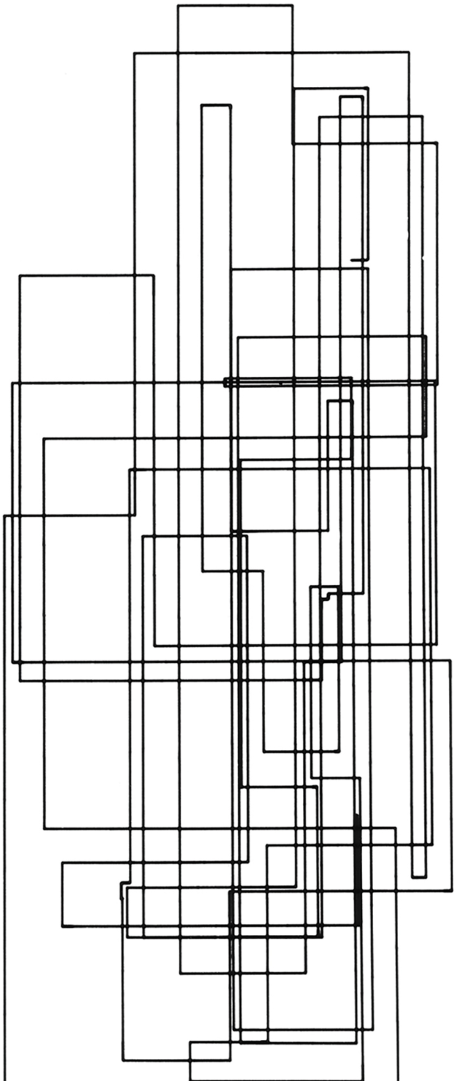
PLATFORM STUDIES

PERIPHERAL VISION

Bell Labs, the S-C 4020, and the Origins of Computer Art



Zabet Patterson

Peripheral Vision

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For A

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Series Foreword

How can someone create a breakthrough game for a mobile phone or a compelling work of art for an immersive three-dimensional environment without understanding that the mobile phone and the 3D environment are different sorts of computing platforms? The best game artists, writers, programmers, and designers are well aware of how certain platforms facilitate certain types of computational expression and innovation. Likewise, computer science and engineering have long considered how underlying computing systems can be analyzed and improved. As important as scientific and engineering approaches are and as significant as work by creative artists has been, there is also much to be learned from the sustained, intensive, humanistic study of digital media. We believe it is time for humanists to consider the lowest level of computing systems to understand their relationship to culture and creativity.

The Platform Studies book series has been established to promote the investigation of underlying computing systems and the ways that they enable, constrain, shape, and support the creative work that is done on them. The series investigates the foundations of digital media—the computing systems, both hardware and software, that developers and users depend on for artistic, literary, and gaming development. Books in the series will vary in their approaches but will share certain features:

- A focus on a single platform or a closely related family of platforms,
- Technical rigor and in-depth investigation of how computing technologies work, and

- An awareness of and discussion of how computing platforms exist in a context of culture and society, being developed based on cultural concepts and then contributing to culture in a variety of ways—for instance, by affecting how people perceive computing.

Acknowledgments

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My parents have offered years and hours of endless patience and support. Matthew, laughter and learning a little something, always. My extended family has offered love and understanding. But the days, weeks, and minutes have belonged to my smaller family: Perdita, Surya, Maya, and, above all, Andrew.

Introduction

In the late 1950s and 1960s, mainframes dominated computing. Their name came from the large metal frames in which banks of circuits were mounted. They were more architecture than object, and their cost was commensurate. As such, these computers were the exclusive province of governmental military agencies, university research centers, and a few of the largest corporations. Their image in popular culture was of switches and blinking lights, emphasizing that first and foremost they were calculation machines—with no necessary relationship to optical media. In the era of the mainframe, the output of text and image was quite literally peripheral. Companies made a range of special-purpose devices to supplement mainframe computers that did not necessarily ship with screens or printers.

Stromberg-Carlson was one of these manufacturers. In 1954, the US Department of Defense contracted with it to supply a special-purpose mainframe peripheral for the SAGE (Semi-Automatic Ground Environment) computerized air defense system—a cathode ray tube (CRT) screen. SAGE was tricked out in firsts: among other things, it famously initiated the coordinated and systemic use of lightguns, duplexing, multiprocessing, modems, and computer networking over telephone lines. Nonetheless, the screen that functioned as a real-time graphical user interface is generally understood to be its most important feature. Manufactured by Stromberg-Carlson, it was the company's first flagship product, and the Defense Department order was its largest to date. The key dilemma for the SAGE designers was the need for highly legible text with a sufficiently rapid refresh rate to allow air force specialists to track aircraft in real time. Stromberg-Carlson engineered a CRT screen called the Charactron. Its shaped beam tube deflected electrons through a mask of alphanumeric characters, transferring these characters to the viewing area at very high resolution with a display rate of ten thousand characters per second.

In 1959, Stromberg-Carlson began manufacturing another mainframe peripheral based on the Charactron screen. This one did not offer real-time interactivity. The S-C 4020 microfilm recorder could be attached to the IBM 7090, 7094, 360, and other existing mainframes to present and preserve images and image sequences in ways that then-contemporary interactive computer screens simply could not. It could produce extraordinarily precise line drawings and text far above the level of pen-based plotters. It was a strange and elaborate apparatus with a tape drive for accepting instructions, a controlling buffer, a Charactron screen sealed in a light-tight compartment with a film camera and a photographic camera, and development equipment for these images. Because the S-C 4020 does not easily fit within linear genealogies of computing that move inexorably toward interactivity and real-time engagement, it has largely fallen "off the radar" of modern computer histories, despite its central importance as a peripheral for visualization for the mainframe computers of the late 1950s to the mid-1980s. Yet its use during that time was sufficiently widespread to prompt its own user group, its own conferences, and even its own specialized scientific journal. All told, the S-C 4020 produced the majority of the computer graphics of the late 1950s and early 1960s.

The Stromberg-Carlson Microfilm Recorder was not a cheap machine. It cost approximately $325,000 in the mid-1960s. The IBM 7094 to which it was it was frequently attached cost $3.5 million dollars. Running the S-C 4020 cost approximately $500 per minute of output.[1] The microfilm plotter's primary market was thus necessarily the same military agencies, research institutions, and corporations that purchased mainframe computers. S-C 4020 deliveries went to places like the University of California Radiation Laboratory, the Naval Ordnance Proving Ground, the Johns Hopkins University Operations Research Office (ORO), Eglin Air Force Base, and the Atlas Computer Laboratory in England. The S-C 4020 was an industrial technology that was widely used in a number of different contexts for more than fifteen years. In each of those contexts, it was upgraded and transformed in various ways. The Atlas lab, for example, has online documentation of some of the various camera upgrades and reconfigurations that took place between 1967 and 1972.

Such a complex history of technological reception and adaptation necessitates a delimited treatment. Thus, this study does not propose a wide-ranging treatment of the S-C 4020 and its relationship to the development of computer graphics across a sweeping international context. Rather, it focuses exclusively on the machine delivered to Bell Labs Research and Development in New Jersey. It does so not because of any inherent differences in the machine that was delivered there but rather because of the extraordinary uses to which it would be put between 1961 and 1972.

The machine purchased by Bell Laboratories was installed at its Murray Hill campus, an industrial lab in the suburban hills of New Jersey some twenty-five miles from the grit and noise of New York City. Surrounded by hundreds of acres of protected forest, scientists and engineers worked in brick and glass buildings while deer grazed on the lawns. Constructed in 1941, the campus was essentially one large building that housed around four thousand people engaged in a wide range of disciplinary research. The building had been designed to facilitate fortuitous and unexpected encounters. Offices and labs were intentionally small and separated into different corridors. Long hallways housed entire research divisions. Walking between corridors, in the atrium, and in the cafeteria, people encountered colleagues, digressions, and problems.

This intellectual ferment made Bell Labs home to some of the most significant breakthroughs in science and engineering from the 1920s to the 1980s. Transistors, lasers, satellites, cellular telephony, information theory: the list is long, and the story has been told many times.[2] Less well known is that in the 1960s, Bell Labs also became a crucial site in an epochal intersection between modern art, science, and technology as important as anything since the Bauhaus of the 1920s—and that a seemingly peripheral device, the S-C 4020 microfilm plotter, was at the heart of that intersection.

Bell Labs often enters the story of new media art via Experiments in Art and Technology (E.A.T.) with Robert Rauschenberg and Billy Klüver. With Experiments in Art and Technology, the artists are the driving, creative force; the engineers show up simply to implement their ideas. The rhetoric of the day emphasizes this: there were artists on one side, and engineers on the other, and their collaboration was the result of fortuitous encounters. Yet this binary is a drastic simplification if not an outright historical falsification, and it should not be allowed to persist. In the early work of Kenneth Knowlton and Michael Harmon, for instance, a coin was flipped to see who would be the engineer and who would be the artist— just one instance of how irrelevant these labels could be. And yet these labels cannot simply be ignored because they often had significant real-world implications—for how this work was made, where it was exhibited and encountered, and the discursive models through which it was discussed and conceptualized.

A close examination of the S-C 4020 and the work made with it leads us to another story, one that has been left out of the histories of that era. This story problematizes sites of exhibition, modes of work, and the collective role played by artists and engineers in producing both artistic advances and scientific innovations. Revealing a much closer overlap between art, science, and technology, this story shows how science and technology enable innovations in art practice, and how artistic practice also reshapes science and technology—transforming ideas about visual perception and innovation in computation.

Stromberg-Carlson advertised the S-C 4020 as offering the easy production of tabular data, graph plotting and design drawings, grid projections and drawing of axes and vectors, automatic forms projection, and permanent storage on microfilm. But the machine made all kinds of previously invisible objects and processes suddenly, startlingly visible—and made previously impossible visualizations remarkably possible. E. E. Zajac made the first computer film, simulating the motion of a communications satellite around the earth. Béla Julesz and Michael Noll made astonishing leaps in understanding depth perception in human vision by writing routines that created random-noise stereographs to answer questions about seeing that had gone unanswered since 1838. Kenneth Knowlton developed innovative techniques for scanning photographs, creating work collected by the Museum of Modern Art (MoMA) in New York. Stan VanDerBeek and Lillian Schwartz used Fortran-based computer languages to produce experimental cybernetic films generally regarded as crucial early works of computer art.

Because of the emphasis that Bell Labs placed on interdisciplinarity, artists were able to access equipment that was far more expensive than anything they could have afforded by themselves, and the presence of artists led scientists to think more expansively about their inquiries. In the history of computer visualization and computational media aesthetics, the importance of Bell Labs—and the work of Zajac, Noll, Knowlton, Harmon, VanDerBeek, Julesz, and Schwartz there—is canonical and established, though certainly not to the degree it deserves within histories of late modern art and aesthetics more generally. Yet what is insufficiently appreciated is the degree to which the work of these pioneers was influenced by the particular affordances of the S-C 4020 and the ways in which those affordances can help us to see important associations between these seemingly heterogeneous works. Literally as well as metaphorically, an acute attention to the peripheral allows us to understand the specific materiality and context of these interactions in ways that would not otherwise be possible.

Taking up the challenge of the Platform Studies series, *Peripheral Vision* provides a meticulous accounting of the hardware of the S-C 4020 that was used at Bell Labs—taking into account its configuration and architecture on the mutually interconnected level of software and hardware, as well as the culture of scientific research and military computing that drove its construction and initially framed its capabilities and possibilities.[3] In this, it works toward a materialist history of computation. It examines how software was developed for this platform and how this software was rewritten and reshaped to take better advantage of the hardware. *Peripheral Vision* considers how the unique technical affordances of this platform reshaped modes of scientific research and led to the creation of some of the most significant works of computer art in the 1960s. It also considers the widely divergent cultural contexts in which these images and films were shown and encountered. Secondarily, it emphasizes that there was not a direct, linear progression that moved ever more surely to personal, interactive computing. Instead, there was a significant period during the 1960s that was dominated by the mainframe computer and the possibilities of a mode of computation that was not based on direct access to a graphical user interface. In doing so, it develops an alternative genealogy of computer art at Bell Labs.

Looking closely at the S-C 4020 helps us to emphasize that computers are not singular machines, complete unto themselves, but complex, hybrid objects that are multiply layered and dependent on external systems. Using the S-C 4020 as an optic provides us with an indirect view of computer history that might serve to challenge some closely held methodological assumptions. Taking such a "peripheral" as our primary object might imply more than simply a rigorous attention to a set of concrete material technologies. It might also serve as a methodological appeal for a more oblique perspective on the history of technology more generally.

For while the mainframe computer has been universally acknowledged for shaping the evolution of graphics computation, the unsung S-C 4020 was just as significant to this history—precisely because of the specific limitations it imposed. Resituating "peripherals" as central to histories and theories of computation would demand that we attend to the historical materiality of particular computational systems not as they were intended at the outset but as they were adjusted and modified in actual practice. It highlights the necessity of considering partial elements, such as screens and disk drives, in any discussion of the "affordances" within any computational system. It emphasizes the need to situate these partial elements within increasingly larger systemic rings—computer systems but also political, social, and economic systems within which the material practices of computation acquire meaning and significance. And finally, it asks that we consider what it would entail to reconceptualize the writing of history—of both computer history and more general histories of technology and culture—from the perspective of this kind of "peripheral vision." This social-materialist model's oblique perspective might enable it to emphasize the key fault lines that inevitably persist beneath the surface of our familiar, overarching narratives.

What Was a Microfilm Plotter?

1

With the Charactron screen, Stromberg-Carlson reshaped the field of computer graphics at a time when the mainframe computer was the rule rather than the exception. The Charactron was originally developed as a standalone screen, a peripheral whose most famous use was in the SAGE system. This chapter examines how the Charactron screen drew straight lines and curves from airplanes navigating the shifting currents and chaotic updrafts of the sky. With the Charactron, points were drawn and labeled, photographic clutter was reduced, and hardware and software combined to imagine a new model of visual perception.

Stromberg-Carlson later built this screen into a general-purpose graphic and text printing device—a machine for generating images that helped the computer "to talk in everyone's language," as their advertisements would have it.[1] *The Stromberg-Carlson 4020 was what became known as a microfilm plotter—a peripheral device that combined several elements, including the Charactron cathode ray tube, a magnetic tape deck, a buffer unit, a forms flash unit, a film camera, and a photo-paper camera.*

This chapter examines the relationship between computer and peripheral by carefully considering the process of programming the S-C 4020 as it was installed at Bell Labs in 1961. It was a complicated routine that involved Fortran, punchcards, an IBM 7094 mainframe, and magnetic tape reels. The chapter concludes with a close reading of the affordances of the S-C 4020 by looking at two examples that, like the screens of SAGE, combine language and vector "drawings"—E .E. Zajac's short film of a satellite orbiting the earth, typically credited as the first digital computer film ever made, and F. W. Sinden's Force, Mass and Motion*, a depiction of Newton's Law using several different central* *force laws. The lines and curves of the films come from the Charactron screen, the jittery black and white from microfilm processing, and the complex physics from the IBM 7094's calculations. Shaped both by the Charactron's screen and a lingering cybernetic theory of vision and visuality, both works privilege the diagram over the photograph as a mode for producing knowledge by simulating the physicality of objects in the world.*

As this chapter lays out, the S-C 4020 is a material collision of a number of different technologies, each with an individual history. The different technologies—magnetic tape, buffer, cathode ray tube, slide unit, cameras, and microfilm—came together in unexpected ways, and using the S-C 4020 required a careful negotiation of these complex affordances. In particular, the Charactron display's straight lines and easy-print characters had a massive effect on the development of the S-C 4020, but so too did its magnetic tape input, microfilm output, drivers, and logic boards, which functioned collectively to make up this complex apparatus.

A Special-Purpose Screen: The Charactron

Imagine, for a moment, that the year is 1958. You are a tracking operator in the air surveillance section of the US Air Force. Your job is to sit in a windowless room and watch a small round screen about sixteen inches in diameter, in a blue-lit room with other specialists stationed at identical screens, with different views. The scope in front of you refreshes itself in a steady clockwise sweep, displaying blips representing all of the air traffic in your sector, generated by long-range radar.

In your right hand is an object shaped like a backward pistol, with a sight on the top. It is attached by a connecting wire to the system you know as Semi-Automatic Ground Environment (SAGE). Within this computerized air defense system, individual moving objects—representing gathered data—are visually represented by small moving blips, which make their way across your screen. Each blip is understood as an object in motion. Aiming—firing—with your lightgun and sight, you select a specific blip on the radar screen, telling the computer to track that object.[2] Unidentifiable blips are immediately relayed to operators in the identification section, who are set to scramble planes to intercept enemy bombers.

This system is reminiscent of the analog computers used as gun controllers in a slightly earlier era. But SAGE was decked out with high-tech novelty: lightguns, duplexing, multiprocessing, modems, and computer networking over telephone lines were only some of its many innovations. Yet for the present discussion, its most important feature was unquestionably the screen that enabled a real-time graphical interface.

However, unlike earlier analog gun controllers, the SAGE system did not itself aim and fire. Rather, it was intended to deploy a squadron of bombers to perform this particular duty. Decisions—to launch planes, to fire missiles—had to be made quickly, by human operators. Thus, the interface for SAGE was straightforward, transparent. Or so *Life* magazine told its readers in 1957, saying that this enormous computer was able to summarize and present data "so clearly that the Air Force men who monitor SAGE can sit quietly in their weirdly lighted rooms watching its consoles and keep their minds free to make only the necessary human judgments of battle—when and where to fight."[3] The sky is an inherently shifting and chaotic space of unclarity—currents and updrafts, clouds and fog. For SAGE to work, the paths of objects and bodies within these spaces had to be rewritten into repeatable, replicable, easily transmissible curves and lines. Instrumentalizing vision, these machines required the human operator to accommodate himself to new paradigms of visualization.

Vision and perception are here reimagined arithmetically, while the human subject is reimagined as "manageable, predictable, productive, and above all consonant with other areas of rationalization."[4] These points are models rather than mimetic representations. This is an informatic relationship with the world. Alexander R. Galloway has recently suggested that "in order to be in a relation with the world informatically, one must erase the world, subjecting it to various forms of manipulation, preemption, modeling, and synthetic transformation."[5] The screens abstract to essentials, reducing visual clutter in favor of structural understanding. These images construct a complex yet structurally integrated system—a dynamic interrelation of elements. Above all, this screen insisted that its abstract vectors and symbols bore an indexical relationship to the world—a truth claim most commonly held to be confined to the domain of the photographic. The dream here is of a vision that might employ automation to permit "rapid, accurate, and detailed central oversight."[6] And "oversight," in this context, is not a term present by happenstance. The becoming-pictorial of computers would be intimately intertwined with a military imperative for command and control, with visual mastery, and as such, with what psychoanalytic philosophy would call the "scopic drive."

As late as 1947, officers of the air staff thought that the kind of surveillance represented by the SAGE project was impossible and that there was no way for the air force to continually monitor the skies over the entire United States for hostile bombers. Full coverage radar, combining electronic monitoring with human observers, was impractical. Worse, it was potentially disastrous, as it left "little room for the air offensive," which was seen as the only hope for real security.[7] The 1947 Air Policy

Commission, assigned by President Harry Truman, also opposed a full-coverage radar system using a similar rationale, arguing it would "divert us—as the Maginot Line diverted France—from the best defense against an atomic attack, the counter-offensive string force" already in place.[8] Calculations changed in 1949, when the Russians detonated an atomic bomb several years ahead of the timetable projected by US intelligence. The cold war escalated precipitously, and Congress granted emergency war powers. Budgets abruptly increased, money flowed like water, and suddenly, a technologically updated Maginot line of integrated radar units that could oversee the skies became a priority for the Defense Department and the National Security Council.

The air force found the technical beginnings for this project in the Whirlwind system, a Massachusetts Institute of Technology project originally built as a flight simulator and subsequently reimagined as an anti-aircraft computer. But as engineers and programmers labored to develop SAGE from this framework, they realized that Whirlwind lacked something crucial—a means of interactive control. It had a screen, but as developer Norman H. Taylor stated, "All we used the display for was testing the various parts of the system."[9] SAGE needed "a man-machine interactive display system to exercise control."[10] Not only did it need screens—it needed a lot of them, enough "to control over 400 aircraft simultaneously. [The original] estimate of 32 consoles grew to 64 and then to 82."[11] And those displays certainly had to be "a little more sophisticated than a point of light on a cathode ray tube."[12]

George Valley, one of the heads of the SAGE project, pointed out that in the 1950s, "relatively few wanted to connect computers to the real world, and these people seemed to believe that the sensory devices would all yield data.... Most sensory devices relied on human operators to interpret noisy and complex signals."[13] Two Stromberg-Carlson employees confirmed this in an article on the screen that they manufactured for SAGE and other applications: "not too long ago in surveillance systems, it was sufficient to present raw radar and supplementary data to observers. The systems performed satisfactorily, since the observer had sufficient time to calculate the necessary information for his task manually from the raw data."[14] But in the present, "it is becoming increasingly important to provide the observer with sufficient quantity and quality of information to make decisions more accurately and rapidly. The problem is being continually magnified because of the increased speed and number of objects under surveillance. As a result, raw radar data and manual calculation are no longer adequate."[15] As a result of this, Stromberg-Carlson was working to link the electronic data-processing equipment directly with character-generating cathode ray tubes: "The data processing equipment converts the raw data into digital form, after which it is presented to the observer as letters, numbers, and symbols by the cathode ray tube."[16]

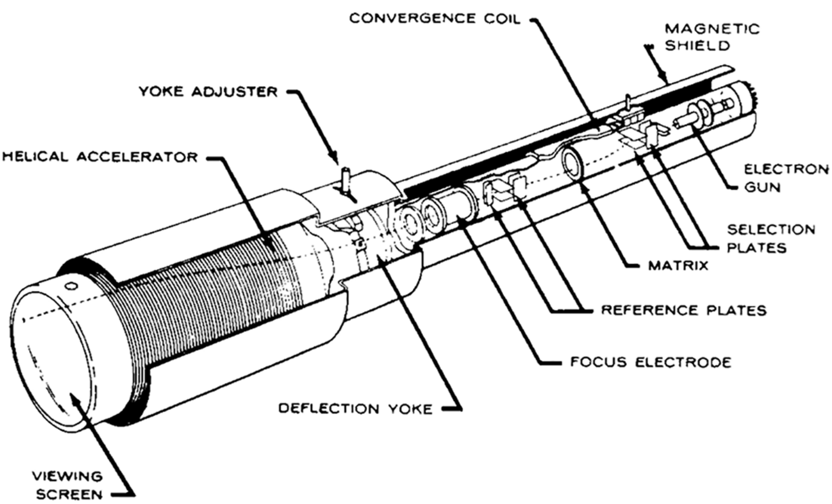
SAGE's computers and screens needed to make noisy and complex signals clear and legible to a human operator. They needed a display that could draw vectors and characters and assemble these elements into orderly message patterns to allow the air force specialists to track airplanes in real time.[17] And it needed this display to have a rapid refresh rate. The solution they found was the Charactron, a special-purpose cathode ray tube that was invented by Joseph T. McNaney for computer readout, high-speed printing, high-speed communications, monitoring, and message display.[18]

The base of the Charactron was the same basic cathode ray tube that was used in televisions and oscilloscopes. Although displaced by flat-screen technology at the beginning of the millenium, the venerable cathode ray tube served as the basis for countless televisions and computer monitors in the second half of the twentieth century. It consisted of a vacuum tube that contains an electron gun (an electron-emitting filament and a control grid), control elements that regulate where the electron beam hits the screen, and a phosphor-coated screen that renders the strike of the electron beam as visible light. The Charactron added something generally called shaped-beam technology to this.

Prior to the Charactron, shaped beam had been used primarily to transmit images rather than as a sort of printing press. As early as 1937, "monotron" CRT screens were made by companies such as National Union and Du Mont.[19] RCA produced a similar tube in 1945, called the "monoscope." Monoscopes were special-purpose CRT tubes equipped with a target printed with a pattern. When the target was scanned with an electron beam, it interrupted the current flow, creating a picture signal that matched the printed pattern.[20] The screen could produce only black and white, but gray could be simulated with delicate lines or newspaper-style halftone dots. RCA's monoscopes were used primarily for fairly intricate television test patterns—the patterns broadcast during a television station's downtime. The monoscope can be understood as a predecessor to the Charactron, but it was designed to display a single image rather than a combination of text and graphics.

Like the monoscope, the Charactron shaped-beam tube adds another element to a simple CRT tube—a metal stencil, generally called a *matrix*, located between the electron gun and the phospor screen. The stencil is tiny, with up to sixty-four characters taking up less than a quarter inch of space. Precisely angled deflection plates guide the beam to a particular area of the stencil. Where the electron beam hits the solid metal of the stencil, it stops. But the portion of the beam that hits the open area passes through and takes on the shape of the stencil. When this "shaped beam" hits the phosphor screen, the visible light is shaped and then positioned on the screen by additional deflection plates. This can produce a sharp, clear image of any number of special characters, in addition to regular alphanumeric symbols. Anything that can be cut into a stencil can be precisely displayed on the screen. After the characters appear on the screen, they can be read or photographed.[21] Because the tube deflected electrons through a mask of alphanumeric characters (transferring the characters at very high resolution to the viewing area rather than tracing the characters onscreen with the beam itself), it meant that a high rate of speed was possible: characters could be displayed at a rate of ten thousand per second. This was a crucial evolution in graphics—but also a stopgap, generated from necessity. Nevertheless, this technology left its mark on the history of computer graphics.

Stromberg-Carlson built the Charactron shaped-beam tube into a hybrid apparatus called the S-C 4020 that consisted of a seven-inch Charactron shaped-beam tube "associated electronic controls and logical circuitry," an automatic operated camera (also controlled by the system), and an input device that utilized magnetic tape.[22] This device, as a whole, was variously called a *microfilm plotter*, a *microfilm printer*, a *microfilm recorder*, or a *computer-operated microfilm* (*COM*) device. The first term links it to the mechanical analog plotter that was used as an output device for mainframe



Charactron tube diagram from a Stromberg-Carlson advertisement.

computers both prior to and after the development of the microfilm plotter. Through digital to analog conversion, the mechanical plotter takes signals from a computer and uses them to direct an armlike machine that draws pencil or pen lines on flat paper or drum carriages of paper. They made precise drawings but were not particularly fast. They were used to make films by means of steady animation but were primarily for producing two-dimensional images on paper. The second term, *printer*, links it to the devices attached to computers to print text, line by line. They were fast but not particularly amenable to graphics. *Microfilm recorder* draws an analogy to either a film or tape recorder and emphasizes the durational nature of the media output. *COM* highlights the computerized aspect of the device. It was also sometimes called a *computer recorder*, further highlighting the hybridity of the apparatus. These terms were often used interchangeably in referring to the device and in advertising it. This speaks in part to a device with widespread use whose use was nonetheless in flux and transition. I have chosen in this text to call the S-C 4020 a microfilm plotter. It is not necessarily the most widely used nomenclature, but it is roughly on par with the term microfilm recorder, and it speaks to both the strangeness of the device and its intimate relationship with prior analog apparatuses used for both input and output.

As would be expected, Stromberg-Carlson and then Stromberg-Datagraphix produced training guides for the operators and technicians who would be responsible for using and repairing the machines. The training guides described how to troubleshoot particular technologies, but somewhat unexpectedly, they also explained the historical background for the device. Three particular elements were singled out—the CRT screen (as has been discussed), magnetic tape, and microfilm processing.[23]

High-Speed Input: Magnetic Tape

Magnetic tape recording devices were initially used in computer systems in 1951 as a replacement of sorts for punchcards.[24] Although crucial for computer development, magnetic tape was a nineteenth-century technology. Danish engineer Valdemar Poulsen successfully experimented with magnetic wire in 1898, creating his "telegraphone," a machine that connected a strung-out steel piano wire and an electromagnet to a microphone. Poulson ran the electromagnet over the wire while talking into the microphone and then played back the recording by connecting the wires from the magnet to a telephone receiver.[25] Recorders with steel tapes were made in Germany in the 1920s, and in 1935, a machine with a plastic base and a magnetic coating was exhibited in Berlin. After that point, the technology developed rapidly, with audio and video applications, and following World War II, data storage.

Paul Ceruzzi calls the rows and rows of spinning magnetic tape reels "the true characteristic of the mainframe," pointing out that "the popular image of these devices was that of 'giant brains,' mainly because of the tapes' uncanny ability to run in one direction, stop, read or write some data, then back up, stop again, and so on, all without human intervention."[26] High-speed computers needed high-speed data to take advantage of the capacities of the machine: "The speed of the automatic computer system is derived primarily from the stored-program concept wherein both the program and the information to be operated upon are contained within the Memory Section."[27]

Memory was fantastically expensive at this point, and magnetic tape served as an "auxiliary memory": it stored information that could then be read and placed in the main memory. Although not as fast as later magnetic disk storage, which offered random access, magnetic tape was still comparatively fast and offered substantial amounts of sequential storage at a time when this was highly desirable. A magnetic tape reader was able to transfer data quickly and easily into the main computer memory.[28]

Or in the case of the S-C 4020, it could transfer data *out* of the main computer memory. As Frank Dietrich points out, "in contrast with today's frame buffers, which hold the image memory in their bit map," the S-C 4020's images "resided in the computer's main memory."[29] More precisely, the image was held in the reel of magnetic tape that was exported from the mainframe computer. Later versions of the peripheral, including the 4060, included a stored program unit, but the 4020 read directly from the magnetic tape.[30] The display driver takes the input from the tape and displays the desired lines and characters on the Charactron. As would be expected, the S-C 4020 understood a limited range of commands. The magnetic tape could carry commands that drew on the screen, including PLOT, EXPOSE LIGHT, EXPOSE HEAVY, TYPE SPECIFIED POINT, TYPE CURRENT POINT, DRAW VECTOR, GENERATE X-AXIS, GENERATE Y-AXIS, and PROJECT FORM. Other commands (SELECT CAMERA 2, SELECT BOTB CAMERAS, EXPAND IMAGE, REDUCE IMAGE, ADVANCE FILM, and PROJECT FORM) controlled camera selection and movement and also allowed for the projection of a blank form template superimposed on the screen.

The vector generator could connect two addressable points with a straight line to produce a geometric graph. The variable-length generator was able to draw a continuous vertical or horizontal line extending the full length or width of the frame, beginning at any plotting position. This added two types of straight-line vector generation to the character matrix. Characters could be positioned by selecting one of 1,024 horizontal positions with one of 1,024 vertical positions. In the normal printing mode, a frame of film could record 64 lines with up to 128 characters on each line; when developed, this translated to a page of output. There was also a typewriter simulator that eliminated the need to generate position data for each character by placing characters automatically on a horizontal line and returning to the "margin" to create a new line when a line was finished.

This narrow range of instructions was nevertheless able to produce fairly complex images quite quickly. An ad for Stromberg-Carlson promoted the speed of the S-C 4020, stating that that it

> will accept data from magnetic tape at input rates up to 62,500 six-bit characters per second. It will record this data on film at speeds in excess of 17,000 alphanumeric or symbolic characters per second. Frames combining characters, vectors and curves vary with the complexity of the specific drawing, but an average annotated graph can be recorded by the S-C 4020 in less than a second.[31]

Information was transferred from tape to the S-C 4020 with a 36-bit input register. The control unit breaks each 36-bit word into its two essential pieces—the operation code and the information (such as specific screen position, character code, or stopping point) that is required to complete the specified operation.[32]

The Output: Microfilm

The S-C 4020 output to microfilm, a nineteenth-century technology that made photography microscopic, allowing for what originally seemed to be an infinite storage capacity. "The whole archives of a nation might be packed away in a small snuff box," opined an optimistic writer for *Photographic News* in 1859: "Had the art been known in the time of Omar, the destruction of the Alexandrian Library would not have been a total loss."[33] Microfilm was thus originally imagined as a hedge against loss, a means of ceaselessly expanding storage capacity that could bypass the fickle nature of paper, which was prone to disintegration and destruction:

> Let us imagine the number of wills or mortgages liable to be destroyed, which would cause boundless litigation.... A microscopic negative of which, carefully stored away ... would give a document as reliable as the original. Hundreds of thousands of such negatives might be put

away to be resuscitated upon the loss of the objects from which they were taken.… I trust that it will be the custom to make microscopic negatives of all valuable public documents.[34]

The microfilm industry began in 1839 with English scientist John Benjamin Dancer, who sold images that had to be examined with a microscope. A technique for making these miniature images was patented in France by René Dagron in 1859. But microfilm became an industrial technology in 1870 during the Franco-Prussian War when it became an answer to the problem of communication over enemy lines. In September 1870, Paris was surrounded by the Prussians and cut off from the rest of France. Telegraph lines were slashed. Mail service was halted. The provincial government in Tours struggled to establish reliable communication with Paris. Sheepdogs failed to traverse enemy lines. Lightweight zinc balls, packed with messages, sunk in the Seine. Balloons transported millions of letters from the city, but return service by the same method was capricious and erratic. The idea they hit upon, finally, was an archaic one—the pigeon. But these were special pigeons, armed with the latest technology.

The Pigeon Post, as it was called, was a startling convergence of multiple technologies and interests. Racing pigeon enthusiasts, balloonists, photographers, and chemists pulled together to create a fairly robust communication network. The pigeons were airlifted out of Paris by balloon to ensure their escape over the Prussian lines. On their return journey, each pigeon carried messages placed in tiny tubes, and tightly attached to the pigeon's feathers. The initial trials used thin paper and handwritten messages, but there were weight and space limits, as well as lapses in penmanship. Microfilm became the linchpin for a national communication system. René Dagron was named the "chef de service des correspondances postales photomicroscopiques." He and his associates were sent to Tours and then Bordeaux, and the microfilm-equipped pigeon dispatch service quickly became operational.[35] In contrast to the handwritten messages, microfilm was extremely light in weight, so a pigeon could carry up to twenty in a small tube.[36] The loaded pigeon flew over the German lines and arrived at a Parisian loft. A bell rang, and the pigeon relinquished its tube to a handler, who transferred it to the Central Telegraph Office. There, each individual microfilm sheet was placed between glass and illuminated via magic lantern. Clerks transcribed the messages for delivery on telegraph forms, taking care to affix a special annotation—"pigeon."[37] But "microfilm" would have been an equally appropriate marker for the 2.5 million messages transmitted.

Over the next seventy years, microfilm took on increasing importance in industry and research. Microfilm began to be used in the financial industry with the development of a machine that made copies of canceled checks for permanent storage by banks. The Library of Congress began to use it as an archival material and microfilmed books and manuscripts. During World War II, it was used to safeguard engineering drawings. With the destruction of cultural artifacts and monuments, war also brought home the need to preserve archives, collections, and cultural documents, and the end of the war saw an uptick in archival preservation using microfilm records.

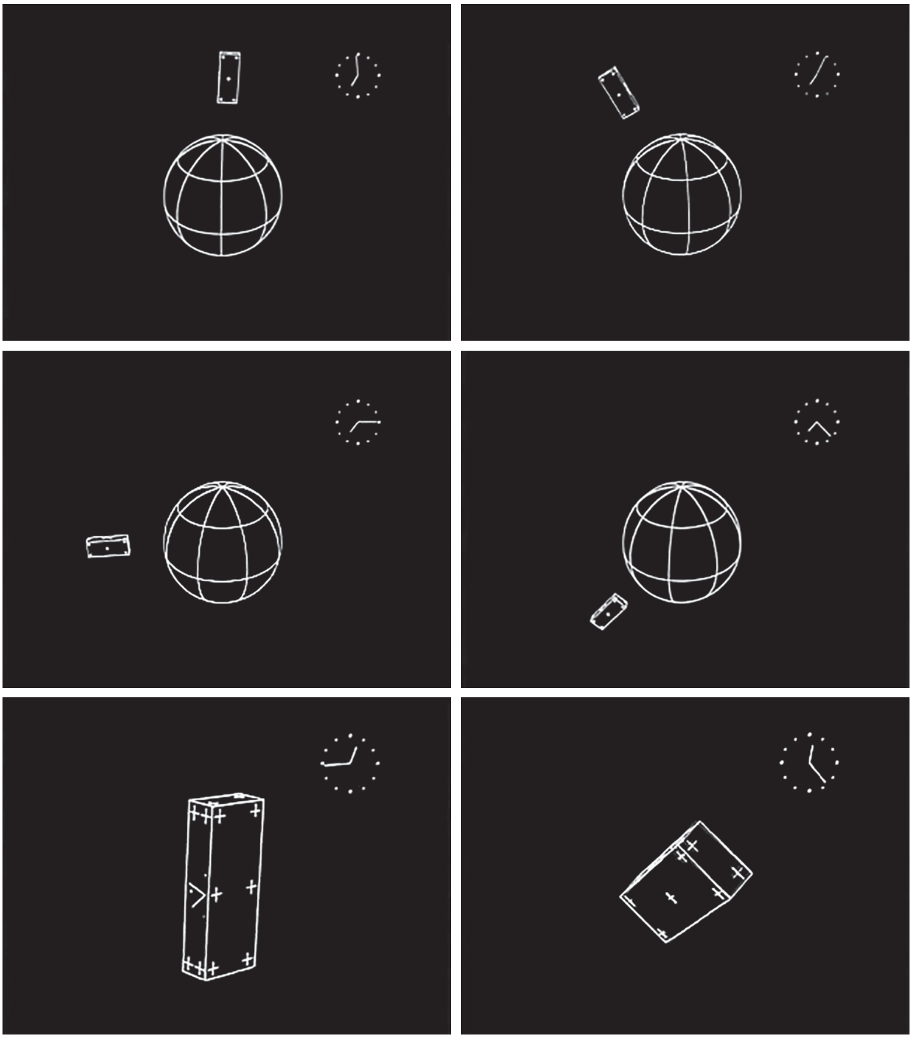
Despite its original purpose as still imagery, by the 1960s, microfilm unexpectedly became a crucial element in computer motion graphics. Microfilm plotters such as the S-C 4020 were, in effect, self-contained systems for film recording, usable by a range of scientists and engineers who did not necessarily have any prior experience—or even interest—in movie making. As Gene Youngblood wrote in 1970, "users of microfilm plotters have found … that their movie-producing capability is at least as valuable as their storage-and-retrieval capability."[38] As such, they quickly became the most utilized output system for the nascent idea of the computer film.

Synthetic Cinematography

A film made by E. E. Zajac on the S-C 4020 is often referred to as the first computer graphics film.[39] It was Zajac's first film, as well, as he was not a filmmaker by either trade or initial inclination. The film is disarmingly simple. A box, drawn in sharp white lines against a black background, slowly tumbles around a gridded sphere, with a dial in the corner counting off the rotations. Partway through, the view switches to focus on the box, which wobbles side to side before gradually stabilizing. It is not an exciting film, but it is sharply evocative of a new paradigm of visualization. The clean lines articulate a system that hews to clear-cut laws and rhythms independent of cinematic observation. The view is of a control and relay system floating around an earth that had only recently been visualized from space, though never from that particular angle. This view could have been hand-drawn in the past, but the precise mathematical rigor of the depiction is new.

The rigor develops because Zajac was not initially interested in computer graphics or animation, per se. Only after writing about the film did he become interested in the possibilities that the microfilm plotter and computer offered for scientific visualization more generally. The film, *Simulation of a Two-Gyro Gravity-Gradient Attitude Control System*, was made because Zajac was interested in real-time modeling of an attitude-control system for an orbiting communication satellite. The abstraction of the film is in part because Zajac was not developing a specific attitude-control system but rather working on developing "general guiding principles and analytic and numerical techniques useful in such a design program."[40]

When Zajac was working on this in the early 1960s, the satellite business was relatively new, and the space above the earth was not yet cluttered



Stills from E. E. Zajac's film *Simulation of a Two-Gyro Gravity-Gradient Attitude Control System* (1963).

with man-made detritus. Bell Labs, in conjunction with the National Aeronautics and Space Administration (NASA), had made an initial foray into space in 1960 with something that it called *Echo* and most people called a "satelloon"—an inflatable satellite described retrospectively as "perhaps the most beautiful object ever to be put into space."[41] Launched in the aftermath of the Russians' 1957 *Sputnik 1*, *Echo 1* was designed not just to enable visual and auditory communication but to be seen and talked about—a man-made American satellite that amateur astronomers could track with telescopes, that would hover in the sky as a signal of American ingenuity and technical know-how. *Echo 1* was a dazzling, highly reflective sphere with a 100-foot diameter and a 31,416 square foot surface of Mylar polyester film covered smoothly with vapor-deposited aluminum. As its name suggested, it was a passive satellite, a surface that could angle a precisely directed signal from, say, California down to New Jersey. Unfortunately, its shape made it a weak passive reflector: it was able to distribute a signal fairly broadly but unable to focus it.

A follow-up project, *Telstar 1*, was far smaller—only 34.5 inches in diameter. It was less aesthetically noteworthy but was substantially more effective at signal broadcast mechanics. As the first active communications satellite, *Telstar* did not just reflect signals but amplified and retransmitted them. Moreover, these signals were not confined to radio transmissions but could be telephone calls, images, or television feeds. *Telstar* was launched on July 10, 1962, at 4:35 in the morning. Later that day, the first television picture—of a waving American flag in Andover, Maine—was transmitted via satellite, marking and laying claim to a new terrain of communication.

Zajac was part of a group working on research and development for a successor to *Telstar 1*.[42] His subgroup was studying the orientation control of satellites.[43] *Telstar* was able to stabilize itself such that during its orbit, one face of the satellite always pointed to earth. But *Telstar* had been an experiment, and Zajac was working on guiding principles for a next-generation stabilization system. He states that "at first, I had the computer print out numbers giving the satellite orientation at successive instants of time. The problem of visualizing the satellite motions from the printed numbers was formidable."[44] Instead, Zajac "wrote a subprogramme which took the numbers that would normally be printed out and used them to compute a perspective drawing of a box representing a satellite."[45] According to Zajac, this had a number of advantages: graphical output was "'natural' … The human eye has great pattern recognition ability: for this very reason the usual first step in handling scientific data is to plot it."[46]

The film was divided into two parts. The first part shows the motion of the satellite around the earth. The switch to a view of just the satellite displays the gyro stabilization but also reveals a striking possibility of computer-generated films—the rapid transformation of perspective. Because the essence of the computer film lies in a numerical input rather than the optical registrations of a physical camera, sudden and dramatic changes in viewpoint could be achieved quite easily.[47]

This 1963 film represents a system—an increasingly pervasive concern for filmmakers who were interested in, as Gene Youngblood put it, "systems aesthetics, scientific discipline, and so on."[48] But Zajac was not a filmmaker. And as Youngblood pointed out, "most computer films are not aesthetically motivated. They are made by scientists, engineers, and educators to facilitate visualization and rapid assimilation of complex analytic and abstract concepts."[49] Zajac's film simulated the motion of a communications satellite around the earth.[50] This simulation was the result of numerical integration of differential equations. The results were depicted as perspectival drawings, giving visual form to a mathematical system in a way that would have been nearly impossible before the advent of the computer. Looking back at 1960s computing, Melvin Pruitt has written,

> the results of computer simulations were printed out on large stacks of paper. The results were numbers. The main problem was that when we looked at page 15 and saw hundreds of numbers, then turned over to page 250 and saw thousands of other numbers, how could we see the relationship between numbers on so many different pages?[51]

Interpreting them was difficult if not impossible. Zajac's film offered a different way of dealing with those hundreds of numbers.

Zajac saw those numbers and their manipulation as the crucial element of his film. He argued that "the advantages of computer animation do not lie with an elaborately versatile cathode ray tube. Rather they lie with the power of a high speed digital computer. Indeed, the special virtue of computer animation is that it brings the power of computing to the film medium."[52] Previously, he pointed out, these kinds of films had to be elaborately drawn by hand, with all of the calculations done by an animator. Although the computer was a crucial part of this operation, the microfilm plotter was clearly just as important. For with the advent of computer output microfilm, the computer could perform the calculations while the microfilm plotter functioned as draftsman—but the limitations and constraints of this apparatus were largely on the side of the S-C 4020.

Programming a Film

The computer that was performing these calculations was a mainframe, a beast of a computer utterly unlike the laptops and desktops that we associate with the term today. The S-C 4020 was used at Bell Labs primarily as a peripheral for the IBM 7090 and 7094 computers. The IBM 7090 filled a room to overflowing and generated an extraordinary amount of noise. Not only was the room noisy, but it was freezing in an attempt to cope with the seemingly endless amount of heat generated by the machine. The 7094 was an upgrade of the IBM 7090, quite literally: a company could purchase a few components to transform its 7090 into a 7094.

If you have seen a mainframe in a Hollywood film, chances are excellent it was a 7094, which, for a time, must have seemed like the platonic ideal of "the computer." It had dials, gauges, switches, and blinking lights. The lights showed the status of the computer's registers, bit by bit. They let the operator read each register in the central processor directly, in binary numbers, in case of glitches or errors. The operator could execute a program one instruction at a time, watching the registers intently. The switches allowed operators to alter the bits on particular registers, giving operators a high level of control over the machine on an exceedingly fine-grained level.[53]

The 7090 was a transistorized computer introduced in 1959, only a year after IBM had begun deliveries of the 709, a vacuum-tube–based computer. The 7090 was architecturally identical to the 709, but it substituted transistors for the suddenly obsolete vacuum tubes. The key reason for the substitution was the US Air Force. IBM bid on an air force contract for a follow-up to the Semi-Automatic Ground Environment (SAGE) air defense system, intending to offer the vacuum-tube–based 709, but the air force was interested only in a transistorized computer.[54] IBM won the contract with the 7090, which maintained the essential architecture of the 709 but used the newer transistor technology. The 7094 was simply an upgrade of the initial system, and functioned very similarly.

According to Paul Ceruzzi, the 7090/7094 "is regarded as the classic mainframe because of its combination of architecture, performance and financial success: hundreds of machines were installed at a price of around $2 million each."[55] It was designed for large-scale scientific and technical operations. It had a flexible design, intended to "ease maintenance and accessibility."[56] Each cabinet had modular sliding frames with two vertical racks that could be pulled from the frame and opened to access the hundreds of transistor cards it contained. The computer is made up of standardized modules to enable easy accessibility and maintenance. Each of the units has two vertical drawers that pull out to reveal two hinged "pages." When these pages are closed, the wiring is exposed, which allows access to all text points. When pulled to an open position, the pluggable printed wiring transistor cards are simple to remove and replace. Modularization is intended to enable efficiency. A typical installation involved a number of these standardized cabinets mounted a few inches over a tiled floor, leaving space for thick cables that connected one cabinet to another.

The IBM 7090 was six times faster than the 709, which IBM attributed to more than fifty thousand transistors coupled with exceptionally fast magnetic core storage. The system was capable of reading and writing electronically at a rate of three million bits of information a second: "In 2.18 millionths of a second, it can locate and make ready for use any of 32,768 data or instruction numbers (each of 10 digits) in the magnetic core storage. The 7090 can perform any of the following operations in one second: 229,000 additions or subtractions, 39,500 multiplications, or 32,700 divisions."[57]

The 7090 was a custom built system, tailored to user specifications. There were some strictly necessary components—a card reader, a printer, a console control unit, core storage, a central processing unit, a multiplexor, a data channel, and a power convertor. But there were other optional elements: a card puncher, two magnetic tape units, and two types of data channels (tape or tape with card), as well as various third-party peripherals. A fully tricked out IBM 7090 system could include eighty magnetic tape units, eight card readers, eight card punches, and eight printers. The product announcement package stated that the system was designed for use with real-time input and output. This "real-time" was highly relative, however. While its speed was leaps and bounds ahead of its predecessors, it was still a far cry from the interactive computing that now is understood as real-time.

The computer was too expensive to ever remain idle; it was always running programs on tape. This mode of programming was called "batch mode": one program was loaded and run at a time. The programmer never had direct access to the machine but had to wait for the results when the program was run. If there was a problem, a new deck had to be submitted and rerun. In the early 1960s, computing at Bell Labs was done primarily on a 7090 or 7094 system in batch mode. Programmers rarely encountered the machine itself. They worked on decks of punched cards. Some programmers did not even keypunch the cards themselves but wrote out sets of instructions on "coding sheets" (a phrase that gives rise to our current reference to computer programming as coding) that were given to keypunch operators to create the cards. An IBM 1401—a small special purpose computer—translated the cards into rolls of magnetic tape.

As noted earlier, magnetic tape drives governed the mainframe. Tapes were the intermediary between the computer, its programmers, and its peripherals. An operator took the tape from the 1401 and loaded it into the IBM 7090. The operator's job was to mount and demount tapes, set switches and punch buttons to put a job into motion, check the flashing lights for occasional problems, and attend to status information printouts. Ceruzzi reminds us that while a few mainframes had video consoles, the 7094 was not one of them, and "such a console would have been useful only for control purposes, since the sequential storage on tapes prevented direct access to data anyway."[58] Video consoles were not generally employed due to their "voracious appetite for core memory."[59]

Peripherals like the S-C 4020 took on an outsized importance because they were the only source of visual display for the mainframe computer. As noted earlier, Zajac argues that the peripheral is not as important for computer animation as the computer connected to it. And from the perspective of the future development of computer animation, his point is well taken. Nevertheless, the composition of Zajac's own film was dictated—far more than he was willing to admit—by the affordances specific to the peripheral. To explain this importance, it is helpful to detail the actual process of programming a film as Zajac presented it in his 1966 article for *New Scientist*.

In this article, Zajac examines how the program for an animated film was written. He starts with a basic line drawing command: "CALL LINE (-5, 3, 15, 22)." This command tells the display device to draw a line between $X = -5$, $Y = 3$ and $X = 15$, $Y = 22$. As Zajac points out, this command is written in Fortran (Formula Translation), which was then a widely used scientific programming language. One of the advantages of Fortran was that its syntax—the set of rules that defines the how symbols are combined—was akin to ordinary algebra and thus familiar to the average scientist or engineer.[60]

With only two simple commands—

```
Y=5

CALL LINE (-15,Y,30,Y)
```

—the programmer can tell the computer to draw a horizontal from the point $X = -15$, $Y = 5$ to $X = 30$, $Y = 5$. A few more commands allow the computer to set up a loop:

```
DO THRU*, I = 1,100
```

```
Y=1

*CALL LINE (-15,Y,30,Y)
```

The DO THRU line sets the loop in process and tells the computer to run the following instructions (up to and including the instruction marked by the asterisk) 100 times: "Each time through the loop, the *Y* coordinate of the line is given the value of the counter, I. So on the 29th pass through the loop *Y* = 29, on the 30th pass *Y* = 30."[61] Zajac's example here directs the computer to draw a hundred parallel lines, each spaced a single unit apart.

These instructions could be used to create an animated film because of some specific attributes of the S-C 4020. The cameras in microfilm plotters did not work like standard cinema cameras. In cinema cameras, the shutter was an integrated part of the camera that was mechanically linked with the film advance function. In microfilm plotters, the computer controlled the shutter and could operate that shutter independently from the film advance mechanism. In practice, this meant a single frame could be held open for as long as it took the CRT to draw a picture—or it could be advanced as quickly as the CRT tube could draw.

Zajac explains this by introducing the instruction "CALL FRAME" to his sample Fortran program. Fortran translates this to a command to the S-C 4020, which tells it to advance the film by one frame. The program now reads as follows:

```
DO THRU*, I = 1,100

Y=1

CALL LINE (-15,Y,30,Y)

*CALL FRAME
```

And with this addition, the S-C 4020 produces a 100-frame animated film instead of a single image. Zajac stresses that there are several points to be made here. First, a computer loop differs in kind from a film loop. A film loop hinges on identical repetition. A computer loop is based on repetition with a prescribed difference. Although it repeats a sequence of commands over and over, "a command, such as *Y* = *I*, may call for a change from the previous passage through the loop. Thus the event produced in each passage through the loop generally *differs in a systematic way* from the event produced in the previous passage."[62] Second, Zajac also points out the ease of changing this program to produce a new, different animation. A change in the value of *Y* from 1 to 1/2, for instance, would make the film last twice as long.[63] Changing the values of *X* changes the length of the line.

This means that a single basic program can generate far more than a single film: "it makes possible a whole *family* of films."[64] Finally, this program can be stored as a subroutine and called up as necessary as a part of a film.

Zajac's film was made possible, in part, by the creation of such a subroutine by F. W. Sinden, who wrote a program that calculated the orbits of massive bodies under central force action. Sinden used this to create a film that, following Zajac's argument, we can see as one of a family of films related to Zajac's. Called *Force, Mass and Motion*, it looks, as might be expected, very similar to Zajac's. But Zajac's work was only incidentally a film. More fundamentally, it was an experiment in stabilization—one that had proven difficult to simulate in the laboratory but simple to calculate with a computer. That the visualization thus produced took the form of a film was something of a happy accident. Sinden, by contrast, had specifically set out to make an educational film—one that would illustrate Newton's basic laws within a two-dimensional format: "Orbits are shown of two massive bodies under central force action for various laws, such as inverse cube, direct cube, etc., as well as for the familiar inverse square law."[65]

Like Zajac's film, Sinden's appears straightforward—white circles on a black background, straight lines, dots and arrows indicating trajectories. It has a bit of the pervasive registration jitter that accompanies all of the early films made with the S-C 4020. It is comprised entirely of dots and straight-line segments. It is divided into several sections, showing the motion of two gravitating bodies under a variety of circumstances, examining what the motion of bodies might look like if the law of gravity were very different:

> Most of the sequences in this film were made by a single programme of some sixty instructions together with a dozen or so named subprogrammes of five or ten instructions each. The latter performed such services as drawing circles, drawing arrows, specifying the law of attraction and controlling sweeps and zooms of an imaginary camera. Only the initial data and the subprogrammes varied from sequence to sequence, yet *visually* the sequences are quite different. This is typical for computer films demonstrating scientific principles. The basic programme defines a general law of nature (in this case, Newton's law of acceleration) while the different sequences show concrete manifestations of the law.[66]

Agreeing with Zajac, Sinden claims that "although the recent availability of precise, automatic microfilm recorders deserves credit for making computer-animation technically possible, the real secret behind it, as behind most computer applications, lies with the powerful techniques of computer programming that have been developed over the last decade and a half."[67] It is doubtless correct to give advances in programming the chief credit for the production of the data that underlie these animations. Yet if these data sets were to be visualized, the terms of that visualization would be given by the particular affordances and restrictions inherent to the S-C 4020 platform.

In drawing a picture, the computer gives a precise location "a horizontal and vertical co-ordinate—for each dot and for the end-points of each line-segment. Thus, pictures of any complexity, especially if they contain curves, require considerable data."[68] The resolution of the image is limited by the width of the electron beam and the specific raster layout of the screen: "The bright dot produced by the electron beam can be positioned only at points of the raster. Thus every dot in the picture must be centered on a raster point and every line segment must join raster points."[69] Sinden claims that this is not so much a restriction as the very condition of possibility for digital filmmaking: "in a digital machine, locations on the face of the tube must be specified by numbers of finite precision, and number of finite precision can specify only a finite set of locations."[70] He contends that under these restrictions, "the easiest and most natural subjects for a computer to animate are those in which both the drawings and the motion are easily specified by mathematical formulae. This means, above all, pictures representing physical and mathematical phenomena."[71] Zajac's film and Sinden's share some crucial assumptions about representation that were aided and abetted by the specific mechanical limitations of the S-C 4020. Crucially, neither of them displayed images that appeared anything like real objects in the world. They were not intended to mimic photographic representation of objects but rather to offer an abstract, *diagrammatic* representation of the systems within which objects were embedded. A traditional film might show a particular example of gravity as it would appear to humans in the real world—an apple falling from a tree, for instance. These films use vector drawings to sidestep the incidental detail of any given physical example.

The operative mechanics of these films? First, the reduction of objects to a schematic outline. Second, the division of the whole into parts for the purpose of recombination. The films are repeatedly referenced not as complete works but as constellations of relational elements. Read through the Fortran programs and the iterability possible with the microfilm plotter, these works do not exist as a stable representations but as ones explicitly designed for mutability. Their value is not their mimetic qualities but rather the ways in which they modeled certain functional and dynamic relationships.

Although revolutionary and powerful, the vector display brought with it certain assumptions regarding the nature of representation and visualization. It was able to present beautiful, clearly defined lines and curves but was troubled by shading and gradations. Practices of photographic and photorealistic representation more akin to human perception remained largely untenable, alien to its logic, and unable to be integrated into its visual system. Crisp and clean in black and white, the films were drawings comprised of simple line segments. Unlike Roland Barthes's description of the photograph—the basis of traditional filmic representation—they did not represent a "message without a code."[72] In fact, to the untrained eye, they would not have looked like much of anything in particular.

The twentieth century belongs, in most accounts, to the photograph—both as a system of representation and as a transformative social phenomenon. These films, in contrast, could more accurately be described as diagrams. The diagram is an older mode of representation—one tied to engineering and architecture, geometry, mathematics, and physics, among other disciplines and practices—that took on a new urgency in the rise of a culture of computation.[73] As with photography, there are various histories of diagrams. In his research on the technical drawing, Wolfgang Lefevre argues that the diagram emerges simultaneously with the figure of the engineer as a result of reorganizations in technology and production that demanded the combination of practical and scientific knowledge—a combination of action and understanding.[74]

Gilles Châtelet claims that the diagram has historically been considered "a subsidiary tool for representing equations."[75] Yet the diagram, as he describes it, serves a similar function in mathematics as in other disciplines: it "does not simply illustrate or translate an already available content. The diagrams are … concerned with experience."[76] According to Châtelet, the diagram does not predict or verify a law but exists as a thought experiment: "If it is 'ideal' or 'theoretical,' it is not because it is impossible to carry out with 'real' instruments, but because it claims to question or uncover processes of idealization."[77] In other words, the diagram both questions and uncovers the process by which ideals are formed in the mind.

Anthony Vidler, for example, has recently explored the history of the diagram as a means of response to its steadily increasing influence on the discourse of architecture. He traces the historical emergence of the architectural diagram to the late eighteenth century, citing Jean-Nicholas-Louis Durand for his claims that early diagrams considered themselves a means of developing a universal language: "drawing serves to render account of ideas … it serves to fix ideas, in such a way that one can examine anew at one's leisure, correct them if necessary, it serves finally to communicate them afterwards, whether to clients or different contractors."[78]

The special resonance of the photograph is understood to come from a privileged connection to reality. As Barthes famously stated, "certainly the image is not the reality, but at least it is its perfect analogon."[79] The diagram, on the other hand, is privileged as a figure of use and transformation—not a representation of reality but something more akin to a stand-in. The diagram—as a mode of representational practice—marks a shift from a concern with the perceptual qualities of the object to a concern with its undergirding conceptual relationships. No longer mimesis—but rather system. This form of drawing transforms the concepts of the image and the object, the real and the virtual—as well as understandings of vision and visuality. It articulates a different approach to aesthetics—this process of making sense.

Whereas incipient virtual reality systems would tumble headlong into traditional representational models in their zeal to create a believable visual world around the user, the films of Zajac and Siden do not propose to trick us into believing that what we are seeing is anything immediately familiar to our lived, phenomenological experience. Composed of abstractions and filled with symbols, they were marked by steadily shifting perspectives and top-down or cross-sectioned views that were unbeholden to the physics of a mechanical camera in the physical world. As such, Sinden and Zajac saw them as affording the unique ability to visualize concepts *that had never before been amenable to photographic representation*. Although employing the material substrate of celluloid film, neither offered "a deposit of the physical object" as might be produced through a process of photographic representation descended from the camera obscura. Instead, they provided an image of a *structural organization* that itself was inimical to photographic capture. This scientific empiricism does not depend on the regime of the photographic for its claim to truth value—and it helped to extinguish the photograph's claim to truth even before digital manipulation ultimately sealed its fate.

Both films are attempts to represent a system by focusing on limited objects that then make up a functional whole. It was a model that represented structure rather than appearance. The "real" of the world is understood through modeling rather than mimesis. This film shows the relations of parts. In this, the satellite is understood not as its appearance but as system. To see something thus is to understand an object as it functions rather than as it appears.[80] To claim this, following Vidler, is to see these drawings as "proposing a world other than that which exists" in a constitutive manner—in other worlds, with real consequences for our understanding of what the world is and how it works. The drawings develop from the model of vision proposed by cybernetics—a diagrammatics of vision that prioritizes abstraction, function, and system above all else. Its potential and its danger lie in the way that it simplifies objects to produce action—an easy, transparent translation between man and machine.

Notes

Introduction

1. Figures in 2014 dollars adjusted for inflation.
2. For a lively account of this history, see Jon Gertner, *The Idea Factory: Bell Labs and the Great Age of American Innovation* (New York: Penguin, 2012). See also Peter L. Bernstein, *Three Degrees above Zero: Bell Labs in the Information Age* (New York: Scribner, 1984).
3. The special-purpose software created for the S-C 4020 at Bell Labs became the basis of operations with the platform in a variety of locales.

Chapter 1: What Was a Microfilm Plotter?

1. General Dynamics advertisement, personal collection of author.
2. Paul N. Edwards, *The Closed World: Computers and the Politics of Discourse in Cold War America* (Cambridge, MA: MIT Press, 1997), 99–101. See also Thierry Bardini, *Bootstrapping: Douglas Engelbart, Coevolution, and the Origins of Personal Computing* (Palo Alto, CA: Stanford University Press, 2000), 86–87; Jan Hurst, Michael S. Mahoney, Norman H. Taylor, Douglas T. Ross, and Robert M. Fano, "Retrospectives I: The Early Years in Computer Graphics at MIT, Lincoln Lab, and Harvard," *ACM SIGGRAPH Computer Graphics* 23 (5) (1989): 19–38.
3. "Pushbutton Defense for Air War," *Life*, February 11, 1957, 62.
4. Jonathan Crary, *Techniques of the Observer* (Cambridge, MA: MIT Press, 1990), 147.
5. Alexander R. Galloway, *The Interface Effect* (Cambridge, MA: Polity Press, 2012), 13.
6. Edwards, *The Closed World*, 131. Also see Eve Meltzer, "The Dream of the Information World," *Oxford Art Journal* 29 (1) (2006): 115–135.
7. Edwards, *The Closed World*, 86.
8. Ibid.

9. Hurst et al., "Retrospectives I."
10. Ibid.
11. Ibid.
12. Ibid.
13. Edwards, *The Closed World*, 69.
14. S. H. Boyd and C. W. Johnson, "The Presentation of Alphanumeric Information," in *Illumination and Visibility of Radar and Sonar Displays: Proceedings of a Symposium Sponsored by the Armed Forces NRC Committee on Vision*, ed. Robert Heath Brown (Washington, DC: National Academy of Sciences, National Research Council, 1958).
15. Ibid.
16. Ibid.
17. IBM Military Products Division, "Introduction to AN/FSQ-7 Combat Direction Central and AN/FSQ-8 Combat Control Central" (Kingston, NY: IBM, 1959).
18. At this time, Joseph T. McNaney was at Consolidated Vultee Aircraft Corporation. General Dynamics Corporation acquired Vultee in 1953 and renamed it the Convair Division. General Dynamics merged with Stromberg-Carlson in 1955, shifting the Charactron project from Convair to Stromberg-Carlson's Data Projects Division. In 1969, the Data Projects Division split off and became a subsidiary of General Dynamics as Stromberg-Datagraphix, which continued to develop screens based on the initial Charactron screen as well as microfilm products intended as computer peripherals. See also Ben Ferber, "The Use of the Charactron with Era 1103," paper presented at the the Eastern Joint Computer Conference: New Developments in Computers, 1956. See also Stromberg-Datagraphix training manual, personal collection of author.
19. Jackie Potts, "For the Computer Gourmet: Graphics" (Bethesda, MD: Naval Ship Research and Development Center, Department of the Navy, August 1974).
20. Eric Barbour, "The Strange World of Memory Tubes," *Tube Collector* 6 (5) (October 2004): 5–12.
21. Joseph T. McNaney, "The Charactron," *Proceedings of the IRE* 40 (2) (March 1952): 231.
22. P. Battey, R. Meijia, P. Baynes, E. Hairston, D. Hardy, and E. Cuthill, "S-C 4020 Microfilm Recorder Programming Manual I," Department of the Navy, David Taylor Model Basin, Applied Mathematics Laboratory, 1961, 2. See also Computer Sciences Corporation, "S-C 4020 Microfilm Recorder User's Manual" (1966); Potts, "For the Computer Gourmet: Graphics."
23. Stromberg-Datagraphix Training Manual, personal collection of author.
24. Paul Ceruzzi, *A History of Modern Computing*, 2nd ed. (Cambridge, MA: MIT Press, 2003), 74. Magnetic tape and punchcards continued to be used in tandem, however, with programs written on punchcards and translated to magnetic tape.
25. Bharat Bhushan, *Mechanics and Reliability of Flexible Magnetic Media* (New York: Springer, 1992), 20.
26. Paul Ceruzzi, *Computing: A Concise History* (Cambridge, MA: MIT Press, 2012), 39.
27. DatagraphiX Training Manual, 85, personal collection of author.
28. Ibid.
29. Frank Dietrich, "Visual Intelligence: The First Decade of Computer Art (1965–1975)," *Leonardo* 19 (2) (1986): 163.

30. John J. Kalagher, "Micromation: Its Impact on the Photocomposing Industry," *Electronic Composition in Printing: Proceedings of a Symposium*, ed. Richard W. Lee and Roy W. Worral (Washington, DC: Center for Computer Sciences and Technology, National Bureau of Standards, 1967), 37–38.
31. Stromberg-Carlson advertisement, "Only one computer output device gives you all three …," personal collection of author.
32. Meijia et al., "S-C 4020 Microfilm Recorder Programming Manual I."
33. H. Garbanati, "Micro-Photography," *The Photographic News for Amateur Photographers* 1 (6) (1859): 262.
34. H. Garbanati, "Negatives of Valuable Documents." *American Journal of Photography* 1, (7) (1858): 100–102.
35. John Douglas Hayhurst, *The Pigeon Post into Paris 1870–1871* (self-published by the author, 1970).
36. Ibid.
37. Ibid.
38. Gene Youngblood, *Expanded Cinema* (New York: Dutton, 1970), 196.
39. *First* is a fraught designation. Other films claim this title, but it was the first film at Bell Laboratories to demonstrate the capability of the S-C 4020 for making computer graphics films.
40. E. E. Zajac and J. A. Lewis, "A Two-Gyro, Gravity-Gradient Satellite Attitude Control System," *Bell System Technical Journal* 43 (6) (1964): 2705–2765.
41. James R. Hansen, *Spaceflight Revolution: NASA Langley Research Center from Sputnik to Apollo* (Washington, DC: National Aeronautics and Space Administration, 1995), 188.
42. After the launch of *Telstar 2*, Bell Labs exited the satellite-development business.
43. E. E. Zajac, "Film Animation by Computer," *New Scientist* 29(1966): 348.
44. Ibid.
45. Ibid.
46. Ibid.
47. We might compare this with the heavy, complex robotic apparatus that Michael Snow employed for his 1971 film *La Region Centrale* to ensure that no camera movement was repeated in the 180-minute work.
48. Youngblood, *Expanded Cinema*, 222.
49. Ibid., 196.
50. Jasia Reichardt, *Cybernetic Serendipity: The Computer and the Arts* (New York: Praeger, 1969), 67.
51. C. G. Watkins, "When Two Worlds Collide," http://www.sidianersatzvanes.com/supplemental/when-two-worlds-collide-2.
52. Zajac, "Film Animation by Computer."
53. Keith Jack and Vladimir Tsatsulin, *Dictionary of Video and Television Technology* (Amsterdam: Newnes Press, 2002), 186.
54. Ceruzzi, *Computing*, 47.
55. Ceruzzi, *A History of Modern Computing*, 73.
56. IBM, "Mainframes Product Profiles: 7090 Data Processing System," http://www-03.ibm.com/ibm/history/exhibits/mainframe/mainframe_PP7090.html.
57. IBM, "7090 Data Processing System Technical Fact Sheet," October 4, 1960, http://www-03.ibm.com/ibm/history/exhibits/mainframe/mainframe_PP7090.html.

58. Ceruzzi, *A History of Modern Computing*, 74.
59. Ibid.
60. Zajac, "Film Animation by Computer," 346.
61. Ibid.
62. Ibid., 347.
63. This modality of filmmaking bears a resemblance to structural film, which incorporates ideas of film as system and the creation of families of films based on particular general principles.
64. Zajac, "Film Animation by Computer," 347.
65. Ibid., 349.
66. J. W. Sinden, "Synthetic Cinematography," *Perspective* 7 (1965): 287–288.
67. Ibid., 280.
68. Ibid.
69. Ibid.
70. Ibid.
71. Ibid., 282.
72. Roland Barthes, "The Photographic Message," in *Image-Music-Text*, trans. and ed. Stephen Heath (New York: Hill and Wang, 1977), 17.
73. See also Hyungmin Pai, *The Portfolio and the Diagram: Architecture, Discourse and Modernity in America* (Cambridge, MA: MIT Press, 2002), which contains an interesting discussion of photography and the diagram in relation to architectural practice.
74. Wolfgang Lefevre, *Picturing Machines 1400–1700* (Cambridge, MA: MIT Press, 2004).
75. Gilles Châtelet, *Figuring Space: Philosophy, Mathematics and Physics* (Dordrecht: Kluwer, 2000), 11.
76. Ibid.
77. Ibid.
78. Anthony Vidler, "Diagrams of Diagrams: Architectural Abstraction and Modern Representation," *Representations* 72 (2000): 9.
79. Barthes, "The Photographic Message," 17.
80. This moves toward Harun Farocki's recent work on computer vision, as well as the recent analyses of Lev Manovich and Alexander Galloway.

Chapter 2: Art Ex Machina

1. Michael Rush, "No Longer an Orphan, Video Art Gives Itself a Party," *New York Times*, February 10, 2002, 35.
2. Leo Castelli, oral history interview, October 24, 1991, by Sharon Zane, Museum of Modern Art Oral History Program.
3. Exhibition announcement for *Computer-Generated Pictures*, April 6–24, 1965, Howard Wise Gallery, New York.
4. Unknown to Noll and Julesz, an exhibition of computer art (including pieces by Frieder Nake and George Nees) called *Computergrafik* had been held only a few months earlier in West Germany at the Technische Hohschule in Stuttgart. See A. Michael Noll, "The Beginnings of Computer Art in the United States: A Memoir," *Leonardo* 27 (1) (1994): 41.
5. Stuart Preston, "Art Ex Machina," *New York Times*, April 18, 1965, X23.

6. Ibid.
7. Ibid.
8. Ibid.
9. See "Computer-Generated Pictures," *New York Herald Tribune*, April 10, 1965, 8, and "Computer-Generated Pictures," *Time*, April 23, 1965, 6.
10. Noll, "The Beginnings of Computer Art in the United States," 41.
11. Ibid.
12. Ibid., 39.
13. Ibid.
14. A. Michael Noll, "Patterns by 7090," technical memorandum, Bell Telephone Laboratories, August 28, 1962, 1.
15. A. Michael Noll, "Computers and the Visual Arts," *Design Quarterly* 66–67 (1967): 65–71.
16. Ibid.
17. See Nick Montfort, Patsy Baudoin, John Bell, Ian Bogost, Jeremy Douglass, Mark C. Marino, Michael Mateas, Casey Reas, Mark Sample, and Noah Vawter, *10 PRINT CHR$(205.5+Rnd(1)); : GOTO 10* (Cambridge, MA: MIT Press, 2013), 117–146.
18. There were exceptions, and many took advantage of a certain amount of programmed randomness—Stan VanDerBeek's and Lillian Schwartz's work at Bell Labs in animated film, John Cage's large-scale performance *HPSCHD*, Alison Knowles's 1967 Fortran programmed poem "House of Dust," and Jackson MacLowe's LACMA-sponsored poetry experiments. Knowles's and Maclowe's works, in particular, utilized the chance operations generally associated with Cage but adapted them to the particular randomization that was possible with the computer.
19. Branden W. Joseph, "HPSCHD: Ghost or Monster?," in *Mainframe Experimentalism: Early Computing and the Foundations of the Digital Arts*, ed. Hannah B. Higgins and Douglas Kahn (Berkeley: University of California Press, 2012), 149. See also Branden W. Joseph, *Random Order: On Robert Rauschenberg, Artist, and the Neo-Avant-Garde* (Cambridge, MA: MIT Press, 2003).
20. Allan Kaprow, "One Chapter from 'the Principles of Modern Art,'" *It Is* 4 (1958): 52, cited in Branden W. Joseph, "Chance, Indeterminacy, Multiplicity," in Julia Robinson, Yve-Alain Bois, Liz Kotz, and Branden W. Joseph, *The Anarchy of Silence: John Cage and Experimental Art* (Barcelona: Museu Dart Contemporani de Barcelona, 2010).
21. Erwin Panofsky, *Tomb Sculpture* (New York: Harry Abrams, 1964), 26–27.
22. A. Michael Noll, "Human or Machine: A Subjective Comparison of Piet Mondrian's 'Composition with Lines' (1917) and a Computer-Generated Picture," *Psychological Record* 16 (1) (1966): 1.
23. Ibid.
24. Ibid.
25. Noll, "The Beginnings of Computer Art in the United States," 39.
26. The year 1965 also saw the publication of an article by Max Bense, translated as "Generative Aesthetic Projects," which addressed some concerns that were similar to those raised in Noll's work. It was not available in English until 1968. See Max Bense, "Projeckte Generativer Ästhetik," in *Rot 19, Computergrafik* (Stuttgart: n.p., 1965).

27. See the 1955 exhibition *Le Mouvement* at Gallerie Denise Rene in Paris.
28. Jon Borgzinner, "Op Art: Pictures That Attack the Eye," *Time*, October 23, 1964, 78–86.
29. William Seitz, *The Responsive Eye* (New York: Museum of Modern Art, 1965), 6.
30. William Seitz, "The New Perceptual Art," *Vogue*, Feburary 15, 1965, 141–142.
31. Ibid., 141–142.
32. Borgzinner, "Op Art."
33. Seitz, "The New Perceptual Art."
34. Not only had this problem gone unsolved, but something as supposedly straightforward as the "persistence of vision" that undergirds the phenomenology of the film and televisual image (and thus much of visual culture of the twentieth and twenty-first centuries) is actually still only dimly understood from within the twenty-first century cognitive perceptual psychology.
35. Jonathan Crary, "Techniques of the Observer," *October* 45 (1988): 25.
36. Julesz references Wheatstone in a number of his works, including his landmark treatise Béla Julesz, *Foundations of Cyclopean Perception* (Chicago: University of Chicago Press, 1971; Cambridge, MA: MIT Press, 2006).
37. Oliver Wendell Holmes, "Sun-Painting and Sun Sculpture," *Atlantic Monthly* 8 (1861).
38. Wheatstone successfully rebutted Brewster's argument with the support of Elliot, who proclaimed that he had not invented the stereoscope. Brewster then looked further back to Jacopo Chimenti, an artist who had created two slightly divergent sketches of a young man with a plumb line and a compass. When Alexander Brown saw them side by side in 1859, he was able to blur his vision sufficiently to see them as a single image with stereoscopic depth. When Brewster was told this, he suggested that the drawings were made to be seen with a stereoscope created by Giovanni Battista della Porta, who had done work on the camera obscura. The debate between Brewster and Wheatstone is detailed in part in H. Ono and N. Wade, "Resolving Discrepant Results of the Wheatstone Experiment," *Psychological Research* 47 (3) (1985): 135–142. The debate is also documented in Nicholas J. Wade, ed., *Wheatstone and Brewster: On Vision* (London: Academic Press, 1983). On the Chimenti argument, see Nicholas J. Wade, "The Chimenti Controversy," *Perception* 32 (2) (2003): 185–200. After measuring the images, it became clear that they were not fully stereoscopic but merely pseudo stereoscopic.
39. Hermann von Helmholtz, *Science and Culture: Popular and Philosophical Essays* (Chicago: University of Chicago Press, 1985), 192.
40. David Brewster, "Optics," in *Edinburgh Encyclopaedia* (Edinburgh: Blackwood, 1821), 750.
41. Béla Julesz, "Stereoscopic Vision," *Vision Research* 26 (1986): 1602.
42. James J. Gibson, *The Perception of the Visual World* (Cambridge, MA: Riverside Press, 1950), 6.
43. Stewart Kranz, *Science and Technology in the Arts: A Tour through the Realm of Science/Art* (New York: Van Nostrand Reinhold, 1974), 91.
44. Ibid. Something of the temporality involved can be seen with John Cage's production of the *William's Mix* in 1952. This pattern-derived musical recording was made by individually cutting and splicing together tens of thousands of audiotape

fragments by hand, a process that took the composer more than three months of manual labor.

45. Béla Julesz and Joan E. Miller, "Automatic Steroscopic Presentation of Functions of Two Variables," *Bell System Technical Journal* 41 (1962): 670.
46. Julesz, "Stereoscopic Vision," 1602.
47. Julesz, *Foundations of Cyclopean Perception*, 3.
48. Ibid., xvi.
49. Ibid., 3.
50. Ibid.
51. Ibid., 6.
52. Ibid.
53. Ibid., 56.
54. A. Michael Noll, "Stereographic Projections by Digital Computer," *Computers and Automation* 14 (5) (1965): 32–34.
55. Ibid.
56. John R. Pierce, "Portrait of the Machine as a Young Artist," *Playboy*, June 1965, 150.
57. Noll, "Stereographic Projections by Digital Computer."
58. Ibid.
59. Ibid.
60. Ibid.
61. Ibid.
62. Pierce, "Portrait of the Machine as a Young Artist," 150.

Chapter 3: *Studies in Perception*

1. Ken Knowlton, "Portrait of the Artist as a Young Scientist," *YLEM Journal* 25 (2) (2005): 10.
2. Among other places, this story is recounted in Knowlton's "A Portrait of the Artist as a Young Scientist," ibid. *Nude*, the first of the *Studies in Perception*, is often reproduced but rarely seriously discussed. Johanna Drucker is among a number of others who dismiss it as "shockingly dull." See Johanna Drucker, "Interactive, Algorithmic, Networked: Aesthetics of New Media Art," in *At a Distance: Precursors to Art and Activism on the Internet*, ed. Annmarie Chandler and Norie Neumark (Cambridge, MA: MIT Press, 2005).
3. Henry R. Lieberman, "Art and Science Proclaim Alliance in Avant-Garde Loft," *New York Times*, October 11, 1967, 49.
4. Ibid.
5. *Some More Beginnings: An Exhibition of Submitted Works Involving Technical Materials and Processes Organized by Staff and Members of Experiments in Art and Technology in Collaboration with the Brooklyn Museum and the Museum of Modern Art*, Experiments in Art and Technology, Brooklyn Museum, Brooklyn, New York, 1968.
6. Leon D. Harmon and Kenneth C. Knowlton, "Picture Processing by Computer," *Science* 164 (3875) (1969): 19–29.
7. J. Hurst, M. S. Mahoney, J. T. Gilmore, L. G. Roberts, and R. Forrest, "Retrospectives II: The Early Years in Computer Graphics at MIT, Lincoln Lab, and Harvard," in *SIGGRAPH '89 ACM Panel Proceedings*, 39–73 (New York: ACM, 1989).

8. Knowlton and Harmon, quoted in Jasia Reichardt, *The Computer in Art* (London: Studio Vista Limited, 1970), 10.
9. Knowlton and Harmon, quoted in ibid.
10. Paul Ceruzzi, *A History of Modern Computing*, 2nd ed. (Cambridge, MA: MIT Press, 2003), 91.
11. K. C. Knowlton, "A Computer Technique for Producing Animated Movies," in *AFIPS '64 Proceedings of the Spring Joint Computer Conference*, 67–87 (New York: ACM, 1964).
12. Ibid.
13. Computer Sciences Corporation, "S-C 4020 Microfilm Recorder User's Manual," 1966, I-2.
14. Ibid.
15. K. C. Knowlton, "A Computer Technique for Producing Animated Movies," in *AFIPS '64 Proceedings of the Spring Joint Computer Conference*, 67–87 (New York: ACM, 1964), 85.
16. Again, note that the Charactron was a hybrid screen but intended primarily for the display of text.
17. Email conversation with Kenneth Knowton.
18. A circuit diagram is a graphical representation of an electronic circuit. It does not represent the physical arrangement of the wires but shows the connections being made. In other words, it patterns the flow of signals and power using a particular symbolic language. It is the starting point for fabricating, for example, printed circuit boards. After the connections are diagrammed, a physical arrangement of material that will allow these connections is generated.
19. David Mindell, *Between Human and Machine: Feedback, Control, and Computing before Cybernetics* (Baltimore, MD: Johns Hopkins University Press, 2002), 134.
20. Ibid., 135.
21. Claude Elwood Shannon and Warren Weaver, *The Mathematical Theory of Communication* (Urbana: University of Illinois Press, 1949), 18.
22. N. Katherine Hayles, *How We Became Posthuman: Virtual Bodies in Cybernetics, Literature, and Informatics* (Chicago: University of Chicago Press, 1999), 54.
23. Note on exhibition record sleeve, Tate Archive.
24. The show was intended to travel to the Corcoran Gallery in Washington, D.C., and the Exploratorium in San Francisco, but the version that did travel was disowned by Reichardt because a substantive portion of the exhibition was destroyed in shipping. See Jack Burnham, "Art and Technology: The Panacea That Failed," in *The Myths of Information: Technology and Postindustrial Culture*, ed. Kathleen Woodward (Madison, WI: Coda Press, 1980).
25. Jasia Reichardt, *The Computer in Art* (London: Studio Vista Limited, 1970), 22.
26. K. G. Pontus Hultén, *The Machine as Seen at the End of the Mechanical Age* (New York: Museum of Modern Art, 1968), 3.
27. Ibid.
28. It was also not material in the sense that material is linked to visibility. Of course, it was material—so that the materiality of the medium and medium-specificity that emerged from it could give way to a dematerialized conceptualism of a post-medium condition.
29. For a detailed analysis of this problematic, see Wendy Hui Kyong Chun, "On Software, or the Persistence of Visual Knowledge," *Grey Room* 1 (18) (2004): 26–51.

30. Hollis Frampton, "For a Metahistory of Film: Commmonplace Notes and Hypotheses," *Artforum* 10 (1) (1971); 32–35, reprinted in Bruce Jenkins, ed., *On the Camera Arts and Consecutive Matters: The Writings of Hollis Frampton* (Cambridge, MA: MIT Press, 2009), 136.
31. Arthur Drexler and Greta Daniel, *Introduction to Twentieth-Century Design from the Collection of the Museum of Modern Art, New York* (New York: Museum of Modern Art, 1959), 94, cited in Felicity D. Scott, *Architecture or Techno-Utopia: Politics after Modernism* (Cambridge, MA: MIT Press, 2007), 80.
32. Ibid.
33. Ibid., 81.
34. Harmon and Knowlton, "Picture Processing by Computer," 22.
35. Richard F. Lyon, "A Brief History of 'Pixel,'" Digital Photography II, IS&T/SPIE Symposium on Electronic Imaging, Paper EI 6069, 2006.
36. Alvy Ray Smith, "A Pixel Is Not a Little Square, A Pixel Is Not a Little Square, A Pixel Is Not a Little Square (and a Voxel Is Not a Little Cube)." Technical Memo 6, Microsoft Corporation, 1995.

Chapter 4: *Poemfields*

1. James Tenney, transcript of "The House of Dust Symposium," University of California, Davis, April 9, 2002, cited in Douglas Kahn, "James Tenney at Bell Labs," in *Mainframe Experimentalism: Early Computing and the Foundations of the Digital Arts*, ed. Hannah B. Higgins and Douglas Kahn (Berkeley: University of California Press, 2012), 135.
2. Robert Russett and Cecile Starr, eds., *Experimental Animation: An Illustrated Anthology* (New York: Van Nostrand Reinhold, 1976), 200.
3. Ken Knowlton, "Reflecting on Collaboration," *animation: an interdisciplinary journal* 5 (2) (2010): 200. Despite the obvious corollary to E.A.T.'s activities, VanDerBeek and Knowlton had met, instead, through a mutual friend.
4. Stan VanDerBeek, "New Talent: The Computer," *Art in America* 58 (1970): 86.
5. Ibid., 91.
6. Michael Noll, "The Beginnings of Computer Art in the United States: A Memoir," *Leonardo* 27 (1) (1994): 39–44.
7. Gene Youngblood, *Expanded Cinema* (New York: Dutton, 1970).
8. VanDerBeek, "New Talent: The Computer," 71.
9. Béla Julesz, *Foundations of Cyclopean Perception* (Chicago: University of Chicago Press, 1971).
10. Youngblood, *Expanded Cinema*, 247.
11. Stan VanDerBeek, quoted in Jasia Reichardt, *The Computer in Art* (London: Studio Vista Limited, 1970), 79.
12. Youngblood, *Expanded Cinema*, 247.
13. Ibid.
14. Ibid., 246.
15. Matthew Fuller, "Visceral Facades: Taking Matta-Clark's Crowbar to Software," http://bak.spc.org/iod/Visceral.html.
16. This brief sequence reminds us of the flicker effects that are present in the computer-generated moving pictures of the Whitney brothers. Flicker effects were the ground for works by Steina and Woody Vasulka and Paul Sharits, as well.

17. Liz Kotz, *Words to Be Looked At: Language in 1960s Art* (Cambridge, MA: MIT Press, 2007).
18. Eve Meltzer, "The Dream of the Information World," *Oxford Art Journal* 29 (1) (2006): 124.
19. Oskar Morgenstern, *The Great Number*, Austriannale, Palazzo dell'Arte al Parco, Milano, 1968, Museum of Modern Art Archives, NY, Information Exhibition Records, 2.56, cited in Meltzer, "The Dream of the Information World," 125.
20. Kotz, *Words to Be Looked At*, 138.
21. Marjorie Perloff, "'Concrete Prose' in the Nineties: Haroldo De Campos's 'Galxias' and After," *Contemporary Literature* 42 (2) (2001): 270–293.
22. Eugen Gomringer, "Concrete Poetry (1965)," in Mary Ellen Solt, *Concrete Poetry: A World View* (Bloomington: Indiana University Press, 1969).
23. Earlier in his career, Bense had hoped to realize a process for rationally generating images. He divided picture surfaces into a grid of tiny squares to investigate the connections between these individual elements and to devise an algorithm for future images. He never created a satisfactory process and turned to informational analysis. His system was appropriated by George Nees and Frieder Nake as a programming technique for art production.
24. Eugen Gomringer, *Zur Sache Der Konkreten* (St. Gallen: Erker, 1988).
25. Ibid.
26. Ibid.
27. Ibid.
28. Rosmarie Waldrop, "A Basis of Concrete Poetry," *Bucknell Review* 22 (1976): 141–151.
29. In some ways, *Poemfields* is a return to his first film *MANKINDa* (1957), which is essentially a long poem and a series of artistic processes that dissolve and recombine words. It was a mode of practice he did not use again until *Poemfields*.
30. VanDerBeek's innumerable unpublished poems bear a similar fascination with the animation of words and the malleability of signification.
31. Reichardt, *The Computer in Art*, 79.
32. Marshall McLuhan, *Understanding Media: The Extensions of Man* (Cambridge, MA: MIT Press, 1994).
33. Ibid.
34. Ibid., 45.
35. Ibid., 79.
36. Stan VanDerBeek, "The Cinema Delimina: Films from the Underground," *Film Quarterly* 14 (4) (1961): 5–15.
37. See Pamela M. Lee, *Chronophobia: On Time in the Art of the 1960s* (Cambridge, MA: MIT Press, 2004), 185. See also Gloria Sutton, "Stan Vanderbeek's *Poemfields*: The Interstice of Cinema and Computing," in *Mainfram Experimentalism: Early Computing and the Foundations of the Digital Arts*, ed. Hannah B. Higgins and Douglas Kahn (Berkeley: University of California Press, 2012).
38. Stan VanDerBeek, quoted in Reichardt, *The Computer in Art*, 79.
39. Stan VanDerBeek, quoted in ibid., 80.
40. Stan VanDerBeek, quoted in ibid., 79.
41. VanDerBeek, "New Talent: The Computer," 91.

42. K. C. Knowlton, "A Computer Technique for Producing Animated Movies," in *AFIPS '64 Proceedings of the Spring Joint Computer Conference* 67–87 (New York: ACM, 1964).
43. Ibid.
44. Stan VanDerBeek, "Culture Intercom: A Proposal and Manifesto," *Film Culture* 40 (1966): 18.
45. Ibid., 16.
46. Tono Yoshaiaki, *Stan Vanderbeek, Wizard of Expanded Cinema* (Tokyo: Kodansha, 1969).
47. VanDerBeek, "New Talent: The Computer," 91.

Chapter 5: Pixillation

1. The majority of the rest were shown in a second show at the Brooklyn Museum called *Some More Beginnings*. The nine selected pieces were shown in both locations. See "Love, Hate and the Machine," *Time*, December 6, 1968, 86–89.
2. K. G. Pontus Hultén, *The Machine as Seen at the End of the Mechanical Age* (New York: Museum of Modern Art, 1968).
3. See ftp://cm.bell-labs.com/who/cocteau.old/lillian/old/index.ep.html.
4. Lillian F. Schwartz with Laurens R. Schwartz, *The Computer Artist's Handbook: Concepts, Techniques and Applications* (New York: Norton, 1992), 6.
5. These works bear some striking similarities to the contemporaneous practice of the "postminimal" sculpture of Eva Hesse.
6. See Schwartz, *The Computer Artist's Handbook*, 7, 238.
7. Ibid., 12.
8. Ibid.
9. Ibid.
10. Ibid.
11. In 1969, AT&T executives commissioned Schwartz to make a promotional film for Bell Labs that would "improve AT&T's image on college campuses." See Walter Forsberg, "Lillian Schwartz Sees in Four-Dimensions," *Incite: Journal of Experimental Media* 3 (2011).
12. See Schwartz, *The Computer Artist's Handbook*. See also Carolyn L. Kane, "Digital Art and Experimental Color Systems at Bell Laboratories, 1965–1984: Restoring Interdisciplinary Innovations to Media History," *Leonardo* 43 (1) (2010): 53–58.
13. Interview with Lillian Schwartz by Walter Forsberg, printed in the booklet accompanying the *Orphans in Space* DVD, available at http://archive.org/stream/OrphansInSpaceBooklet_sm/Orphans_in_Space_booklet_low-res_djvu.txt.
14. B. Coffey, "In the Mind of … Lillian Schwartz," *Computer Pictures* (January/February 1984): 52–56.
15. Schwartz, *The Computer Artist's Handbook*, 183.
16. This statement could readily be disputed, but it spoke to the role that she played in the Labs. See ftp://cm.bell-labs.com/who/cocteau.old/lillian/old/index.ep.html.
17. Schwartz, *The Computer Artist's Handbook*, 5. She is citing Meyer Schapiro on Seurat.

18. Ibid., 32.
19. Ibid.
20. Ibid.
21. Ibid.
22. Ibid., 34.
23. Ibid., 151.
24. It later was used for a variety of applications, including Béla Julesz's continuing experiments in vision, as well as teaching and research projects.
25. The program was designed for the IBM 7094 and the S-C 4020, but the initial implementation was a series of emulations—an IBM 360/50 emulating an IBM 7094 (with hardware-based convert instructions) and a Stromberg-Datagraphix 4060 using a hardware-based 4020 emulator. Both Schwartz and Harmon considered that they had worked on editions of the earlier machines and refer to them interchangeably. The majority of the material aspects of the microfilm plotter were identical. The primary difference was in the number of commands it could accept, but Knowlton and Schwartz limited themselves to those available with the original machine by working with the emulation.
26. Ken Knowlton, "EXPLOR: A Generator of Images from Explicit Patterns, Local Operations and Randomness," *UAIDE: Users of Automatic Information Display Equipment—Proceedings of the Ninth Annual Meeting* (San Diego, CA: Stromberg-Datagraphix, 1970), 560.
27. Ibid., 544.
28. Ibid., 545.
29. Ibid., 544.
30. Ibid., 559.
31. Ibid., 560.
32. Ibid., 562.
33. Ibid.
34. This was the unpredictability that the new wave of artists employing video recording technology in the late 1960s and early 1970s had begun to avoid. Rather than the traditional photochemical process of development with still and motion picture photography, whereby precise results remained unknown until often days later, video technology allowed for the continuous monitoring of the shoot in real time—radically transforming the possibilities and affordances of the moving image for contemporary art.
35. Lillian F. Schwartz, "The Artist and Computer Animation," in *Computer Animation*, ed. John Halas (London: Focal Press, 1974), 160.
36. Ibid.
37. Schwartz, *The Computer Artist's Handbook*, 153.
38. Forsberg, "Lillian Schwartz Sees in Four-Dimensions."
39. Dick Moore wrote a second soundtrack using a program completed at roughly the same time as EXPLOR. It was called GROOVE (Generated-Realtime-Operations-On-Voltage-Electronics) and used a computer, an analog synthesizer, and a speaker.
40. Schwartz, *The Computer Artist's Handbook*, 153.
41. Knowlton, "EXPLOR," 562.
42. Schwartz, *The Computer Artist's Handbook*, 115.

43. Ibid.
44. Ibid.
45. Interview with Lillian Schwartz by Walter Forsberg.
46. Ibid.
47. Paul Sharits, "Notes on Films, 1966–1968," *Film Culture* 47 (1969): 14.
48. See the beginning of Tony Conrad's *The Flicker* (1966).
49. See Felicity D. Scott, *Architecture or Techno-Utopia: Politics after Modernism* (Cambridge, MA: MIT Press, 2007).
50. Amos Vogel, *Film as Subversive Art* (New York: Random House, 1973), 118.
51. Press release, Whitney Museum of American Art, New York, February 17–23, 1972.
52. Schwartz was drawing on theories of perception developed by Edwin H. Land at Polaroid.
53. Schwartz, *The Computer Artist's Handbook*, 116.
54. Robert Lehman, "Mind Bogglers: 'Moceptions,'" *Today's Filmmaker* 2 (2) (1972): 6.
55. Schwartz, *The Computer Artist's Handbook*, 116.
56. Lillian F. Schwartz, "Motion Picture / Computer System for Visuals and Sound," Lillian Feldman Schwartz Collection, Ohio State University Libraries, 1970. See Kane, "Digital Art and Experimental Color Systems at Bell Laboratories."
57. Matthew Kirschenbaum, in "Vector Futures: New Paradigms for Imag(in)ing the Humanities," *Poetess Archive Journal* 2 (1) (2010), links bitmapping directly to photorealism in an extended contrast with vector graphics. Ron Burnett, in *How Images Think* (Cambridge, MA: MIT Press, 2005), links digital imaging most clearly to television. Lev Manovich, in *The Language of New Media* (Cambridge, MA: MIT Press, 2002), ties digital imaging and the figure of the computer to the cinematic image. William Mitchell, in *The Reconfigured Eye: Visual Truth in the Post-Photographic Era* (Cambridge, MA: MIT Press, 1994), interrogates the digital image in relation to the photographic. Vivian Sobchack, "The Scene of the Screen: Envisioning Cinematic and Electronic 'Presence,'" in *Materialities of Communication*, ed. Hans Ulrich Gumbrecht and K. Ludwig Pfeiffer (Stanford: Stanford University Press, 1994) ties it to electronic imaging, by which she means the televisual.
58. She experimented with three different recordings, as with *Pixilation*, to see how the different soundtracks would shift the viewer's experience.
59. Lehman, "Mind Bogglers."
60. Schwartz, *The Computer Artist's Handbook*, 151.
61. Ibid., 152.
62. William Moritz, "Visuelle Musik: Larry Cuba's Experimentalfilm (Visual Music: Larry Cuba's Experimental Film)," *Mediagramm, ZKM (Center for Art and Media)* 24 (1996): 12–13.
63. Ibid.
64. Malcolm LeGrice, *Abstract Film and Beyond* (Cambridge, MA: MIT Press, 1977), 80.
65. Douglas Davis, "The Artist and the Computer," *Newsweek*, September 13, 1973, 81.
66. Quoted in Kerry Brougher, *Visual Music: Synaesthesia in Art and Music since 1900* (London: Thames & Hudson, 2005), 82.

1. F.R.A. Hopgood, “Pioneering Images,” paper presented at a meeting of the BCS Displays Group, San Diego, CA, December 1991.
2. Bob Hopgood, “Report on U.S.A. Visit, 1971,” http://www.chilton-computing.org.uk/acl/literature/reports/p021.htm.
3. Ted Nelson, *Computer Lib/ Dream Machines*, self-published, 1974, 104.
4. Transcription from *The Mark of Man*. General Dynamics.