994 total and 69.1 % of the 1998 total [1,120]. Aircrew training devices were not counted as VR systems.

[6] Around this time, Curtiss-Wright sought unsuccessfully to trademark the words "simulation" and "simulator," and Link Aviation sought to protect the term "Link Trainer," after competitors began establishing "link trainer" departments [110]. General Precision Equipment Corporation acquired Link Aviation in 1954 and merged with The Singer Company in 1%8 [ibid.] to form Singer-General Precision, Inc., which registered the trademark "LINK Trainer" [139] in a further effort to protect product identity.

[7] Three years earlier, Jay Forrester had begun building a digital computer for the Navy's Airplane Stability Control Analyzer.

of training in the Link was equivalent to no less than a half hour in the aircraft, and for slow-flight training an hour in the Link equaled an hour in the air" [58]. This does not imply that simulator training could replace all flight training on a two-for-one basis. The marginal substitutability of simulator training for flight training may (and probably does) vary with the ratio of simulator training time to flight training time at which substitutability is assessed, the total amount of training, and the particular tasks that are taught in the simulator.

Summarizing the research, Roscoe wrote [58]:

> *The measurement of [training] transfer is a complex business.* . . . [Simulator training in one flight maneuver transfers not only to its airborne counterpart; it transfers to other similar maneuvers performed either in the simulator or in the airplane, as does training in the airplane itself. Furthermore, training in one aspect of the overall flight task, say verbal communication, may appear to transfer to another quite different aspect, say motor coordination, simply because the early mastery of the first may thereafter allow the student to concentrate more on the second. . . .
>
> One consistent result was that instrument flight training produced less transfer . . . than did contact flight training [i.e., by visual reference to the ground and horizon] . . . .
>
> In general, procedural tasks, such as starting the airplane, resulted in more effective transfer . . . than did psychomotor skills, such as level turns. . . . Apparently higher transfer occurs with procedural tasks than with psychomotor tasks because the former are less adversely affected by the imperfect simulation of such dynamic factors as physical motion, visual and kinesthetic cues, and control pressures.
>
> . . . [Opportunity for the transfer of new learning diminishes as a pilot masters more and more elements common to various tasks. . . .
>
> *Further research is needed. This* perennial plea of the scientific community applies to the whole field of educational strategy, not only to the training of pilots. It is strikingly notable, however, that vast sums are invested in new and innovative pilot training devices and programs in the virtual absence of experiments providing quantitative estimates of relative transfer effectiveness attributable to the variable characteristics of the devices and training strategies employed.

Surprisingly, simulated instrument flight training was found to produce less transfer than simulated contact flight training. Because it is easier for a simulator to realistically simulate instrument conditions (e.g., zero visibility) than the visual scene that a pilot would see in clear weather, one would expect the opposite to be true. Roscoe speculated that simulated instrument-flight training produced less transfer than did simulated contact-flight training because pilots generally learn contact flying before learning instrument flying. Hence by the time a pilot begins instrument training, he or she has already learned the basic flying skills, which are also used in instrument flying. Thus the phenomenon is consistent with the other conclusion that "opportunity for the transfer of new learning diminishes as a pilot masters more and more elements common to various tasks." That is, in economic jargon, there are diminishing returns to scale as one invests more in training, either in a simulator or a cockpit.

The quantitative data that these conclusions summarize were collected only after the simulators were built. It is difficult to imagine how transfer effectiveness (or savings or averted cost) could have been estimated objectively or measured accurately before both a simulator and the system that it simulates were available for experimentation. The advent of electronic (especially digital) simulators has made it possible to vary simulator parameters, such as display detail and frame rate, in order to see how decreasing them would degrade learning and performance of specific partial tasks (e.g. approach to landing) in the simulator and transfer of proficiency to actual flight operations.

The Whirlwind Computer (1946) and the SAGE Air Defense System (1958)

The use of the ENIAC in 1945 to simulate aspects of a thermonuclear detonation and, later, to simulate the flight of artillery shells [87] were the first

uses of an electronic digital computer to simulate details of combat. However, the first use of a digital computer to simulate combat as it would be perceived by one or more combatants probably occurred in the development of the Air Force's Semi-Automated Ground Environment (SAGE) air-defense system. The SAGE system evolved from a Navy flight simulator development program, the Airplane Stability Control Analyzer (ASCA) program, which began during World War II. In 1946, Jay Forrester, of the Massachusetts Institute of Technology (MIT), persuaded the Navy to use a digital computer instead of an analog computer for ASCA, and he began building one, called Whirlwind, at MIT. In 1949 the Soviet Union detonated an atomic device, and the U.S. Department of Defense became more concerned about improving air defenses. MIT, a leading developer of radar systems in World War II, became involved, as did Whirlwind. In 1950 digital radar data were transmitted from the Microwave Early Warning (MEW) radar at Hanscom Field in Bedford, Massachusetts, to Whirlwind at MIT in Cambridge, Massachusetts.

By 1953, the Cape Cod System, a scaled-down technology demonstrator for SAGE, was demonstrating what is now called virtual human-machine distributed interactive simulation, in which radar operators and weapon controllers reacted to simulated targets presented to them as real targets would be in war. This was relatively easy to do, the human-computer interface being a radar screen. Presenting a tank gunner or a fighter pilot with a detailed, rapidly changing *visual* scene required further decades of advances in computer image generation (CIG) technology.

By 1955, the Air Force had contracted with the RAND Corp. to develop the System Training Program (STP) for SAGE. As John F. "Jake" Jacobs, an architect of SAGE, recounts:

> One of the features of SAGE was the extensive use of simulation programs and operational testing aids; the STP program created simulated airplanes by signals entered into the system at the radar sites. These and other simulated inputs were integrated so as to create a simulated scenario against which the operators could direct intercepts and be scored on their performance. Dave Israel pushed for a battle simulation program with the [SAGE] direction center and internal to the FSQ-7 [digital computer]. In this system, an internal program simulated airplane signals that could be mixed with live signals generated by real aircraft. The simulation was an extremely useful feature and was coordinated with the STP design.

The SAGE system later pioneered the networking of two collocated computers, for reliability, and eventually the networking of remote computers for distributed computing, including distributed interactive live and virtual simulation.

The "Sword of Damocles" Head-Mounted Display (1966)

Development and integration of an assortment of technologies to provide (or approximate) the experience now called *virtual reality* is more recent than the development of Link Trainers and the SAGE system. Much of the vision of virtual reality was articulated by Ivan Sutherland of DOD's Advanced Research Projects Agency (ARPA) in a conference paper, "The Ultimate Display," read and published in 1965. He proposed the use of eye trackers and many other innovations:

> Machines to sense and interpret eye motion data can and will be built. It remains to be seen whether we can use a language of glances to control a computer. An interesting experiment will be to make the display presentation depend on where we look.

The following year, at MIT's Lincoln Laboratory, he began developing the frost head-tracker-controlled head-mounted display (HMD), now the trademark, if not *a sine qua non,* of virtual reality. Later in 1966 he joined the University of Utah, where he continued refining the hardware and software until it was functional on New Year's Day in 1970 [41] (cf. [17]). The heavy HMD was suspended from the ceiling by a gimballed mechanical apparatus equipped with electromechanical sensors that determined the direction in which the "wearer" was looking, so that the computer could generate the image of the virtual world that the wearer should see. The assembly's precarious

mounting over the user's head led to its being called the "sword of Damocles." The best modem HMDs are much lighter. They, and the CIG hardware and software that feed them imagery, provide imagery vastly more detailed and realistic than the wire-frame imagery displayed by Sutherland's first HMD.

VIRTUAL REALITY

Much of the material in this section (up to **Observations)** that is not otherwise attributed has been excerpted or paraphrased from a popular electronic text by Jerry Isdale [98].

The term virtual reality (VR) means different things to different people. To some, VR is a specific collection of technologies—a head-mounted display, a glove-input device and an audio synthesizer. Some other people stretch the term to include books, movies, or unaided fantasy. We view VR as an interactive, usually computer-mediated, experience characterized by a suspension of (or inattention to) disbelief in the unreality of the experience.

A good film or novel maybe so engaging as to cause most viewers or readers to suspend disbelief in the unreality of the vicarious experience, but the experience is neither interactive nor computer-mediated and hence is not usually considered VR. However, flying an analog (rather than digital) airplane cockpit simulator that generated imagery by moving a video camera over a model board could be VR. A recent NASA report offered this definition:

> Virtual reality is the human experience of perceiving and interacting through sensors and effecters with a synthetic (simulated) environment, and with simulated objects in it, as if they were real [137].

The book *Silicon Mirage [8]* defines "virtual reality" as "a way for humans to visualize, manipulate and interact with computers and extremely complex data."

Here visualization refers to the computer generating visual, auditory or other sensory outputs to the user of a world within the computer.

This world may be a computer-aided design (CAD) model, a scientific simulation, or a view into a database. The user can interact with the world and directly manipulate objects within the world. Some worlds are animated by other processes, perhaps physical simulations, or simple animation scripts. Interaction with the virtual world with at least near-real-time control of the viewpoint is usually considered an essential element of virtual reality. Some definitions require the view of the world to be three-dimensonal; they exclude Lucas Film's Habitat and Club Caribe [149], Fujitsu Habitat [149], the DIASPAR ™ Virtual Reality Network [42], and the online surrogate travel demonstration [146] at the National Institute for Standards and Technology, all of which use two-dimensonal (nonperspective) graphical presentations,[8] but other definitions would include them. There is more than a spectrum of virtual reality—there are several dimensions of virtual reality, and experiences have varying degrees of each.

Some people object to the term "virtual reality," saying it is an oxymoron. Other terms that have been used are Synthetic Environments, Cyberspace, Artificial Reality, Simulator Technology, etc. VR is the most common. It has caught the attention of the media.

The applications being developed for VR span a wide spectrum, from games to architectural and business planning. Many applications are worlds that are very similar to our own, like CAD or architectural modeling. Some applications, such as scientific simulators, telepresence systems, and air traffic control systems, provide views from an advantageous perspective not possible with the real world. Other applications are very different from anything most people have ever directly experienced before. These latter applications maybe

[8] The DIASPAR™ Virtual Reality Network also offers a three-dimensional virtual world, the Polygon Playground, that can be shared by two users.

the hardest and most interesting: visualizing the ebb and flow of the world's financial markets, navigating a large corporate information base, etc.

Types of VR Systems

VR systems maybe categorized according to their user interfaces. This section describes some of the common modes used in VR systems.

Cockpit (or cab) simulators are the oldest, most mature, and-for many important military missions—most realistic VR systems. They evolved from the Link Trainer of 1929 and the Navy's Airplane Stability Control Analyzer (ASCA) of World War II.

Some systems use a conventional computer monitor to display the visual world. This is often called *desktop VR* and has been called a window on a world (WOW) [98]. This concept traces its lineage back to Ivan Sutherland's 1965 paper, "The Ultimate Display" [162].

A variation of the WOW approach merges a video input of the user's silhouette with a two-dimensional computer graphic. The user watches a monitor that shows his body's interaction with the world. Myron Krueger has been a champion of this form of VR since the late 1960's. At least one commercial system, the Mandala system, uses this approach. This system is based on a Commodore Amiga with some added hardware and software. A version of the Mandala is used by the cable TV channel Nickelodeon for a game show (Nick Arcade) to put the contestants into what appears to be a large video game.

The ultimate VR systems completely immerse the user's personal viewpoint inside the virtual world. These "immersive" VR systems are often equipped with a head-mounted display (HMD). This is a helmet or a face mask that holds the visual and auditory displays. The helmet may be free ranging, tethered, or it might be attached to a boom.

One type of immersive system uses multiple large projection displays to create a room in which the viewer(s) stand. An early implementation was called "The Closet Cathedral" for the ability to create the impression of an immense environment within a small physical space. A more recent implementation is the CAVE Automatic Virtual Environment (CAVE) at the Electronic Visualization Laboratory of the University of Illinois at Chicago [32]; it has been so highly publicized that the term "cave" is now being used to describe the generic technology. A futuristic extrapolation of the technology is the "Holodeck" used in the television series "Star Trek: The Next Generation."

Telepresence is a variation on visualizing complete computer-generated worlds. This technology links remote sensors in the real world with the senses of a human operator. The remote sensors might be located on a robot, or they might be on the ends of waldo-like tools. (A *waldo is* a hand-like tool that mimics the motions of a user's hand. The term was coined by Robert A. Heinlein in his 1942 science-fiction story "Waldo" [82].) Firefighters use remotely operated vehicles to handle some dangerous conditions. Surgeons are using very small instruments on fiber-optic cables to do surgery without cutting a major hole in their patients. The cable carries light to the surgical site and guides light reflected by tissue thereto a video camera outside the body. The image is displayed on a video monitor which the surgeon observes while manipulating the instrument [3,179].

Robots equipped with telepresence systems have already changed the way deep sea and volcanic exploration is done. NASA plans to use telerobotics for space exploration. There is currently a joint U.S.-Russian project researching telepresence for space rover exploration. Military uses of telepresence include guidance of the camera-equipped GBU-15 bombs that provided stunning TV scenes from the Persian Gulf war, unmanned aerial vehicles (also used in the Gulf War), and unmanned space and undersea vehicles.

Merging the telepresence and virtual reality systems gives the mixed reality or seamless simulation systems. Here the computer-generated inputs are merged with telepresence inputs and/or the user's view of the real world. A surgeon's view of a brain surgery is overlaid with images from

earlier computed axial tomography (CAT) scans and real-time ultrasound. A fighter pilot sees computer-generated maps and data displays inside his fancy helmet visor or on cockpit displays.

The phrase "fish tank virtual reality" has been used to describe a Canadian VR system that combined a stereoscopic monitor display using liquid-crystal shutter glasses with a mechanical head tracker. The resulting system is superior to simple stereo-WoW systems due to the motion parallax effects introduced by the head tracker.

Cockpit Simulators

Cockpit and cab simulators use a compartment-a mock-up, in engineering terminology-to enclose the user, whose out-the-window view of the virtual world is provided by either a directly-viewed display device, such as a cathode ray tube (CRT) monitor or a liquid-crystal display (LCD), or a projection screen on which imagery is projected from the front or rear. Many types of projection systems have been used, including projection CRTs and liquid-crystal light valves. Potentially applicable is the technology of the Digital Micromirror Device (DMD) developed by Texas Instruments with Defense Advanced Research Projects Agency (DARPA) funding [154].

Cockpit simulators have a history dating back to the Link Trainer introduced in 1929. The cockpit is often mounted on a motion platform that can give the illusion of a much larger range of motion. Bridge simulators, such as the Link CART (Collision Avoidance Radar Trainer) [110], are a variant that simulate the steering, and response, of a ship as it would be experienced from the bridge.

Cab simulators are used in driving simulators for locomotives,[9] earth-moving equipment,[10] trucks, tanks, and BattleMechs, the fictional walking tanks featured in Virtual World Entertainment's BattleTech Center in Chicago (which opened in 1990 [140]) and its 13 other Virtual World centers—six in the United States and seven in Japan. Each center has about 24 cockpit simulators (of several types—not just BattleMechs), which are being networked by CyLink™ long-haul links over Integrated Services Digital Network (ISDN) lines.[11]

Experts consider the best cockpit simulators to be more realistic and immersive than the best HMD-based systems, in the sense of engaging a subject's attention and suspending her or his awareness of simulation. Dave Evans of Evans and Sutherland, a pioneer in computer image generation for cockpit simulators as well as HMDs, has said that one pilot flying a Boeing 747 airplane simulator fainted when his virtual airplane hit a ditch on landing. Professor Frederick Brooks, quoting him, said that nothing so dramatic had happened to a trainee wearing an HMD [17]. HMDs do, nevertheless, provide realistic and sometimes threatening experiences. Some psychologists are using HMDs to give acrophobia subjects the impression of being in a high location, in order to identify sensory cues that produce physiologically measurable stress and design desensitization therapy [88,1 15,1 16].

A 1993 Air Force Institute of Technology Master's thesis rated domed aircraft cockpit simulators higher than HMDs in each of five "immersion" attributes (field of view, panorama,

9 The SD-45 locomotive simulator produced by the Link division of General Precision Equipment Corporation for the Santa Fe Railroad in the late 1960s had a number of interesting features, including a hydraulic motion-base platform, digitally-controlled electronically synthesized stereophonic sound (along with mechanically generated sound), and scenery projected from 16-mm film. "A unique lens mounted before the front window provided images up to infinity with realistic depth of field. This lens forced the viewer to refocus his eyes as he would in the real world when looking at varying distances" [1 10].

10 Caterpillar has developed a simulator that includes a real steering wheel, gearshift, levers, pedals, and other controls but relies on a HMD for visual presentation [41].

11 Virtual World Entertainment is not using the DIS protocol [97], because it wants the network to pass details of collisions (e.g., crashing into a cliff) that are valued by patrons for entertainment but for which DIS protocol data units (PDUs) have not been defined.

perspective, body representation, and intrusion) as well as in visual acuity, a "visualization" attribute [53]. Similarly, recent Center for Naval Analyses memorandum concluded that HMD technology was not yet sufficiently mature for application to strike training and mission rehearsal [210].

I Image Generators

A number of specialized types of hardware devices have been developed or used for virtual reality applications. One of the most computer-time-consuming tasks in a VR system is the generation of the images. Fast computer graphics opens a very large range of applications aside from VR, so there has been a market demand for hardware acceleration for a long while.

The simulator market has spawned several companies that build special-purpose computers and software for real-time image generation. These computers often cost several hundreds of thousands of dollars. The manufacturers include Evans and Sutherland, Inc.; the General Electric Co. (GE); Division, Ltd.; and Silicon Graphics, Inc. (SGI). Evans and Sutherland, Inc., was founded in 1968 to create electronic scene generators; it has sold scene generators for aircrew training devices to the airlines and the military and currently markets the ESIG-2000 graphics system for VR applications (including cab and cockpit simulators). SGI graphics workstations are some of the most common processors found in VR laboratories, including DOD simulators. SGI boxes range in price from under $10,000 to over $100,000. The latest is the scalable SGI Onyx Reality Engine.

There are currently several vendors selling image generator cards for personal computers. The cards range in price from about $2,000 up to $10,000. Many of them use one or more Intel i860 microprocessors. A recent offering in this class, by Division, Ltd., is the Merlin graphics card designed for IBM PC/AT-compatible computers.[12] There are two versions of the Merlin graphics card; both are a variant of Division's VPX graphics card (described below). One version of Merlin has the same architecture and performance as the VPX. The other version of Merlin is a depopulated board-i.e., it has fewer i860 microprocessors and hence is slower than the VPX and will cost less, although Division has not announced pricing as this background paper goes to press. Like the VPX, the Merlin card supports a variety of video formats, but with Merlin, software allows the user to select the desired format. VPX cards had 10 video output connectors-one per format-and the user would select the desired format by connecting a video cable to the appropriate connector. A fully populated Merlin card draws 19 amperes of current and generates more heat than can be safely dissipated in a typical PC/AT enclosure, so Division offers a separate enclosure with chassis and power supply for Merlin cards.

The VPX card, announced on Feb. 1, 1994 [46], uses the Pixel-Planes 5 rendering architecture developed by Professor Henry Fuchs at the University of North Carolina at Chapel Hill with funding from the National Science Foundation and later DARPA [172]. The Pixel-Planes architecture uses an array of processors-8,192 on the VPX board-to compute pixel data in parallel, with each processor dedicated to one or more pixels on the screen. This provides significant performance advantages, particularly where complex lighting and texture mapping is required on each pixel. Designed for Division's PROVISION 100 VR system and the original equipment manufacturer (OEM) market, the VPX is a single card that

12 Division also retails the PC dVIEW and MAC dVIEW image-rendering cards.

is compatible with the extended industry-standard architecture (EISA) bus. The card is capable of rendering up to 300,000 photo-textured,[13] *Gouraud-shaded,*[14] specularly lit polygons[15] and 300,000 spheres per second[16] at over 160 million pixels per second in a variety of formats with a maximum resolution of 1,024x768 pixels in synchronized stereo using multiple cards [44]. OEM prices for a single VPX board started at £12,000 when they were introduced [46]. Prices in the United States now start at about $21,000 [143].

Manipulation and Control Devices

A VR system must provide a means for its user to move around in the virtual world to explore; to select objects to be manipulated; and to grasp, carry, paint, throw, or drop them. The simplest control hardware is a conventional mouse, trackball, or joystick. Although these devices are normally used to control the position of a cursor in a two-dimensional (2-D) space (a monitor screen), creative programming can use them for six-dimensional (6-D) controls.[17]

There are a number of 3-D and 6-D mice, trackballs, and joysticks on the market. These have extra buttons and wheels that are used to control not just the translation of a cursor in the two dimensions of the screen (X and Y), but its apparent depth (Z) and rotation about all three axes (X, Y, and Z). The Global Devices 6-D Controller is one such 6-D joystick. It looks like a racquetball mounted on a short stick. A user can pull and twist the ball in addition to the left/right & forward/back of a normal joystick. Other 3-D and 6-D mice, joysticks, and force balls are available from Logitech, Mouse System Corp., and others.

A less common but more distinctive VR device is the instrumented glove. The use of a glove to manipulate objects in a synthetic environment was pioneered by Thomas Zimmerman at the Atari Research Center. In 1983, after leaving Atari, he began collaborating with Jaron Lanier, improving the design. Together they founded VPL Research, Inc., in 1985 and sold their first product, the DataGlove, to NASA. VPL was granted a U.S. Patent for the DataGlove and licensed Mattel to manufacture and sell an inexpensive version, called the PowerGlove, for use with home video games. In 1992 VPL sold the patent to Thomson-CSF of France [174].

The DataGlove is outfitted with sensors on the fingers as well as an overall position/orientation tracker. There are a number of different types of sensors that can be used. VPL Research, Inc., made several types of DataGloves, mostly using fiber optic sensors for finger bends and magnetic trackers for overall position. For a short time Mattel manufactured, under license, a related glove in-

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13 In computer graphics, a *texture* describes the pigmentation, reflectivity, transmissivity, and smoothness of a surface. This allows the creator of an *object file* (a digital description of an object or scene to be rendered) to specify very concisely that a surface is to look like polished aluminum, burlap, finished maple, or whatever. The rendering software chooses the color and brightness of each point in the picture (each picture element, or pixel) to achieve the specified effect. photo-texturing, also called image-map texturing, refers to the use of a digital image to generate a texture for an object surface. A related process, color-mapping, uses a digital image to generate the color or pigment pattern on an object's surface.

14 In *Gouraud shading*, a color value is calculated for each vertex of a polygon based on the polygon's orientation, the orientation of each polygon that shares the vertex, the pigmentation specified for the part of the object represented by the polygon, and the color of the light source. The color values for interior pixels of a polygon are interpolated from the color values of its vertices in order to yield a smooth shading effect. Rendering an object in this fashion takes longer than simply making all pixels of a polygon the same color, which is called *flat shading.*

15 A *polygon* is a plane figure bounded by straight line segments. Most *modeling programs* used to create object files specify the forms of objects in terms of polygons such as triangles; some also specify curvilinear shapes.

16 polygons per second (or poly-Hz) is a useful measure of performance for image-generating systems, because more complicated scenes (having more polygons) typically take longer to render, and the resulting frame rate (frames per second) is lower. The poly-Hz metric adjusts for scene complexity in characterizing rendering speed.

17 The more accurate phrase "six degrees of freedom" (6-DOF) is sometimes used instead. It refers to movement in three directions (for example, forward, right, and up) and rotation about three axes (for example, pitch, roll, and yaw).

put device—the PowerGlove-for use with the Nintendo game system. The PowerGlove is easily adapted to interface to a personal computer. It provides some limited hand location and finger position data using strain gauges for finger bends and ultrasonic position sensors. These data are used to display the user's hand correctly in the virtual world, and the computer can also be programmed to recognize several hand gestures and interpret them as commands, such as "fly forward." The gloves are getting rare, but some can still be found at Toys 'R' Us and other discount stores.

The concept of an instrumented glove has been extended to other body parts. Full body suits with position and bend sensors have been used for capturing motion for character animation, control of music synthesizers, etc., in addition to VR applications.

Some boom-mounted stereoscopic displays, such as the Binocular Omni-Orientation Monitor (BOOM, described below), require the user to grasp and steer the display unit with one or two hands, which makes it difficult to use a glove input device or a joystick to select and manipulate objects.[18] Buttons on the BOOM handgrips can be used to perform a limited set of software- and user-determined functions, but for convenience some systems, such as the Multi-Dimensional User-Oriented Synthetic Environment (MUSE™) [30,1 11,138] and the Virtual Interactive Environment Workspace (VIEWS™) [5] developed at Sandia National Laboratory, have been given a capability to recognize commands spoken by the user.

It is awkward for a BOOM or HMD user who is completely immersed in a virtual world (e.g., repairing a virtual jet engine in a training course) to enter commands to the computer system (e.g., requests for maintenance manual pages) by means of a keyboard. There are several potential solutions to this problem. One is to have the user type on a virtual keyboard using a glove input device. At present, glove input device gesture recognition is not discriminating enough to approach touch-typing speed and accuracy, and most glove input devices do not provide haptic feedback. An alternative is to use a chording keyboard, such as the KAT (Keyboard-Alternative Technology) keyboard by Robicon Systems, Inc., that the user holds or wears in the palm of one hand. It has a button for each fingerand one for the thumb [140]. It provides haptic feedback, and a wearer can use it while walking or suspended in a harness. Yet another approach is to use voice command recognition. This is the most natural approach and works very well if the system is "trained" to recognize the user's voice. Performance can be quite good without any training.

| Position Tracking

One key element for interaction with a virtual world is a means of tracking the position of a real world object, such as a head or hand. There are numerous methods for position tracking and control. Ideally, a technology should provide three measures for position coordinates (X, Y, Z) and three measures of orientation (roll, pitch, yaw). One of the biggest problems for position tracking is latency, or the time required to make the measurements and preprocess them before input to the simulation engine.

Mechanical armatures can be used to provide fast and very accurate tracking. Such armatures may look like a desk lamp (for basic position/orientation) or they may be highly complex exoskeletons (for more detailed positions). The drawbacks of mechanical sensors are the encumbrance of the device and its restrictions on motion. EXOS, Inc., builds one such exoskeleton for hand control. It also provides force feedback. Shooting Star system makes a low-cost armature system for head tracking. Fake Space Labs and LEEP Systems, Inc., make much more expensive and elabo-

18 Other boom. mounted stereoscopic displays are strapped to the user's head and leave the user's hands free to gesture or type on a virtual keyboard. Such displays are not head-supported but are sometimes called head-mounted.

rate armature systems for use with their display systems.

Ultrasonic sensors can be used to track position and orientation. A set of emitters and receivers are used with known relationships between the emitters and between the receivers. The emitters are pulsed in sequence and the time lag to each receiver is measured. Triangulation gives the position. Drawbacks to ultrasonics are low resolution, long lag times, and interference from echoes and other noises in the environment. Logitech and Transition State are two companies that provide ultrasonic tracking systems.

Magnetic trackers use sets of coils that are pulsed to produce magnetic fields. The magnetic sensors determine the strength and angles of the fields. Limitations of these trackers area high latency for the measurement and processing, range limitations, and interference from ferrous materials within the fields. However, magnetic trackers seem to be one of the preferred methods. The two primary companies selling magnetic trackers are Polhemus and Ascension.

Optical position tracking systems have been developed. One method uses an array of infrared light-emitting diodes (LEDs) on the ceiling and a head-mounted camera. The LEDs are pulsed in sequence and the camera's image is processed to detect the flashes. Two problems with this method are limited space (grid size) and lack of full motion (rotations). Another optical method uses a number of video cameras to capture simultaneous images that are correlated by high-speed computers to track objects. Processing time (and cost of fast computers) is a major limiting factor here. One company selling an optical tracker is Origin Instruments.

Inertial trackers have been developed that are small and accurate enough for VR use. However, these devices generally only provide rotational measurements. They are also not accurate for slow position changes.

I Stereo Vision

Stereo vision is often included in a VR system. This is accomplished by creating two different images of the world, one for each eye. The images are computed with the viewpoints offset by the equivalent distance between the eyes. There are a large number of technologies for presenting these two images. One of the simplest is to present the images side-by-side and ask the viewer to cross her or his eyes while viewing them. There are techniques for assisting the viewer in this unnatural task. The images can be projected through differently polarized filters, with corresponding filters placed in front of the eyes.

Another technique is to present anaglyphic images (anaglyphs), which are false-color images analogous to double exposures. Each anaglyph is a superposition of a red image intended to be seen by one eye and a blue image intended to be seen by the other eye. The anaglyph is designed to be viewed with special eyeglasses having a red filter for one eye and a blue filter for the other eye; the viewer sees a monochromatic image with apparent depth.

The two images can be displayed sequentially on a conventional monitor or projection display. Liquid crystal (LC) *shutter glasses* are then used to shut off alternate eyes in synchronization with the display. When the brain receives the images in rapid enough succession, it fuses the images into a single scene and perceives depth. A fairly high display swapping rate (at least 60 Hz) is required to avoid perceived flicker. A number of companies made low-cost LC shutter glasses for use with TVs (Sega, Nintendo, Toshiba, etc.). Software and diagrams for circuits to interface these glasses to a computer are available on many computer bulletin-board systems (BBSs) and Internet FTP[19] sites. However, locating the glasses themselves is getting difficult as none are still being made or sold for their original use. StereoGraphics

[19] File Transfer Protocol: a standardized procedure communications procedure for transferring a data file from one computer to another over the Internet.

Corp. sells a model, called CrystalEyes, that weighs only 85 g. It is considered to represent the "highend" of the spectrum of shutter glasses, both in price and in quality [98,158]. One reviewer, however, described them as "incredibly fragile" as well as "very nice."

Another method for creating stereo imagery on a computer is to use one of several split-screen methods. These divide the monitor into two parts and display left and right images at the same time. One method places the images side by side and conventionally oriented. It may not use the full screen or may otherwise alter the normal display aspect ratio. A special hood viewer is placed against the monitor which helps position the eyes correctly and may contain a divider so each eye sees only its own image. Most of these hoods, such as the Fresnel stereopticon viewer included (along with software) with the book *Virtual Reality Creations [158],* use Fresnel lenses to enhance the viewing. An alternative split screen method orients the images so the top of each points out the side of the monitor. A special hood containing mirrors is used to correctly orient the images. Simsalabim Systems sells a unit of this type, the Cyberscope, for under $200 [156]. Split-screen or dual-screen methods are used in head-mounted displays, which are discussed in the next section.

Head-Mounted Displays

One hardware device closely associated with VR is the head-mounted display (or device), which uses some sort of helmet or goggles to place a small video display in front of each eye with special optics to focus and stretch the perceived field of view. Most HMDs use two displays to provide stereoscopic imaging. Others use a single larger display, sacrificing stereoscopic vision in order to provide higher resolution.

HMDs attracted public attention in 1991, when W Industries, Ltd.—now called Virtual Entertainment, Inc. (VEI)-sent its networked Stand-Up Virtuality arcade machines equipped with the Visette HMD (introduced late in 1990 [73]) on a tour of the United States [140]. VEI recently introduced its second-generation Stand-Up Virtuality machine [73].

Most lower priced HMDs (those costing $3,000 to $10,000) use LCDs. Others mount small CRTs, such as those found in camcorders, alongside the head. The price of low-end liquid-crystal HMDs is decreasing, but their resolution is inadequate for many applications. One of the least expensive, listed at $750, is "The Alternative" HMD, which weighs about 6 pounds and provides a monoscopic view using a 3.8-inch-diameter LCD with an effective resolution of 240 pixels horizontally by 146 pixels vertically. The actual LCD resolution is greater, but a grouping of three monochrome pixels-one for each of three primary colors—"is necessary to produce one color pixel. The field of view is approximately 70 degrees horizontally by 60 degrees vertically. For comparison, a NTSC[20] color television displays 525 lines (or pixels) vertically, with a field of view that depends on the distance from the viewer to the screen but is typically less than 60 degrees vertically. Thus the low-end LCD provides a less detailed (more grainy or blurred) picture than does an ordinary television, but over a larger field of view.

There are many higher priced liquid-crystal HMDs on the market. An example-one of three winners of a *CyberEdge Journal 1993* Product of the Year Award in the hardware category-is the VIM™ personal viewer™ developed by Kaiser Electro-Optics, Inc., of Carlsbad, California. The Model 500pv VIM™ personal viewer™ uses full color multiple active matrix LCDs, currently manufactured in Japan, with 232,300 color elements (77,433 color groups) providing a 50-degree (horizontal) field of view with a 4:3 aspect

20 National Television Standards Convention. This standard, proposed by the National Television System Committee, specifies details of television signal format-such as scan lines per frame, frames per second, and interlacing of scans-that U.S. television broadcasters have used for over four decades.

ratio. It accepts two channels of NTSC TV video input. It weighs 24.5 ounces and lists for $2,975. Kaiser's Model 1000pv VIM™ personal viewer™ is similar but has twice as many pixels, provides a 30-degree (vertical) by 100-degree (horizontal) field of view, and uses a custom video format. It weighs 26.5 ounces and lists for $9,975 [104,86].

The more expensive HMDs ($60,000 and up) use special CRTs. Examples are the Color SIM EYE™ HMD systems produced by Kaiser Electro-Optics, Inc. The SIMEYE™ 40 HMD is capable of displaying full stereo imagery (i.e., with 100-percent overlap of the images from the two CRTs) over a 40-degree circular field of view, or of providing a 40-degree (vertical) by 60-degree (horizontal) field of view with full stereo imagery in the central 20 degrees. It supports several video formats, including 1,280 by l,024 pixels 2: 1 interlaced (in color, or noninterlaced monochrome) at a frame rate of 50 or 60 Hz. It weighs 4.5 pounds and is listed at $145,000 (or $128,000 each, in quantity).

The SIMEYE™ 60 HMD uses a different optical relay system to display full stereo imagery over a 60-degree circular field of view, or it can provide a 60-degree by 80-degree field of view with full stereo imagery in the central 40 degrees or a 60-degree by 100-degree field of view with full stereo imagery in the central 20 degrees. It weighs 5.1 pounds and is listed at $165,000 ($146,000 each in quantity). Kaiser will lease either SIMEYE™ model at $13,000 per month for one year or $7,500 per month for two years. Both SIMEYE™ models are see-through-i.e., they superimpose images of virtual objects on the actual visible background [103]. SIMEYE™ HMDs have been purchased by the U.S. Air Force, the U.S. Navy, NASA, the Australian Defence Force, and others [86].

Another type of HMD, called a fiber-optic HMD (FOHMD) uses a bundle (viz., cable) of optical fibers to pipe the images (e.g., one for each eye) from nonhead-mounted displays, either CRTs or LCDs. The Army Research Institute at Fort Rucker, Alabama, is experimenting with a FOHMD developed by CAE Electronics, Ltd., of Montreal, Canada. The Naval Air Systems Command (PMA-205) is investigating the effectiveness of FOHMD technology for naval applications [210].

One of the most ambitious concepts for an HMD is the Virtual Retinal Display (VRD) mentioned by Thomas Furness in the 1991 Senate hearing on virtual reality [65]. As of mid-1993, the University of Washington's Human Interface Technology Laboratory had built a bench-mounted technology demonstrator producing a 500 by 800-pixel monochromatic image using a single diode laser, an acousto-optical horizontal scanner, and an electromechanical vertical scanner. Planned improvements include use of an array of multicolored diode lasers (or incoherent light-emitting diodes, in a different version) to generate a color image with almost 12 million pixels, and different scanning methods that promise a reduction in size and weight [1 13,126].

An HMD requires a head position and (especially) orientation tracker, so that the graphics processor can determine the field of view to be rendered. A tracking device can be mounted on the helmet(or head). Alternatively, the display can be mounted on a boom for support and tracking.

There is some concern about potential health hazards from HMDs. There have been a number of anecdotal reports of HMDs and other stereoscopic displays causing stress, but there have been few good clinical studies of the hypothesis. One of them-a study by the Edinburgh Virtual Environment Laboratory of the Department of Psychology of the University of Edinburgh—found that stereoscopic HMDs caused stress in many subjects. The basic test was to put 20 young adults on a stationary bicycle and let them cycle around a virtual rural road setting using an HMD (VPL LX EyePhone and a second HMD LEEP optic-equipped system). After 10 minutes of light exercise, the subjects were tested. An article in the lay press summarizing the results said, "The results were alarming: measures of distance vision, binocular fusion and convergence displayed clear signs of binocular stress in a significant number of the subjects. Over half the subjects also reported symptoms of such stress, such as blurred vision" [79].

The article described the primary reason for the stress—the difference between the image focal depth and the disparity. Normally, the when a person's eyes look at a close object they focus (accommodate) close and also rotate inward (converge). When they accommodate on a far object, the eyes look more nearly in the same direction. However, a stereoscopic display does not change either the effective focal plane (which is set by the optics) or the disparity depth. The eyes strain to decouple the signals. The article discussed some potential solutions but noted that most of them are difficult to implement. It speculated that monoscopic HMDs, which were not tested, might avoid the problems. The article did not discuss non-HMD stereoscopic devices.

Olaf H. Kelle of the University of Wuppertal in Germany reported that only 10 percent of his users showed signs of eye strain [98]. His system has a three-meter focal length, which seems to be a comfortable viewing distance. Others have noted that long-duration monitor use often leads to the user staring or not blinking. Video display terminal users are often cautioned to look away from the screen occasionally in order to adjust their focal depth, and to blink.

John Nagle provided the following list of other potential problems with HMDs: electric shock or bum, tripping over real objects, simulator sickness (disorientation caused by conflicting motion signals from eyes and inner ear), eye strain, and induced post-HMD accidents: with "some flight simulators, usually those for military fighter aircraft, it been found necessary to forbid simulator users to fly or drive for a period of time after flying the simulator" [98]. In some cases "flashbacks" occurring some hours after spending hours in a simulator have nearly caused fatal automobile accidents. "We have gone too fast technologically," opined researcher Robert Kennedy, who has studied simulator sickness for 15 years [101].

| Haptic Transducers

Sensations in the skin-pressure, warmth, and so on—are *haptic* perceptions. In the context of virtual-reality, *haptics* refers to the design of clothing or exoskeletons that not only sense motions of body parts (e.g., fingers) but also provide tactile and force feedback for haptic perception of a virtual world. If users are to feel virtual objects, haptic transducers are needed to turn the electrical signals generated by a computer into palpable stimuli.

Haptics is less mature than are stereo image and 3-D sound generation, partly because haptic perception is less important than visual perception and audio perception for most tasks, partly because haptic perception is less well understood, and partly because some transduction tasks that may be imaginable and desirable are simply quite difficult to achieve. Others are quite simple. For example, treadmills have been used for years in walk-throughs of virtual architectural prototypes; walking on the treadmill makes the scene presented in a walker's HMD change and also gives the walker a realistic sensation of exertion. Similarly, stationary bicycles have been used in arcade systems to allow a customer to pedal through a virtual world displayed on a screen (or to pilot a virtual pterodactyl).

Semiconductor thermoelectric (TE) heat pumps are being incorporated into gloves to allow wearers to feel the temperature of virtual objects [28,56]. Shape-memory metal wires have been incorporated into gloves and electrically actuated to provide limited force feedback. Larger, heavier electromechanical actuators—in some cases on exoskeletons—provide more forceful feedback [160]. One of the first such devices was the GROPE-II virtual molecule manipulator developed at the University of North Carolina and completed in 1971. Its effectiveness was severely limited by the computational power available at that time. Its successor, GROPE-III, begun in 1986, was better and proved to be a useful research tool for chemists. Specifically, the haptic feedback that it provided reduced the time required for chemists to perform certain subtasks necessary to find the best (i.e, lowest potential energy) site for docking a virtual drug molecule to a virtual enzyme molecule [16]. Overall elapsed time was not significantly reduced, but the subjects were gener-

ally able to find better (i.e., lower potential energy) docking sites than were found by a common computational technique that does not require visual or haptic human-computer interaction.

Today haptic interface technology is still little used; most visitors to virtual worlds cannot feel and wield virtual instruments, tools, and weapons. If technological advances make haptic interfaces lighter, smaller, less expensive, and more realistic, they could see wider use in military applications, including aircrew training, telesurgery, and assessment of the design of habitable spaces on ships.

Analysts at the Center for Naval Analyses have described the need for tactile feedback in aircrew training devices as follows [210]:

> . . . in a virtual cockpit, an image of the user's hand would be displayed (on either a CRT or an HMD) along with a virtual control panel. The user interacts with buttons and switches on the control panel by moving his hand to manipulate them.
>
> When a virtual switch has been flipped, the user should be given some form of feedback or indication. This can take the form of visual, auditory, or tactile cues. But unless the system provides tactile feedback, the user will not feel any resistance as the object is touched. Without tactile cues, the user may be uncertain whether contact has been made with the switch.

There is a similar need in surgical simulators and systems for minimally invasive surgery and telesurgery. Researchers at the Georgia Institute of Technology are trying to simulate surgery on the human eye with force feedback. Some researchers speculate that force feedback may be useful in certain types of endoscopic oncological surgery,[21] because cancerous tissue is often detected by touch [3]. A solicitation issued by DOD's Advanced Research Projects Agency in January 1994 [179] announced the creation of a program in Advanced Biomedical Technology, stating that:

> The purpose of this effort is to develop and transition these technologies [remote sensing, secure broad bandwidth communications, teleoperation, advanced imaging modalities, virtual reality and simulation] to the medical arena to reduce the battlefield casualty rate by an order of magnitude through early intervention. A primary objective is to demonstrate that critical medical information can be acquired by body-worn, noninvasive sensors and rapid therapeutic intervention can be applied through telemedicine.

ARPA solicited proposals in three technology areas. In the area of Remote Therapeutic Intervention, ARPA sought "a capability to perform accurate surgical procedures from a central workstation to a mobile remote operative site (which contains all requisite logistical support)":

> The ideal workstation would have 3-D video, at least 6 degree of freedom (DOF) master, and sensory input. The remote site must have 3-D camera, 6 DOF manipulator slave, and tactile, force feedback and audio sensors. Manipulator latency must be less than 100 milliseconds. The interface should be intuitive and transparent, and support multiple digital imaging technologies.[22]

A more recent ARPA solicitation [180, 181,1 82] sought proposals to develop and demonstrate technology for "simulation-based design"

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21 In endoscopic surgery, a surgeon guides an optical-fiber cable through an orifice or incision in the patient. Some fibers carry light from a light source to illuminate the cavity or tissue just beyond the end of the cable; other fibers carry reflected light back to a video camera outside the patient, which sends its video signal to a monitor watched by the surgeon. The tip of the same cable, or a separate one, may have a surgical instrument that is manipulated by the surgeon from outside the body.

22 ARPA also solicited proposals in the area of medical simulation, saying "The next critical advancement in medical education appears to require a virtual environment (cadaver) of human anatomy that permits education in basic and abnormal (e.g., military wounds) anatomy. Such a simulation should have realistic interaction capable of supporting surgical simulation for training. There is also interest in a virtual environment for individual simulated soldiers and medics which is compatible with SIMNET for use in medical forces planning and training. These various components must be individually useful while also integratable into a single large medical support system which uses ATM/SONET technology in gigabit-rate network."

(SBD) of complex systems such as naval ships. One of many possible applications of VR to this task is the *experiential prototyping* [1 18] of ships to assess the design of habitable spaces. Bumping into pipes, stanchions, bulkheads, and so forth is a real hazard that cannot be assessed readily by VR without force feedback. A VR system can detect whether a user bumps her head into a virtual pipe even if the user cannot feel it, but if the user cannot feel it, the user will not learn the adaptive behavior that, on a real ship or a mockup, would tend to reduce the incidence of such collisions.

Haptics remains a challenging research area—and a potentially dangerous one. Too much force feedback by an exoskeleton could crush a wearer's hand. It maybe a long time before a pilot wearing an HMD and a force-feedback suit and gloves will be able to reach up and feel his virtual canopy, or the effort of moving his virtual stick or throttle. When it does become feasible, it may not be as cost-effective as simply building a cockpit mockup for the pilot to sit in—the approach used in Link trainers and even earlier aircrew training devices [139, fig. 3-l].

| Degrees of Virtual Reality

Although there is a bewildering variety of virtual reality systems that differ from one another in details of hardware and software, connoisseurs like to sort them into a few categories describing the degree or level of VR that they provide. The price tag is often a good index, but other levels have been defined. The following are categories defined by Jerry Isdale; other writers have proposed different categories.

An *entry-level VR* system takes a stock personal computer or workstation and implements a WOW system. The system may be based on an IBM clone (MS-DOS/Windows) machine or an Apple Macintosh, or perhaps a Commodore Amiga. The DOS-type machines (IBM PC clones) are the most prevalent. There are Macintosh-based systems, but few very fast-rendering ones. Whatever the computer, it includes a graphic display, a 2-D input device like a mouse, trackball or joystick, the keyboard, hard disk, and memory. The term *desktop VR is* synonymous with entry-level VR.

Although desktop VR systems rank lowest in performance, they are by far the most common type of VR system. The promise of virtual reality for making desktop computers user-friendly and thereby increasing their effectiveness for education and other uses, including military uses, will depend to an important degree on the quality, variety, and cost of desktop VR software.

Stepping up to *basic VR* requires adding some basic interaction and display enhancements. Such enhancements would include a stereographic viewer (LCD Shutter glasses) and an input/control device such as the Mattel PowerGlove and/or a multidimensional (3-D or 6-D) mouse or joystick.

The next step up, *advanced W?,* adds a rendering accelerator and/or frame buffer and possibly other parallel processors for input handling, etc. The simplest enhancement in this area is a faster display card. Accelerator cards for PC-class machines can make a dramatic improvement in the rendering performance of a desktop VR system. More sophisticated and costly image processors use an array of processors to achieve stunning realism in real-time animation. An advanced VR system might also add a sound card to provide mono, stereo, or true 3-D audio output. With suitable software, some sound cards can recognize a user's spoken commands to fly, turn left, stop, grasp an object, and so forth, and translate them into electronic commands that the virtual environment system can respond to. This is especially useful for *immersive* VR systems, the next higher (and highest) degree of virtual reality.

An *immersive* (or *immersion)* VR system adds some type of immersive display system, such as an HMD, a BOOM, or multiple large projection displays (as in the CAVE). A command- and data-entry system other than an ordinary keyboard is a very useful adjunct to immersive systems; a voice command recognition system or a single-handheld chording keyboard are options. An immersive VR system might also add some form of haptic interaction mechanism so that the user can feel virtual objects. Some writers further classify

immersive systems as *garage VR* systems, if they are constructed in a labor-intensive manner from relatively inexpensive components and subsystems, or *high-end VR* systems, if they use expensive commercial equipment.

Shared Virtual Reality

Jaron Lanier, then-president of VPL Research, Inc., emphasized at the 1991 Senate hearing on VR that "it is important to remember that virtual reality is a shared social experience, very much like the everyday, physical world" [1 18]. VPL Research, founded in 1985, pioneered the development of software and equipment—such as its Eyephones HMD, DataGlove glove input device, and DataSuit (a full-body version of the DataGlove)—with which several persons could experience a virtual world in which they could see and hear one another. Earlier, DOD projects from SAGE to SIMNET allowed several persons to experience a virtual world in which each could see others' actions on a radar screen (SAGE) or simulated periscope (SIMNET).

Increasingly, similar networking is being done for entertainment, both in arcades [73] and from home. Enthusiasts on different continents may dial one another to play Capture (capture the flag) in virtual armored vehicles [73], Energy Duel (a dogfight), or Cyberball [206]. One can dial a host computer to play cat-and-mouse (wearing a cat or mouse face) with another player in a three-dimensional "Polygon Playground" [42] or drive a virtual tank and fight (and talk to) others in the Parallel Universe multi-player demonstration offered by the Virtual Universe Corporation of Alberta, Canada. Office workers whose workstations are linked by local-area networks (LANs) team up after hours to fight Former Humans, Former Human Sergeants ("much meaner, and tougher"), Imps, Demons, Spectres, and the like on a virtual military base on Phobos, in the popular computer game DOOM (by id Software). Others link up by LAN or Internet to dogfight in virtual fighter planes (in Airwarrior).

All this requires networks, and networking requires standards. Networked DOD simulations from those of SAGE to those of SIMNET have used the public telephone network. Today, a variety of other networks are also used, including ad-hoc LANs, the Intemet,[23] and the Defense Simulation Internet (DSI).

The DSI was originally known as the Terrestrial Wide Band Network (TWBNet), which was part of the North Atlantic Treaty Organization's (NATO's) Distributed Wargaming System (DWS), which was sponsored by DARPA and by NATO's Supreme Allied Commander-Europe (SACEUR). TWBNet was orphaned briefly after the Cold War ended but was later adopted by NATO's Warrior Preparation Center (WPC), DARPA's SIMNET project, DOD's Joint Warfighting Center (JWFC), and the Walker Simulation Center in the Republic of Korea. The DSI has grown to over 100 nodes and is now being managed jointly by DOD's Advanced Research Projects Agency (ARPA), which developed the technology, and the Defense Information Systems Agency (DISA), which will be responsible for the DSI when it is fully operational.

The DSI (together with other networks) has linked heterogeneous simulators in exercises that have included engagements of simulated tanks, other armored vehicles, ships, helicopters, fixed-wing aircraft, cruise missiles, and teams of Marines equipped with laser designators to designate targets for Air Force aircraft equipped with laser-guided bombs. Simulators physically located in the continental United States, Germany, and the Republic of Korea have participated in the same exercise, operating on the same virtual battlefield. The DSI is used for video teleconferencing (VTC)

23 The Internet is a collection of many networks that exchange digital information using the TCP/IP suite of protocols, including the Transmission Control (TCP), the Internet Protocol (1P), the File Transfer Protocol (FTP), the Simple Mail Transfer Protocol (SMTP), and others.

in support of traditional wargaming, as well as for distributed interactive simulation.[24]

The SIMNET program defined a communications protocol—a specification of electronic message types and formats, and other matters—to be used by vehicle simulators so they could interoperate over a network and share the same virtual battlefield. The SIMNET protocol is still used by some simulators, but it has been superseded by IEEE Standard 1278-1993, which is based on the SIMNET protocol but defines additional message types to permit simulation of additional types of vehicles and phenomena.

OBSERVATIONS

| Synthetic Environment Technology Is Dual-Use

Much of the hardware and software used by DOD for combat simulation, including synthetic environment technology, has commercial application. DOD appears to be using or adapting commercial equipment wherever possible, in order to reduce cost and acquisition time, and it has participated in the deliberations of nongovemment standards bodies, such as the Institute of Electrical and Electronic Engineers (IEEE) to steer industry standards in directions responsive to DOD's needs. IEEE Standard 1278-1993, for distributed interactive simulation communication protocols, is one product of that process.

DOD will have to pay for the development of some simulator software and hardware for which there is no commercial market, and for the validation of the software and hardware that it uses. However, the location-based entertainment (i.e., arcade) industry provides a surprisingly large and rapidly growing *commercial* market for distributed interactive *combat* simulators. Some of the products being developed for this market are very sophisticated, realistic, and expensive. An example is the Hornet-l F/A-18 flight simulator developed by Magic Edge. Its user sits in a cockpit in a capsule on a three-degree-of-freedom motion base that can roll the capsule 60 degrees left or right, pitch the nose up 45 degrees or down 25 degrees, and provide 32 inches of vertical motion. The user looks out the canopy at a projection screen on which a state-of-the-art, high-end computer image generation system projects a scene of sky, ground, and up to five other F/A-18s controlled by the pilots of other Hornet-l simulators, while a four-channel surround-sound synthesizer provides a background of engine whine and tactical radio traffic.

To be commercially successful, the Hornet-l need only be sufficiently realistic, or at least entertaining, to draw a crowd. It need not have the fidel*ity* required to train Navy pilots to land safely on aircraft carrier decks. Future Navy ATDs may use similar hardware and software, but DOD must bear the cost of determining whether they faithfully represent critical aspects of reality (i.e., DOD must validate the simulation) and deciding whether they are acceptable for the intended purpose (i.e., DOD must accredit the simulators). Most likely, in order to be accredited, some of the software (and perhaps hardware as well) may need to be designed to DOD specifications.

DOD will also have to pay for the communications infrastructure or service (or combination of infrastructure and service) required to link simulators with low latency. The Distributed Interactive Simulation (DIS) Steering Committee has reported that the primary bottleneck has been local-area networking—the connection of simulators to others nearby and to wide-area network nodes [43].

The DSI is being expanded to meet the need for wide-area networking. Access to the DSI costs **$150,000 to $300,000** per node per year [43]. DOD has used, and will continue to need to use, the rapidly growing commercial, academic, and nonmilitary government networks, such as those that are part of the Internet, for wide-area networking.

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24 SIMNET, DIS, and the DSI will be discussed in greater detail in a forthcoming OTA background pa~r.

One reviewer of a draft of this paper stated that the biggest problem on the DSI has been the encryption of data for transmission for transmission over wide-area networks; he argued that DOD should rely as much as possible on commercial technology and focus its spending on development of technology addressing needs peculiar to DOD, such as security and DIS protocol support for use with commercial *multicast* equipment—hardware and software that examines the addresses of digital messages (e.g., simulation data) and makes copies and re-addresses them to send to particular computers (e.g., the processors of simulators participating in a particular simulation).

The Naval Postgraduate School Network (NPSNET) Research Group has been experimenting with multi-vehicle combat simulations in which data are formatted into SIMNET or DIS Protocol Data Units (PDUs) [97] and multicast to participating simulators over the Multicast Backbone (MBONE or MBone)—an experimental virtual network operating on portions of the physical Internet [23]-or using MBONE protocols [214]. The MBONE is being developed to transmit live audio and video (e.g., from a rock concert) in digital form to a large audience on the Internet. It uses special procedures to insure that the digital messages (packets) containing the audio and video signals will be delivered faster than, say, those containing parts of e-mail messages. These features are just what is needed for networked multivehicle combat simulation, and it costs little to set up an MBONE router (software is free and can run on a personal computer) and connect it to the MBONE.

Internet access providers are now debating the merits of charging for data transfer (rather than for access privilege, as is now done) in dollars per bit, depending on the availability required and latency that can be tolerated. If such a pricing scheme is adopted, DOD might be able to pay for the connectivity, bandwidth, and availability that it requires when it needs it—for example, during exercises. DOD will also continue to need some dedicated links, but perhaps fewer as a proportion of the whole.

| Cost-Effectiveness Is Increasing

The scale—i.e., the number of transistors-of microprocessors continues to increase roughly in accordance with Moore's law—i.e., it doubles every two years. The information storage capacity of memory chips shows a similar trend, and CD-ROMS and other media are now commonly used for high-capacity archival storage. Flat-panel display chips—such as LCDs, active-matrix LCDs, and micromechanical mirror-arrays-show a similar trend. These trends and others (including parallel processing, networking, and production of software to exploit the new hardware to full advantage) allow new simulators and simulator networks to simulate processes with unprecedented realism and speed.

Intel envisions that by 2000 it will be able to produce a "Micro 2000" processor chip with four dies (pieces of silicon), each containing 80 to 100 million transistors switching on and off 250 million times per second (250 MHz). The multiprocessor chip will be able to execute over two billion instructions per second. Newer, higher-density chips cost more than earlier chips, but the cost per unit of performance-instructions per second for a processor, or storage capacity in bits for a memory chip-has been decreasing.

As a result, the average cost of a fully immersive virtual reality system-one with head-tracking, a head-mounted display, and "three-dimensional" sound-declined from about $1 OO,OOO in early 1991 to about $50,000 two years later. As the price halved, sales increased tenfold, from 50 to 500, probably the result of both the price elasticity of demand and the contagiousness of technology adoption. An industry forecast predicts that average cost will decline to about $10,000 in 1998, when sales will reach 16,000 systems. This volume (if not the revenue: $160 million) will be dwarfed by the volume of "desktop" virtual reality systems that provide interactivity with simulated 3-D objects using, in some cases, only ordinary office workstations running special software, some of which is distributed free

on the Internet and on dial-up computer bulletin-board systems.

This trend in virtual reality systems is reflected in other computer-intensive simulators as well. Technological advances have allowed prices to fall while performance increases. Many proposed applications of high-tech simulation technology that were not heretofore cost-effective now are or soon will be, but such questions as "which?" and "when?" must be answered on a case-by-case basis.

CHALLENGES

| High-Density, Color Flat-Panel Displays

A widely recognized challenge for the development of some types of virtual simulators is the development of high-density, color, flat-panel displays for use in head-mounted displays (HMDs) and other applications. "High-density" in this context refers to the number of picture elements (individual dots, called pixels or pels) per inch or per square inch. In some applications—e.g., wall-mounted television screens—a detailed picture may be displayed by using a large display screen. In order for an HMD to display a similarly detailed picture, the picture elements must be closer together, so the display is small enough and light enough to wear.

LCDs currently used in HMDs provide only about a fourth of the visual acuity obtainable in domed flight simulators, which remain the technology of choice for tactical aircrew training devices. The displays must be lightweight to be useful (or competitive) for HMDs, and they must be less expensive if they are to find wider application. The best LCDs for HMDs are currently made in Japan; American economic competitiveness would benefit if U.S. industry could manufacture a competitive product, a point made often in the 1991 hearings on virtual reality. Since then, DOD has funded a number of projects intended to stimulate domestic production of world-class flat-panel displays for use in military systems, as well as in commercial systems, which would reduce the costs to DOD for purchasing similar or identical displays.[25]

A recent Center for Naval Analyses memorandum to the Navy's Director for Air Warfare suggested [210]:

> The best approach for the Navy would be to leverage the developments in virtual environment technologies being pursued by the entertainment industry. Once that technology—particularly the technology for head-mounted displays—matures, applications for aircrew training should be considered.

| Fast Head Tracking

When an HMD wearer turns his or her head quickly, it take a fraction of a second for the display to catch up and show the scene as it should appear from the new direction of gaze. The wearer sees the scene pan to catch up after head rotation has stopped. This effect is called swimming. It not only destroys (or inhibits) the illusion that the HMD wearer is in a virtual world, it can also cause simulator sickness, which is related to motion sickness.

Some of the delay, called latency, maybe the result of slow image rendering by the CIG system. However, when very fast CIG systems are used, the latency of the head tracking device becomes the limiting factor. Several technologies, described above, have been used for head tracking; magnetic tracking systems have been prominent in high-end VR systems.

Optical trackers now in development are a promising alternative to the magnetic trackers widely used with HMDs. One type of optical tracker uses one or more TV cameras on the HMD to transmit images of the scene (possibly including pulsing infrared light-emitting diodes mounted on the ceiling) to a video processor that calculates the position and orientation of camera by analyzing the positions of the infrared LEDs in

25 These initiatives will& described in an appendix on flat-panel displays in the volume of case studies, to be published in 1995, that will supplement OTA'S final report on its assessment of civil-military integration [169].

the TV image it produces. By adding "offsets," the processor also calculates the position and orientation of the wearer's head (which may be needed for correct body representation in a shared virtual world) and the position and orientation of the wearer's eyes (the points of view from which the stereoscopic images should be rendered). Optical tracking can be very fast, but an optical tracker is heavier than a magnetic tracker (this may change) and requires more computation, making it expensive. It allows the wearer freedom of motion within a large volume, but if it requires an array of light-emitting diodes, the cameras' view of them cannot be obstructed. Research on this challenge continues.

Wideband Networks With Low Latency

Another challenge is that of building the data communications infrastructure required: a network connecting all the simulators (as well as any real vehicles, weapons, and other systems) that are to participate in a simulation, capable of transferring large quantities of information at aggregate rates that, using the DIS protocol, must grow at least in proportion to the number of participating entities (simulators, etc.). The network need not be dedicated to combat simulation; it can be shared with other users and used for other tasks, but it would be wasteful if a large simulation were to be interrupted by, say, a digital movie being transferred over a link of the network for leisure-time viewing. As was noted above, under **Synthetic Environment Technology Is Dual-Use,** nondedicated networks will continue to complement the Defense Simulation Internet. Wider use (and improvement) of multicasting protocols can reduce the network bandwidth required for simulations (and other uses), and proposed Internet subnetwork usage-pricing schemes may allow DOD to pay for the low latency it needs for simulations.

Multilevel Network Security

Yet another challenge is that of ensuring that each human or computer participating in a simulation cannot acquire secret information used in the simulation without proper authorization. In distributed interactive simulations, multilevel security is the preferred operating mode. For example, a participating U.S. Army tank driver usually does not need and is not authorized to obtain all of the information used by a participating U.S. Army intelligence analyst, and the simulator used by a participating Luftwaffe (German Air Force) fighter pilot does not need and generally is not authorized to obtain all of the information that might be generated by a participating U.S. Air Force fighter simulator. In the former case, security is enforced by a variety of techniques including manual procedures that DOD would like to automate. In the latter case, much of the problem is intrinsic and not amenable to automation. If a foreign pilot is not authorized to know the dash speed of an Air Force at full military power, it should not be flown at that speed within range of his radar, either in a live exercise or in simulation.

The end-to-end encryption systems presently used to provide security for the communication links used by distributed interactive simulations are imposing severe limits on the amount of data that can be put through them, according to the DIS Steering Committee [43]. A challenge is to minimize the impact of these constraints by improving the performance of the encryption systems or finding alternatives to them that provide adequate levels of protection, but with greater throughput. The challenges and opportunities of multilevel secure use arise in many applications and are by no means unique to combat simulation.

Automating Object and World Description for Scene Generators

Another challenge is automating the tedious process of generating data files that image-generating computers need to display terrain, other backgrounds, objects, and scenes. In 1991 testimony, Fred Brooks, Professor of Computer Science at the University of North Carolina at Chapel Hill, said: "The house model that you saw there with the pianos in it has about **30,000** polygons and 20 textures in its present version. We have been working on that model for years" [17]. Clearly,

rapid experiential prototyping will require better software tools for object model development. There are similar problems in the development of virtual objects and environments for military training and mission preview.

There has been progress, but the process remains time-consuming and hence costly. For example, in April 1994 OTA staff rode a virtual "magic carpet" over simulated terrain of a world hotspot. The terrain database had been prepared earlier to help policy makers visualize the terrain, but in order for them to drive virtual vehicles over the terrain, roads—initially "painted" onto the terrain from photographic data by an automated process—had to be "cut" into the grade by a manual process that required a day per five kilometers.

Some DOD simulators are now using PowerScene rendering software developed by Cambridge Research Associates of McLean, Virginia. It can render 3-D images (i.e., 2-D images from any specified point of view) from overhead stereoscopic images (e.g., aerial photos). This obviates hand-modeling of cultural features but requires overhead stereoscopic images of the area to be modeled in whatever resolution is needed. A scene rendered from SPOT satellite imagery, which has 10-m resolution, would not show all the detail visible to a pilot flying lower than 8,000 feet [210].

The issue of acquiring, formatting, storing, and distributing global terrain (and more generally, environmental) data is a policy issue discussed below in the section "Infrastructure." Here we focus on the problem of rapidly fusing such data with other data (e.g., technical intelligence on enemy weapon system platforms) to create a virtual environment for a simulation. A particularly challenging aspect of this problem is the need to realistically model changes in terrain and structures (buildings, bridges, etc.) that would be caused by the combat activities being simulated, for example, small-arms fire, artillery fire, and aerial bombardment. That is, "dynamic terrain" must be simulated. This need is being addressed by the Army Research Laboratory's (ARL's) Variable Resolution Terrain (VRT) project [188]:

> The Variable Resolution Terrain (VRT) model was developed at the U.S. Army Research Laboratory to address the shortcomings of Defense Mapping Agency (DMA) terrain data. DMA terrain data lack the high degrees of detail and flexibility required by combat models and simulations for individual soldiers. Using the VRT model, high-fidelity geotypical terrain can be rapidly generated by computer. The level of detail of an area of terrain can be computed to any resolution. VRT-generated terrain is dynamic. Terrain events, such as cratering from artillery, which occur during a combat simulation can be quickly reflected. VRT-generated terrain is also user definable. A limitless number of terrain surfaces, ranging from mountainous areas to coastal plains, can be specified by a user. . . .
>
> The VRT model will be applied at ARL as part of a real-time combat simulation environment for individual soldiers. This implementation will be accomplished using a client-server distributed computing paradigm. The paradigm will consist of a heterogeneous cluster of high-performnance RISC-based workstations and a variety of parallel and vector supercomputers. In this arrangement, a single workstation (the master server) will act as the primary terrain controller. It will manage the operation of all other computers involved in the terrain generation process. This will allow for maximum flexibility permitting changes in the available computing power response to specific terrain computational requirements. Application of the VRT model in this manner is necessary due the computational demands of the model. Its implementation will produce high-detail terrain which is responsive to rapidly changing battlefield conditions in a real-time environment. This will enhance the realism of combat simulations.

| Simulating Infantry and Noncombatants

Another challenge is simulating individual infantry troops and noncombatants. Infantry troops are critical to the success of most phases of land combat, and noncombatants are present on many battlefields, especially in urban combat and low-intensity conflicts. Mission rehearsal systems have been developed for special operational

forces and security personnel, but dismounted infantry troops (or units) are not simulated in networked simulations that use the DIS protocol [97], a deficiency that critics argue makes the outcomes "predicted" by SIMNET exercises of questionable relevance to likely combat, especially low-intensity conflict in which U.S. forces are most likely to be involved in the near future.

Infantry fireteams (units consisting of a few individuals) have been simulated collectively in SIMNET simulations [109] but in a stereotyped manner; the representations are not controlled by the body movements of individual participants on a one-to-one basis.[26] For some purposes, modeling only fireteams and mounted infantry (in armored vehicles) is a useful and economical approximation. For training of dismounted infantry troops or investigating their performance, it is not. DOD and the Army are conducting research to simulate individuals (infantry troops, medics, and others) in netted or stand-alone simulations.

Notable work in this area is being done by the Army's Integrated Unit Simulation System (IUSS) project and the Navy's Individual Port (I-Port) project. Applications include the testing of systems carried and used by individuals (communications equipment, armor, etc.) in complex and stress inducing environments and the injection of complex individual behavior into a virtual exercise.

IUSS is a very high-resolution simulation of dismounted soldier interaction in a battlefield environment. Its resolution is from individual soldier to company-level groupings of soldiers. IUSS is used to study the effects that changes in soldiers' personal equipment, conditioning, and capabilities have on the accomplishment of small unit missions. IUSS provides the ability to perform real-time analysis of soldier/unit/equipment performance both during and after simulation execution using commercially available software. The Dismounted Battle Space Battle Laboratory has sponsored addition of DIS compatibility to IUSS[43].

I-Port inserts an individual into a virtual exercise by applying sensors to the human body that can determine direction, velocity, and orientation of that body, converts the information to DIS-like protocol data units (PDUS), and transmits them. The virtual world is presented to the individual via a head-mounted display or projected displays on surrounding screens. Three I-Ports were demonstrated in February 1994 at the 1994 Individual Combatant Modeling and Simulation Symposium held at the US Army Infantry School in Fort Benning, Georgia. The soldiers in the I-Ports demonstrated the capability to walk and run through the virtual environment, give overhead hand and arm signals, assume a prone position, throw a grenade, dismount from a Bradley fighting vehicle, and point and fire a rifle.

The demonstration was a joint effort of the Naval Postgraduate School NPSNET Research Group, SARCOS Research Corporation, Inc., the University of Pennsylvania, and the University of Utah. SARCOS and the University of Utah provided the mobility platform and the upper body instrumentation for the demonstration. The measurements from the upper body suit and mobility platform were analyzed and processed by the Jack software developed by the University of Pennsylvania. All computer graphics displays, including the three-walled walk-in synthetic environment, were generated by the NPSNET Research Group, using a modified version of NPSNET-IV, a low-cost, student written, real-time networked vehicle simulator that runs on commercial, off-the-shelf workstations (Silicon Graphics, Inc., IRIS computers). NPSNET-IV uses SIMNET databases and SIMNET and DIS networking protocols [214], and one version uses multicasting [12].

[26] OTA staff observed an example in the May 1994 Multi-Service Distributed Training Testbed (MDT2) exercise, which was conducted on the DSI. A simulator for a man-portable ground-based laser target designator team participated in the simulation from the Naval Research and Development Activity in San Diego, California [55].

The Army Research Laboratory, Simulation Technology Division, Simulation Methodology Branch is also addressing the need for synthetic environments technology for the individual soldier [187]:

> A virtual environment has been developed for research into embedding real and computer generated people into DIS. The environment, internally called Land Warrior, provides a 3-D view of the virtual world for real players instrumented with body position sensors. The environment has three modes, stealth, simulator, and remote control. In stealth mode, a user can view the virtual environment passively. In simulator mode, a user at a monitor and a keyboard can interact with other entities in the environment. In remote control mode, other simulation programs such as the Stair-Stepper can view the virtual environment, move around in the environment, and interact with other simulation entities by firing a weapon. Short-term development will provide a feedback mechanism to simulations from the virtual terrain, allowing adjustment of stair-stepper resistance as a function of terrain shape. In addition, methods of modifying the virtual environment database in real-time will be studied to allow the display of damage due to small-arms fire. The environment includes models to compute the movement of vehicles and people. Other models can be inserted easily into the environment for manipulating other objects.

ARPA has expressed "interest in a virtual environment for individual simulated soldiers and medics which is compatible with SIMNET for use in medical forces planning and training" in its solicitation [179] for proposals to develop advanced biomedical technology for dual-use application. One potential use for such a system would be to estimate scenario-dependent mortality rates, which are needed as input by theater-level medical operations models such as the Medical Regulating Model (MRM) used at the Wargaming Department of the Naval War College for support of seminar war games. Estimation of casualties for operational planning might require more validity than is required for seminar war games, but this is a question of accreditation.

ISSUES

I Validation

DOD Directive (DODD) 5000.59 defines *validation* as "the process of determining the degree to which a model is an accurate representation of the real-world from the perspective of the intended uses of the model." Department of the Army Pamphlet 5-11 uses an almost identical definition for validation and applies it to simulations as well as models. It also defines specific steps in the process of validating a model or simulation: data validation, structural validation, and output validation. Output validation is arguably the most difficult of the three, because the outputs (i.e., predictions) of a model are unlikely to be valid if the model is based on invalid data. Similarly, outputs are unlikely to be valid if the model is based on invalid structural assumptions, although some models—essentially fitted curves-have few structural assumptions. Output validation is also the type of validation that directly reflects the quality and reliability of model-derived or simulation-derived information presented to Congress—for example, estimates of the cost and operational effectiveness of proposed weapon systems or of likely casualties if U.S. forces are committed to some armed conflict.

For two decades the validity of combat models used by DOD has been questioned—for example, in [161,199,57,200,38]. However, the last of these critiques [38] was prepared before DOD, at the request of Congress [165,171], established the Defense Modeling and Simulation Office [190,195] and issued DODD 5000.59, both of which were intended to improve the practice and management of modeling and simulation within DOD, including verification, validation, and accreditation (VV&A) of models and simulations. These actions have had visible beneficial effects-especially in promoting joint development (or confederation) and use of models and simulations. However, verification requires man-hours, and validation requires data, much of which will have to be collected in exercises and on test ranges, which is costly. It remains to be seen whether verification, accreditation, and (especially) validation

will be funded well enough to be well done and to change the existing culture, in which validation is not considered mandatory and is often waived with the justification that it would be too difficult, expensive, or time-consuming. OTA will address these matters in its final report on military modeling and simulation. In this section, we simply note some philosophical issues.

A tank simulator connected to the Defense Simulation Internet may provide a valid simulation of combat from the perspective of its crew, if the purpose is to develop coordination in driving, target acquisition, and gunnery. This could be checked by live simulation using real tanks, as was done in the Army's Close Combat Tactical Trainer (CCTT) Program [72] and as is being done in the Army Materiel Systems Analysis Activity's Anti-Armor Advanced Technology Development (A^2ATD) Program [24]. There have also been efforts to validate both a virtual DIS and a constructive simulation (Janus) on the basis of combat data collected during the Gulf War [26].

The simulator may not provide a valid simulation of combat from the perspective of the loader (a crew member), if the purpose is to develop his coordination and upper-body strength so that he can correctly select and quickly load 55-pound rounds in a tank sprinting over rough terrain [72]. That shortcoming could probably be remedied at considerable expense by developing a moving base for the tank simulator, and whether it had been remedied could be checked by live simulation. But how can one tell whether an exercise, or the average of 100 exercises conducted with 100,000 netted simulators, would predict the chance of winning the next large campaign, wherever it may be? Even if one limits consideration to a handful of strategic scenarios, there are so many possible operational variables to consider that one cannot test the validity of the simulations under all conditions of interest. Analysts have noted that "the reason for using simulation paradoxically precludes any complete validation (because we cannot afford to create the same conditions in real life)" [59]. Essentially the same thing was said in a 1992 workshop on validation [68]:

> In extremely complex and difficult modeling situations, the requirements for comparing real world results and model results may be difficult, if not impossible, to meet. . . . Ironically enough, it is this inability to replicate (or even to understand) the real world that drives one to the use of a model in the first place.

Subjective judgment must be used in the output validation of some combat models and simulations [68,37], just as it has in nuclear reactor safety assessments and space launch reliability estimates [6]. There are rigorous methods for making subjective uncertainty explicit, quantifying it, combining estimates of different subjects, and updating the combined estimate in a logical manner when relevant data become available [6]. One analyst who advocates such methods for validation notes that "this validation process is unquestionably subjective, but not capriciously so" [37].

Simulation, computer animation, and virtual reality are now being used as evidence in criminal and personal-injury trials, and their validity is at issue [71 ,52]. The armed services' security forces (the Army's Military Police, the Navy's Shore Patrol, and the Air Force's Security Police) and investigative units (the Army's Criminal Investigation Division, the Naval Investigative Service, and the Air Force's Office of Special *In*vestigations) may consider using such forensic simulations and will be interested in their validity, including the admissibility of their results as evidence in court. Conversely, civil investigators might benefit from DOD-developed validation methods and examples.

Standardization

Standardization is a perpetual issue, because technology is dynamic. This is particularly true of computer networking and distributed simulation.

DOD participated in the deliberations of the IEEE Standards Board, a nongovemment standards body (NGSB), to influence the drafting and adoption of IEEE Std 1278-1993, the industry standard for protocols for distributed interactive simulation applications. This approach has many advantages over simply issuing a military stan-

dard; it facilitates civil-military integration, the potential benefits of which are discussed in OTA's report on civil-military integration [170]. The October 20, 1993 revision of Office of Management and Budget (OMB) Circular A-119 encouraged federal agencies to participate in NGSB deliberations and allowed federal employees to participate on job time. Of course, this participation requires funding, but it can be money well spent.

Because DIS technology is so dynamic, there are already calls for revising or superseding IEEE Std 1278-1993. Critics argue that simulations compliant with "the DIS protocol" (IEEE Standard 1278) cannot be scaled to accommodate the 100,000 entities (e.g., vehicle simulators) that ARPA hopes to have netted together in its Synthetic Theater of War (STOW) program by 1997. Others propose that the DIS standard be revised to accommodate the exchange of additional kinds of data, such as economic data, that are not now modeled. These issues of scalability and flexibility are discussed below. Issues of network synchronization and multilevel security will also be mentioned.

Scalability

The DIS protocol requires every entity in a simulation to broadcast certain changes (e.g., in its velocity) to every other entity in the simulation ("on the net"). In most cases information about an airplane's change in heading maybe needed only by entities within a 100-km radius in the simulated world. However, if someone wants to connect an over-the-horizon (OTH) radar simulator to the net to see how much it would influence combat, it would need heading and other information from aircraft halfway around the simulated world. In drafting the DIS protocol, it was simpler to require broadcasting of certain information than to draft special clauses for all the combinations of fighters, helicopters, OTH radars, and other entities that one can imagine. The approach has worked well to date, but that does not imply that it will work at all if the number of entities in the simulation is increased 100-fold.

If 1,000 entities are on the net, and if each makes one reportable change per minute, then each of the 1,000 entities will be receiving 999 (roughly l,OOO)messages per minute. If thenumber of entities on the net is increased to 100,000, then each of 100,000 entities must receive and process 100,000 messages per minute. The aggregate (over all entities) computational capacity devoted to reading the messages must increase 10,000 times. The aggregate capacity devoted to other simulation tasks, such as image generation, may increase by a much smaller factor. Today, the computational resources devoted to scene rendering dominate those devoted to message processing, but if the number of simulators were increased by a sufficiently large factor (which OTA has not estimated) and no other changes were made, messaging computation (and cost) would dominate computation for other simulation tasks. The aggregate network communications capacity ("bandwidth") servicing the entities would likewise increase in proportion to the square of the number of entities, and the marginal cost of adding one more simulator to the network would begin to increase approximately in proportion to the square of the number of simulators already on the network. Thus, there is a limit on the number of entities that can be netted economically, and there is a limit on the number that can be netted at all, although technological advances are constantly increasing these limits.

There is also a problem of nonsalability in configuration control. The software for each *type* of entity (e.g. vehicle or weapon) must be modified when one new type of entity is allowed in the simulation [147].

Developing a scalable DIS protocol is a challenge to DOD and industry. Alternatives to data broadcasting that have been investigated recently include 1) the Event Distribution Protocol (EDP) developed by the MITRE Corp. [213] as a modification to the Aggregate Level Simulation Protocol (ALSP) (which is not DIS-compliant but uses broadcasting), and 2) the Distribution List Algorithm developed by NASA's Jet Propulsion Labo-

ratory and the MITRE Corp. [159]. The developers of the Distribution List Algorithm claim that it also has a more logically rigorous method of synchronizing entities, which, they argue, is needed for "analytic studies" but is not as critical for the real-time training and systems acquisition decision-aiding uses to which DIS has been applied.

Flexibility

Some critics have urged that the successor to the DIS protocol be flexible enough to allow the modeling and distributed simulation of a variety of processes other than those related to weapon and sensor platforms. Weather, epidemics, and economic (especially industrial) activity are processes that some would like to see modeled [147]; all can be relevant to combat. For example, the success of World War II's Operation Overlord hinged on the weather on D-Day [18]; the risk that Iraqis might use biological weapons and cause an epidemic affected planning, logistics, and operations in Operation Desert Shield and Operation Desert Storm [153], as did the rapid development, production, and fielding of GBU-28 earth-penetrating bombs and optical beacons ("Budd Lights" and "DARPA Lights" [166]) for distinguishing friend from foe. Such interactions between operational need and industrial response cannot now be simulated in realtime (or faster) except in refereed games. ARPA's Simulation-Based Design program is undertaking to facilitate simulation of selected industrial activities and their effects on combat capabilities.

The flexibility to simulate diplomatic and domestic political processes might also be valuable for training those who would manage the those dimensions of the national response to a crisis. Referreed political-military exercises have been used for this purpose for decades. They are of questionable validity as predictive models but are nevertheless considered useful for training.

After the 1992 Senate Armed Services Committee hearing on advanced simulation technology, Senator Strom Thurmond asked witness General Paul German, USA-Ret., Chairman of DOD's Simulation Policy Study, to answer the following question for the record [173]:

> . . . I would imagine that if you could model political and economic factors, you could make simulators for crisis management training as well. Have you recommended any analysis in this area?

General German replied [72, p. 728]:

> . . . My experience makes [me] a strong supporter of simulation as a way of preparing for future crises. That same experience leaves me doubtful that we will ever be able to adequately model political and economic factors. . . . Modeling war is comparatively simple. Battle outcomes, after all, are rooted in fairly discrete physical phenomena, and we are now well versed on how to allow humans realistically to interact with simulations of these phenomena. . . .

German's pessimism concerning crisis games echoes the skepticism expressed by RAND analyst Robert A. Levine in 1964 [123]:

> . . . if gaming is used, any research conclusions should stand and be defended entirely on the basis of non-game "real-world" evidence.

This is another way of saying that if crisis games are to be used as predictive models, then they should be validated—just as any other type of model should be. A difficulty with output validation of crisis games is that there is seldom more than one real crisis evolving from a particular initial scenario against which game results may be compared.[27]

The Advanced Research Project Agency is funding the development and demonstration of human-computer interaction (HCI) technology applicable to crisis management, health care, and education and training. "The vision of the HCI program is to greatly increase the ease and natural-

[27] The same is true of battles and campaigns. In some cases, there are more data for validating platform engagement models.

ness of human interactions with complex computer-based systems, and to reduce the difficulty and risk associated with user-system interface development," according to the solicitation for proposals [177]. The solicitation does not mention virtual reality by name, but VR technology could contribute to or benefit from the program.

I Effectiveness

In the 1992 SASC hearing on advanced simulation technology, Senator Thurmond asked General Paul German an important question about the effectiveness of virtual simulation [173, p. 718]:

> Although I support the use of simulators for training our service personnel, I realize that it cannot constitute the sole training method. What percentage of training using a tank crew as an example, can effectfully be accomplished through the use of simulators?

General German replied that the question requires "a long and complicated answer," but he gave a short one. He said that [networked virtual] simulators are "very good at showing tactical relationships." He cited one example of a training task that simulators are not very good at: providing an environment in which the loader, a member of a tank's crew, can learn to load 55-pound shells while the tank turret is moving as it would in combat.

OTA believes that that particular problem could be solved, at considerable expense, by building motion-base tank simulators using the technology developed for aircraft cockpit simulators, even before the first Link Trainer [139]. However, as noted above, providing haptic feedback to dismounted infantry soldiers remains a challenge. So does providing the "long and complicated answer" that General German said Senator Thurmond needed. The answer must begin by rephrasing the general question as a list of specific questions, because the answer depends on many variables, such as the specific tasks to be learned. If a list of tasks were in hand, it might be possible (but would be costly) to answer the simpler, focused question: "Could simulators substitute for x percent of these training hours (or dollars)?" A closely related but more difficult question is: "Would it be cost-effective to use simulators to substitute for x percent of these training hours?"

| Cost-Effectiveness

Assessing cost-effectiveness requires assessing effectiveness (e.g., measuring training transfer effectiveness) as well as measuring, estimating, or forecasting cost data. Hence it is even more difficult than assessing effectiveness. Just as one cannot describe the effectiveness of simulators or simulation in general; neither can one describe the cost-effectiveness of simulators or simulation in general. It is necessary to ask the cost-effectiveness of a particular simulator or simulation for a particular purpose, and to do this again and again, once for each combination of simulator and purpose.

As part of its assessment of combat modeling and simulation, OTA is searching for analyses of simulator and simulation cost-effectiveness. OTA will report its findings in its final report on this assessment, which is due in 1995.

| Infrastructure

Some of the technical challenges noted above—the development of better LCDs or other flat-panel displays for HMD, and the construction of a wideband secure computer network—are issues of industrial and civil infrastructure with implications extending far beyond combat simulation, even to national economic competitiveness. They have been recognized as such by the Administration and by the committees of Congress with jurisdiction over commerce, defense, and other affected activities. Some funding has been provided to address these issues-directly, or by stimulating industry-through programs such as those now included in the Defense Technology Conversion Council's Technology Reinvestment Project (TRP). Progress and needs are reviewed annually, and funding is provided through the Department of Commerce (National Institute of Standards and Technology), the Department of Defense (Advanced Research Projects Agency),

the Department of Energy, the National Aeronautics and Space Administration, and the National Science Foundation.

Collection and organization terrain and cultural data into databases in formats that can be readily used in virtual simulation is another issue with implications extending beyond the scope of virtual military simulation [167,168]. Regarding its importance in naval applications of VR to strike training and mission rehearsal, a Center for Naval Analyses memorandum recently recommended to the Navy's Director for Air Warfare [210]:

> Because the realism of the simulators used for aircrew training and mission rehearsal is driven by the fidelity of the underlying databases, Navy requirements should focus on the specification of database characteristics and close coordination with the Defense Mapping Agency to ensure timely availability of the required products.

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A

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Appendix B: Glossary of Acronyms

B

3-D	Three-Dimensional
6-D	Six-Dimensional
A^2ATD	Anti-Armor Advanced Technology Demonstration
ADM	Advanced Development Model
ALSP	Aggregate Level Simulation Protocol
ARPA	Advanced Research Projects Agency (formerly DARPA, originally ARPA)
ATD	1. Aircrew Training Device 2. Advanced Technology Demonstration
ATM	Asynchronous Transfer Mode
BOOM	Binocular Omni-Orientation Monitor
CAD	Computer-Aided Design
CART	Collision Avoidance Radar Trainer
CAT	Computed Axial Tomography
CAVE	CAVE Automatic Virtual Environment (a recursive acronym)
CCTT	Close Combat Tactical Trainer
CD-ROM	Compact Disk Read-Only Memory
CIG	Computer Image Generator
COEA	Cost and Operational Effectiveness Analysis
CORBA	Common Object Request Broker Architecture
CRT	Cathode-Ray Tube
DARPA	Defense Advanced Research Projects Agency (originally and now ARPA)
DIS	Distributed Interactive Simulation
DISA	Defense Information Systems Agency
DMD	Digital Micromirror Device
DOD	Department of Defense
DODD	Department of Defense Directive
DOS	Disk Operating System
DRR	Digital Radar Relay
DSI	Defense Simulation Internet
DWS	Distributed Wargaming System
EDP	Event Distribution Protocol
EISA	Extended Industry-Standard Architecture
ENIAC	Electronic Numerical Integrator and Calculator (or Computer)
FAA	Federal Aviation Administration
FOHMD	Fiber-Optic Head-Mounted Display
FTP	File Transfer Protocol
GE	General Electric [Company]
GRIP	Graphical Interaction with Proteins
HCI	Human-Computer Interface
HMD	Head-Mounted Display
HPCCIT	High-Performance Computing and Communications and Information Technology

IBM	International Business Machines (Corporation)
IEEE	Institute of Electrical and Electronic Engineers
IFFN	Identification, Friend or Foe or Neutral
I-Port	Individual Port
ISDN	Integrated Services Digital Network
IUSS	Integrated Unit Simulation System
JWFC	Joint Warfighting Center
KAT	Keyboard-Alternative Technology
LAN	Local Area Network
LC	Liquid Crystal
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
MBONE	Multicast Backbone
MDT^2	Multi-Service Distributed Training Testbed
MEW	Microwave Early Warning
MIT	Massachusetts Institute of Technology
MOSAIC	Models and Simulations, Army Integrated Catalog
MRM	Medical Regulating Model
MS-DOS	Microsoft Disk Operating System
MUSE	Multi-dimensional User-oriented Synthetic Environment
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Alliance
NGSB	Non-Government Standards Body (or Bodies)
NPS	Naval Postgraduate School
NPSNET	Naval Postgraduate School Network
NSTC	National Science and Technology Council
NTSC	1. National Television System Committee 2. National Television Standards Convention 3. Naval Training Systems Center
OEM	Original Equipment Manufacturer
OMG	Object Management Group
OTA	Office of Technology Assessment
OTH	Over-the-Horizon
PC	Personal Computer
PDU	Protocol Data Unit
RADAR	Radio Detection and Ranging (radar)
RDT&E	Research, Development, Testing, and Evaluation
RISC	Reduced Instruction Set Computer
RSAS	RAND Strategy Assessment System
SACEUR	[NATO'S] Supreme Allied Commander-Europe
SAGE	Semi-Automatic Ground Environment
SBB	Synthetic Battle Bridge
SBD	Simulation-Based Design
SBDS	Simulation-Based Design System
SGI	Silicon Graphics, Incorporated
SIMNET	Simulator Networking
SMTP	Simple Mail Transfer Protocol
SONET	Synchronous Optical Network
SPOT	Système pour l'Observation de la Terre
STEP	Standard for Exchange of Product Model Data
STOW	Synthetic Theater of War
STP	System Training Program
TCP	Transmission Control Protocol
TCP/IP	Transmission Control Protocol/ Internet Protocol
TE	Thermo-Electric
TRP	Technology Reinvestment Program
TV	Television
TWBNet	Terrestrial Wide Band Network
URL	Uniform Resource Locator
Us.	United States
USA	United States Army
USAF	United States Air Force
UTD	Unit Training Device
VCASS	Visually Coupled Airborne Systems Simulator
VCR	Video Cassette Recorder
VEI	Virtual Entertainment, Incorporated
VHS	Video Home System
VIEWS™	Virtual Interactive Environment Workspace
VIM™	Vision Immersion
VITAL	Virtual Image Takeoff and Landing
ViVED	Virtual Visual Environment Display (pronounced vivid)
VPL	1. Virtual Programming Language

ViVED	Virtual Visual Environment Display (pronounced vivid)
VPL	1. Virtual Programming Language 2. VPL Research, Inc.
VR	Virtual Reality
VRD	Virtual Retinal Display
VRT	Variable Resolution Terrain
VTC	Video Teleconferencing
VV&A	Verification, Validation, and Accreditation
wow	Window on a World
W C	Warrior Preparation Center
WWW	World Wide Web

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