Critical Hardware: The Circuit of Image and Data

Kyle Stine

There is nothing more powerful—more instant, efficient, direct, and unambiguous—than an image.

—Greg James, Visual 6502 project

Critical studies has come to sing a chorus of collective disavowal of the computer's visuality. Nicholas Mirzoeff writes, for instance, that computers are not "inherently visual tools,"[1] and Jacob Gaboury has made the case recently even more emphatically: "The computer is not a visual medium."[2] The reasons for these statements seem relatively straightforward when taking into account the authors' subsequent explanations. Mirzoeff goes on to say: "The machines process data using a binary system of ones and zeros, while the software makes the results comprehensible to a human user."[3] Gaboury refines his point by arguing that the computer is "primarily mathematical, or perhaps electrical, but it is not in the first instance concerned with questions of vision or image."[4] Indeed, given these explanations, there would appear to be no surer illustration of W. J. T. Mitchell's argument that "there are no visual media"—that all media are instead "'mixed media,'" comprising multiple sensory modalities—than computer hardware,

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1. Nicholas Mirzoeff, *An Introduction to Visual Culture* (New York, 1999), p. 6.
2. Jacob Gaboury, "Hidden Surface Problems: On the Digital Image as Material Object," *Journal of Visual Culture* 14 (Apr. 2015): 40.
3. Mirzoeff, *An Introduction to Visual Culture*, p. 6.
4. Gaboury, "Hidden Surface Problems," p. 40.

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those rarely seen guts of electronic architecture, the ground-level materiality that undergirds the vibrant colors and sleek displays of the interface.[5]

Yet since 1959, when Jean Hoerni at Fairchild Semiconductor invented the planar process of circuit fabrication, the most basic and powerful components of computer systems have been produced using visual techniques through a process called photolithography. The product of this technique—the integrated circuit—integrates what had been separate components into a single semiconductor chip, exposing the computational architecture to an open field of view and allowing for successive phases of miniaturization. Reflecting on the integrated circuit in the 1980s, Donna Haraway recognized the peculiar invisibility at play in these microscopic chips created through techniques of vision: "The silicon chip is a surface for writing; it is etched in molecular scales disturbed only by atomic noise, the ultimate interference for nuclear scores."[6] Impossible at these infinitesimal scales are the manual and mechanical techniques of writing that prevailed before modernity. Integrated circuits instead rely on optical techniques of photochemical etching, drawing from the traditions of photography and cinematography and capitalizing on the unique feature of automatism that André Bazin observed in photography: "between the originating object and its reproduction there intervenes only the instrumentality of a nonliving agent."[7]

So extensive is this sphere of nonhuman action that current circuit complexity means that integrated circuits cannot be produced without being supplemented by digital imaging technologies at nearly every point in their manufacture, including computer graphics for circuit design, visual simulation for verifying designs, and machine vision for automated assembly and inspection (figs. 1–2). Visual media are thus not only the ben-

5. W. J. T Mitchell, "There Are No Visual Media," *Journal of Visual Culture* 4 (Aug. 2005): 257.

6. Donna Haraway, "A Cyborg Manifesto: Science, Technology, and Socialist-Feminism in the Late Twentieth Century," *Simians, Cyborgs, and Women: The Reinvention of Nature* (New York, 1991), p. 153.

7. André Bazin, "The Ontology of the Photographic Image," in *What Is Cinema*? trans. and ed. Hugh Gray, 2 vols. (Berkeley, 1967), 1:13.

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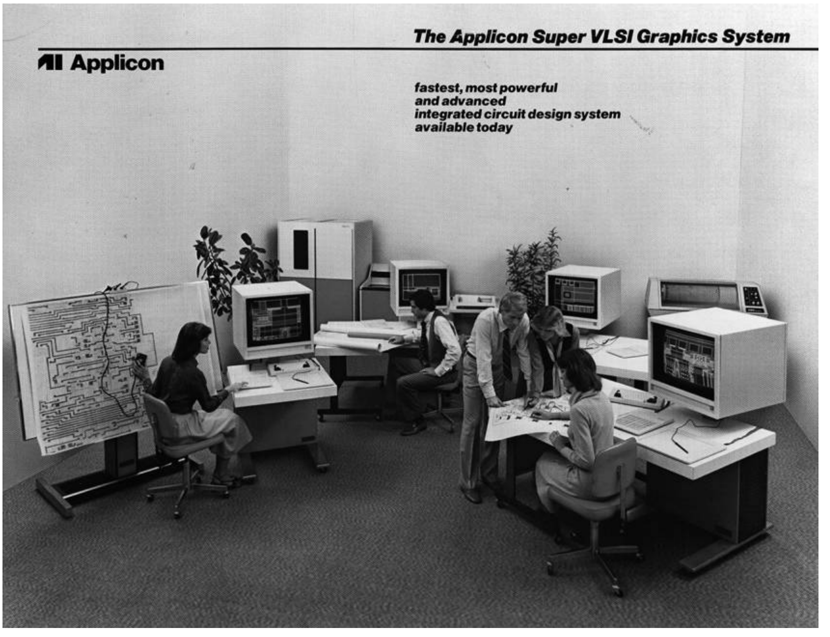

FIGURE 1. Trade catalogue cover for Applicon's graphic design system for VLSI circuit layout. Image courtesy of the Smithsonian Archives Center from the ICE Integrated Circuit Collection.

eficiaries of digital technologies but also, along certain paths of application, their source. The popular media of photography, cinema, and computer graphics lead a life of subterranean influence on the architectures and infrastructures of our lives deeper than cultural and ideological critiques have acknowledged. They not only consist of architectures—no digital offering exists without an indispensable system of data centers, satellites, radio towers, winding nets of cable, and machine hardware—but also function to build them.

It is all too understandable why scholars have insisted that the computer is not visual. With emphasis on the screen, they separate the visual processes of the interface from the supposedly merely material functions of computational switching. This opens several critical doors for deanthropomorphizing the machine and understanding those processes that the computer performs, to draw on an idea from Ian Bogost, *not for us*.[8] In untying visuality from computational functions, however, these argu-

8. See Ian Bogost, *Alien Phenomenology, or What It's Like to Be a Thing* (Minneapolis, 2012), p. 10.

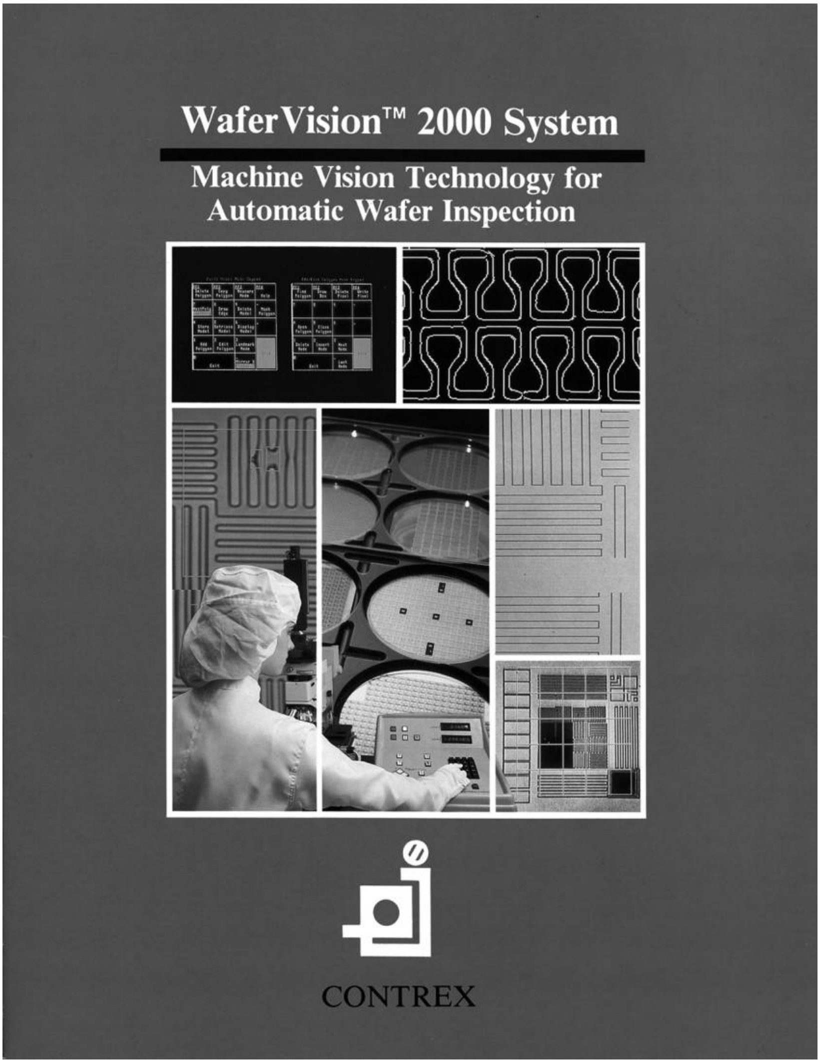

FIGURE 2. Trade catalogue cover for Contrex's machine vision system for automated inspection. Image courtesy of the Smithsonian Archives Center from the ICE Integrated Circuit Collection.

ments bind visuality ever more steadfastly to the user, preventing consideration of how visuality functions within the machine in ways *for itself*. Even when thinkers such as Mirzoeff, Gaboury, and David Golumbia find fault with the scholarly overemphasis on visuality in describing computing, they nonetheless uphold this tacit association between visuality and human consumption.[9] My objective in this article is to pull apart the association between vision and the human and to show that both the electronic components and the logic of computing derive from the interchange between images and data.

In *The Language of New Media*, Lev Manovich presents a now-canonical narrative of the relationship between computing and visual media, which, for shorthand, I will call the parallel-paths narrative. While Manovich notes the striking historical correspondence between the invention of photography and Charles Babbage's first mechanical computer in the 1830s, he insists that from that moment forward the two technical endeavors ran "in parallel without ever crossing paths."[10] Along one path stretched computing from Herman Hollerith to Alan Turing, and along another unfolded cinema from Thomas Edison and the Lumière brothers to the global industry of the mid-twentieth century. Only when digital computing became powerful enough to remediate imagery in the form of digital cinema and the graphical user interface did the two paths truly meet. Later in the book, Manovich adopts what Alexander Galloway calls a "layer metaphor" to describe how cinematographic media become the surface output of computers. Galloway writes: "The use of a layer metaphor is telling. At one layer is cinema, at a second layer are bits and bytes, at a third algorithm. Manovich's new media thus follow the same structure of the *mise en abîme*: an outside that leads to an inside, which leads to another inside, and on and on."[11]

In response to these arguments that separate hardware from software, or what the computer does *for itself* from what the computer does *for us*, I would like to set aside the parallel paths narrative and the layer metaphor and propose instead the metaphor of a circuit in which practices of computing and imaging continually loop back and interchange with one another and in so doing adopt what I call a "critical hardware" approach to studying the circuit of media production.

The integrated circuit is a unique figure for a critical approach to hardware in part because of its pervasiveness but more radically because of its

9. Golumbia cites and agrees with Sven Birkerts's association of computerization "with a tendency to privilege the visual" (David Golumbia, *The Cultural Logic of Computation* [Cambridge, Mass., 2009], p. 6).

10. Lev Manovich, *The Language of New Media* (Cambridge, Mass., 2001), p. 23.

11. Alexander R. Galloway, "What Is New Media? Ten Years after *The Language of New Media*," *Criticism* 53 (Summer 2011): 383. See also Manovich, *The Language of New Media*, p. 180. It is worth remarking on the insight of Manovich's choice to ground new media studies using the tools of critical analysis, particularly drawn from cinema studies. The alliance between computing and imaging is, if anything, stronger than he indicated. Moving past the materialist critiques of his approach, it may be time to revisit Manovich's emphasis on the visual.

amplification of technological reproduction.[12] At some point in their production and distribution, nearly all cultural images and texts today pass through binary code and thus through the microscopic channels of integrated circuits. This means that the communication techniques and design processes involved in producing circuits themselves pass through their channels. Microchips represent not only engineering accomplishments but also, to build on an insight from Gilbert Simondon, the facility of a much wider field of technology and culture. In discussing how technological objects can serve as metonyms of technological systems, Simondon writes: "It would not be an exaggeration to say that the quality of a simple needle expresses the degree of perfection of a nation's industry."[13] Just as the sharpness of a needlepoint consolidates a vast range of technical feats from the refinement of ores to the temperature control of furnaces, the line widths of integrated circuits embody the perfection of numerous physical, chemical, and informational processes.

Considered together, microprocessors and memory chips, the two dominant types of integrated circuits, serve as centering points in an intensifying feedback loop. Microprocessors circulate the instructions of automated machine systems and are themselves fabricated by automated machine systems. Memory chips track exacting environmental variables, such as temperature and ventilation, and are themselves the result of meticulous environmental, material, and chemical control. Data processing, beyond spurring the economic demand for semiconductors, has contributed to every facet of their production, from the ascertainment of materials through spectroscopy and materials processing to the management of automated shipyards and other transportation systems. Whatever utilizes data avails itself of these vanishingly small objects produced by astonishing quantities of data. They are the ideal commodity, both producer and consumed, an ouroboros.

In analyzing this circuit of reproduction, however, it is important to avoid a potentially inert materialism that would take hardware as merely a matter or substance at the base of media and computing. Instead, it becomes necessary to think form and matter together. To touch on a point that I will return to in the conclusion, I want to suggest that the integrated circuit embodies the insights of deconstruction in a particularly felicitous way as a figure of the patterning of matter as information. The register of the image is crucial to understanding this patterning.

12. Among the first uses of integrated circuits was signal amplification.

13. Gilbert Simondon, *On the Mode of Existence of Technical Objects*, trans. Cécile Malaspina and John Rogove (Minneapolis, 2017), p. 73.

The Visual 6502 Project

On the website of the Visual 6502 project one gains a unique window into the computational process (fig. 3). Microchip components generally hidden from view flash out as rapid patterns of color. The display can seem impossibly complicated and foreign, but even for onlookers unversed in electronics the circuit operations hold a transfixing appeal simply as moving images. Transistors switch in coordinated patterns. Electrical currents flicker red, green, and yellow, marking diffusion processes and connections to power and ground. The processor's clock, found just off the upper right-hand corner and designated in the component list as "clko," alternates at great speed between red, signifying "on," and black, signifying "off," displaying the steps that power the entire chip. Along the edge of the circuit are contact pads, larger blocks that form the basic communicational posts that send information out to other computer components. On the original

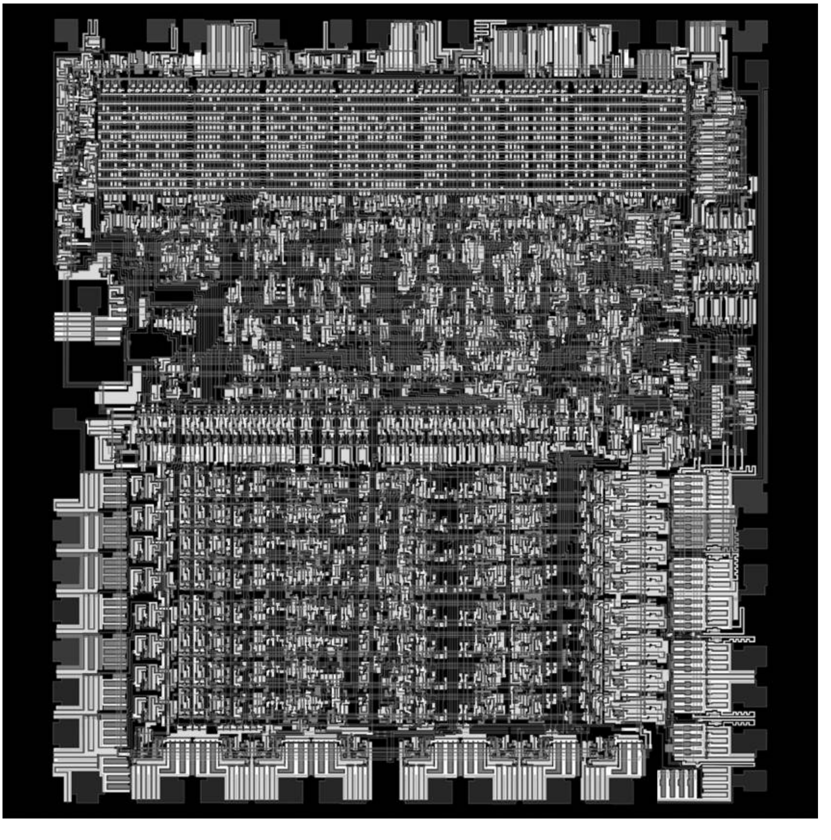

FIGURE 3. Still frame of the Visual 6502 circuit simulation. Image courtesy of Greg James and the Visual 6502 project.

chip, gold wires called lead bonds, soldered to these contact pads, connect to pins protruding from dense plastic packaging whose goal is to protect the delicate wires from movement or metal fatigue and the chip surface from scratches that could destroy its circuitry, with the pins being used to mount the package securely to the motherboard. At the interior of the chip, sectors of finer components rhythmically pulse, too quickly even with the simulation's intentionally slowed clock speed to be adequately compared to the regular stamping of ocean waves, yet suggesting their powerful sublimity in the controlled chaos of glinting points, like the water's wrinkled crests catching sun. Thousands of transistors gleam momentarily and switch off in the blink of an eye, counting bits, passing along instructions, closing down operations, and setting up new ones. Every operation that the chip could perform has been translated into light.

A three-person team of software and graphics engineers debuted this innovative circuit visualization project at SIGGRAPH Los Angeles in 2010. The creators, San Francisco–based graphics specialist Greg James and software developers Barry Silverman of Toronto and Brian Silverman of Montreal, describe the project as an effort in digital archaeology, an "excavation" of the digital past, seeking "to preserve, document, and understand historic computer systems, and to present them in a highly visual manner for education and inspiration."[14] The project takes its name from one of the most famous microprocessors in history, the MOS 6502, first manufactured in 1975 and used at the heart of the Commodore PET personal computer and the Nintendo Entertainment System, a processor so inspirational, it would appear, that an archived photo of Steve Jobs and Steve Wozniak shows a poster-size, framed die shot of the processor behind their workstation in homage to the chip that powered the Apple I and Apple II computers. Since its inaugural simulation, the project has gone on to spark an online community of researchers and hobbyists that explore the chip's functions and has initiated subsequent simulations of the Motorola 6800, a foundational processor for early personal computers, and the ARM1, a direct predecessor of today's smartphone processors.

The team's efforts take part in a wave of interest in recreating classic computing devices in response to a set of practical problems that threaten the archive of early software development. Classic software and games from the 1970s and 1980s, written in assembly code specific to particular microprocessors, risk obsolescence because they are operable only on the original chips used to run them. Each year, the number of consoles and computers

14. Greg James, Barry Silverman, and Brian Silverman, "Visualizing a Classic CPU in Action: The 6502," SIGGRAPH 2010, 27 July 2010, visual6502.org/docs/6502_in_action_14_web.pdf

still fit to run these programs diminishes, threatening, in time at least, to reduce them to untranslatable relics. To save the software, it becomes necessary to save the chips, but because the original architectures of these out-of-production circuits are not always available, their physical layouts hidden behind hard plastic packaging and their original mask designs often lost from having never been digitized, vintage software enthusiasts have resorted to emulating the processors, or creating software platforms that mimic their known characteristics. Emulators for classic game consoles have enjoyed immense popularity since the mid-2000s, but they offer only approximations of the original chip designs that, while effective for normal use, have limitations. Timing glitches and stability issues can sap system resources and cause the emulators to crash, and, being significantly less efficient than the original chips, the emulators require longer and more complicated code.

The Visual 6502 project should be distinguished from these emulators for its concentration on creating exact visual reproductions of original chips. The goal is not so much to make classic games functional (though it can certainly be used to do this) but instead to serve as an educational resource for analysis and understanding. For this reason, the creators of the project have chosen the high-fidelity approach of simulating historic processors. Far more than emulation, simulation is a research-intensive project, requiring advanced technical resources and, just as significant, copious amounts of time. This is why the preferred method has largely been to emulate old microprocessors. The great advantages of simulation, however, make it worth the cost: simulation replicates the entire circuit layout down to its finest detail. Each electronic component, as a material function, such as a transistor switching on and off or a resistor curbing electrical flow, becomes a symbolic function in the simulation. In an interview with me, Greg James explained:

> Everything is in the visualization, and everything needed to run the computational process is captured in our geometry. In a real chip, the physical parts are subject to the laws of electricity, and computation flows through. We've got those same parts but in digital form, and what our simulation code does is to supply our own laws of electricity. That gets the same computation going through our virtual chips.[15]

As its name suggests, the Visual 6502 project simulates these functions in the order of the image. Yet in contrast to usual notions of the image, it is not simply a *representation* of the MOS 6502; it *is* the processor in its actual operation.

15. Greg James, email to author, 17 June 2016.

Operational Images

The computational images of the Visual 6502 project expose the fundamental image operativity of integrated circuits. Integrated circuits, designed as successive layers of images, can be simulated in the order of the image because their logic is always already composed as an image. The circuit's clock, which alternates between on and off to step through different computational states, functions in much the way the shutter and feed mechanism function in traditional 35mm motion picture cameras. The circuit advances through different states or frames, to borrow a concept from cinema studies, in which the circuit changes its electrical pattern instantaneously. Within each frame, the polarities of the image, in the form of the polarities of doped silicon, compose a pattern that is nothing other than the sublation of computational language into materiality, the patterning of material as information. Each frame contains latencies that might actuate in subsequent frames, so that matter is always charged, already mapped and oriented, from the start.

Throughout his career, Harun Farocki took particular interest in such images that, rather than representing reality, acted upon reality. He used the terms *operative images* or *operational pictures* to describe them. In an essay on his film series *Eye/Machine* (2001–2003),[16] Farocki reflected on his inspiration for this idea from Roland Barthes's assessment of political language in *Mythologies*, a language that Barthes described in contrast to the inaction of myth as being "transitively linked to its object."[17] For Farocki, operational images are those images transitively engaged in any number of technical practices, whether incorporated into social institutions or automated on factory floors; they are images that take direct objects, work on them, and transform reality. Significantly, operative images themselves have evolved, following a definite path whose terminus can be seen in today's integrated circuits.

At some fundamental level, images always perform work beyond mere representation; however, the balance between representational meaning and functional meaning has shifted throughout the history of imaging technologies. Farocki and Ali Hossaini have called attention to the important role of imaging in architectural design and city planning, emphasizing how images shape the lived social environments of human societies, with Hossaini going so far as to suggest that the origins of photography should

16. Harun Farocki, "Phantom Images," trans. Brian Poole, *Public* 29 (2004): 17, 21.

17. Roland Barthes, "Myth Today," in *Mythologies*, trans. and ed. Annette Lavers (New York, 2001), p. 146.

be located in practices of ancient Sumerian land surveying.[18] More recent examples include John Tagg's catalog of the ways photographs were introduced into nineteenth-century social practices of identification and discipline and Allan Sekula's writing on the aerial images used during World War I to rationalize and coordinate artillery attacks, from which he coined the term *instrumental images*.[19] In all of these cases, images—more than representing reality—facilitate its shaping. Buildings are erected, city streets laid down, human beings identified and classified, bodies conscripted for war and imprisoned, all with reference to images.

Yet what has changed is that the intervening human role in reading and performing operations based on images, so essential to these early processes, has progressively waned. The circuit from $image_1$ to $image_2$, which historically wended its way through the affairs of human beings, has progressively shortened so that images interface with automated computing processes that interface with further automated images. Calculation, once a process performed as a separate action in relation to image data, now works directly through images. In this regard, Farocki points to machine vision, which automates operations of analysis and inspection and calculates pictorial information through image processing.[20]

The Visual 6502 project indexes these changes from humanly meaningful calculations to levels of complexity that can exist only when images and data interface with one another independently of human intervention. Significantly, the chips selected for the project come from the early years of integrated circuit manufacture in the 1970s and early 1980s and thus possess transistor counts that are amenable to visualization and relatively accessible to user understanding, whereas subsequent generations, given the regular doubling of circuit complexity, become impossibly dense. As computer historian and reverse-engineering expert Ken Shirriff notes, while the simulation allows for education into an earlier chip, it runs on current chips that "would be almost hopeless to try to understand."[21] Even in 1990 when Cara McCarty organized the first art exhibition of the microchip at

18. See Farocki, "Reality Would Have to Begin," in *Imprint: Writings*, trans. Laurent Faasch-lbrahim, ed. Susanne Gaensheimer and Nicolaus Schafhausen (New York, 2001), pp. 186–212, and Ali Hossaini, "Vision of the Gods: An Inquiry into the Meaning of Photography," *Logos* 2 (Summer 2003), www.logosjournal.com/hossaini.htm

19. See John Tagg, *The Burden of Representation: Essays on Photographies and Histories* (Minneapolis, 1988). See also Allan Sekula, "The Instrumental Image: Steichen at War," in *Photography Against the Grain: Essays and Photo Works, 1973–1983* (Halifax, 1984), pp. 33–51.

20. For further theoretical perspective on automated perception, see John Johnston, "Machinic Vision," *Critical Inquiry* 26 (Autumn 1999): 27–48.

21. Ken Shirriff, "The 6502 CPU's Overflow Flag Explained at the Silicon Level," Ken Shirriff's Blog, 13 Jan. 2013, www.righto.com/2013/01/a-small-part-of-6502-chip-explained.html

the Museum of Modern Art, two years before the first Semiconductor Roadmap and three years before the first Pentium-series chip, a note had to be made in relating the images to attendees that the awe they experienced in beholding the intricate, microscopic circuit patterns resulted from a design process that was impossible for human beings to perform unaided: "They are the most complex patterns people have ever made, and because of their intricacy they can be deciphered completely only by a computer."[22] In the ensuing years since McCarty's exhibition, the complexity of microchips has only expanded, and exponentially, as set out by the industry's guiding self-fulfilling prophecy of Moore's Law. This has meant that ever more powerful computers have been tasked with creating ever more complicated circuit designs in a continual process of disadjustment and readjustment.

Walter Benjamin's notion of the optical unconscious, the idea that films could show more than their makers intended, is an all too apt characterization of these circuits that, optically produced, carry out operations beyond human vision and open up possibilities that could hardly have been imagined when they were first invented.[23] Although human beings are certainly part of the process of circuit design, fabrication, shipment, and use, they cannot easily be said to be determinative in the final form or eventual use of circuits, which can result only from an indissoluble relation between humans and nonhumans at a scale larger than any individual. "Indeed," Bogost writes, "for the computer to operate at all *for us* first requires a wealth of interactions to take place *for itself*."[24] On a long enough timeline, the actions taking place *not for us* far outweigh those taking place *for us*.[25] Photography and cinema, technologies historically catered for human sense enjoyment, serve as cases of technologies that have already, even while submitting to human desires, achieved significant nonrepresentational and nonhuman ends right in front of our eyes. Similarly, while the integrated circuit images involved in the Visual 6502 project are designed intentionally *for us*, their necessity and the material basis of their operation indicate a vast range of processes *not for us*.

22. Quoted in Jon Harwood, *The Interface: IBM and the Transformation of Corporate Design, 1945–1976* (Minnesota, 2011), p. 258 n. 3.

23. See Walter Benjamin, "The Work of Art in the Age of Mechanical Reproduction," in *Illuminations*, trans. Harry Zohn, ed. Hannah Arendt (New York, 1969), pp. 235–37.

24. Bogost, *Alien Phenomenology*, p. 10.

25. In this regard, Ed Finn notes that even today top engineers at companies such as Facebook, Google, and Netflix admit to having only a limited understanding of "some of the behaviors their systems exhibit" (Ed Finn, *What Algorithms Want: Imagination in the Age of Computing* [Cambridge, Mass., 2017], p. 16).

Photolithography and Photography

When the MOS 6502 was being manufactured in the late 1970s, design and fabrication processes for integrated circuits were still largely manual. As early developers from MOS-competitor and industry leader Intel have recounted, "Schematic and layout for the first ten years of Intel [from 1968 to 1978] was done by hand. Engineers would produce draft schematics that a schematic designer would transfer onto D-sized vellum sheets. These would then be hand checked and signed off by the engineer."[26] Saving such hand-designed schematics was not a high priority for most companies. It was a luxury not available, in any case, for the MOS 6502, the design for which had been sold, never archived, and eventually lost. Accordingly, the researchers for the Visual 6502 project had to find a different way to access the chip design. The method they settled on used reverse engineering in a very literal sense. They would peel back the layers of the production process to reveal the physical layout and logical design of the chip, and, like traditional archaeology, their digital archaeology had to break some ground along the way. The process began by removing the final phase of the production process, de-capping the chip by squirting hot sulfuric acid on the plastic packaging, a method with a small margin for error that resulted in several lost chips. Tracing back along the 6502's original assembly line, the de-packaged chip revealed the silicon die as well as the lead bonds once attached to connect the photolithographic surface to the package pins, likely placed by women in Southeast Asia in the late 1970s in a difficult process using a microscope. Doubling back along this path, the researchers used high-powered microscopes to focus on the chip surface, taking seventy-two microphotographs to be recomposed to create a full shot of the circuit. Because the 6502 used a two-layer photolithographic process, they then stripped away the upper layer of metal and polysilicon to reveal the substrate beneath for an additional seventy-two microphotographs (figs. 4–5). Beyond revealing the diffusion areas of the conductive substrate, this excavation also in a crude way tracked back through the photolithographic process that initially constituted the chip.

Photolithography is in fact as old as photography itself. Among the early inventors of photography, Joseph Nicéphore Niépce in France in the 1820s and Henry Fox Talbot later in England in the 1840s conceived of photographic systems as means of automating practices of lithography. Talbot, for instance, called his process photolytic engraving to designate it as a

26. Andrew M. Volk, Peter A. Stoll, and Paul Metrovich, "Recollections of Early Chip Development at Intel," *Intel Technology Journal* (2001): 6.

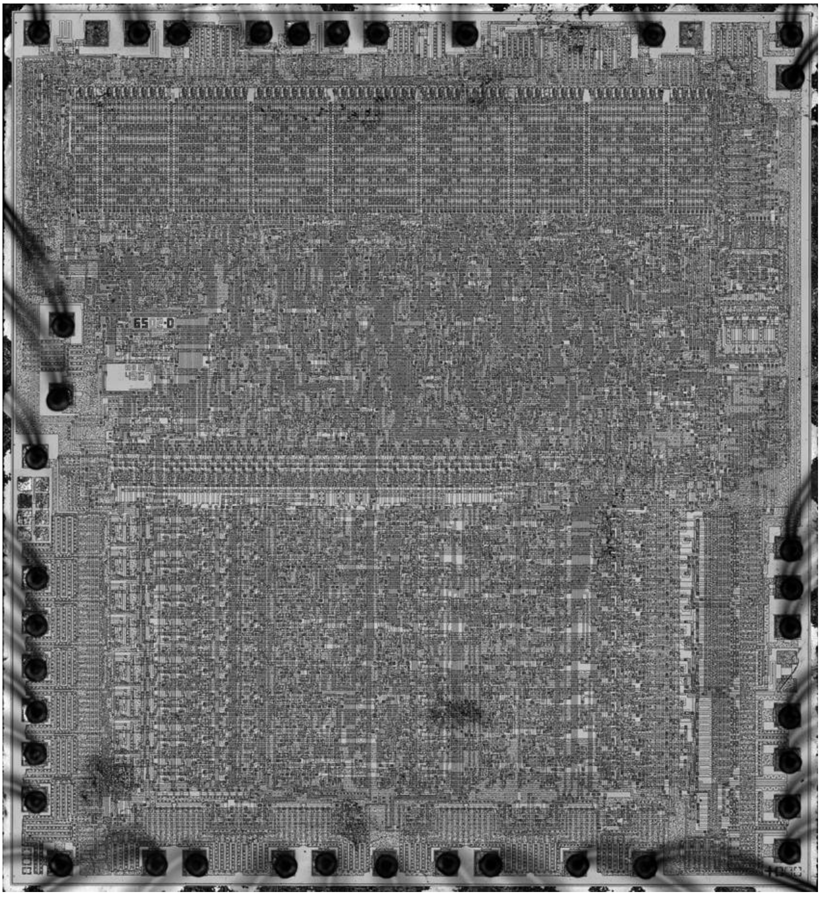

FIGURE 4. Composite microphotograph of the MOS 6502 microprocessor. Image courtesy of Greg James and the Visual 6502 project.

form of photomechanical etching.[27] Niépce's marginalized place in the history of photography, and so too his process of *heliography*, or sun-writing, proceeds at least in part from the daguerreotype's rendering his initial aims of photolithography impracticable because the delicate process could not withstand being "subjected to the pressure of a roller."[28] Lesser known but following the same impulse, A. A. Turner devised a photolithographic process that was used to print the book *Villas on the Hudson* in Upstate New

27. See H. Fox Talbot, "Photoglyphic Engraving of Ferns; with Remarks," in *Transactions of the Botanical Society of Edinburgh* 7 (Edinburgh, 1863): 568–69.

28. Josef Maria Eder, *History of Photography*, trans. Edward Epstean (New York, 1978), p. 237.

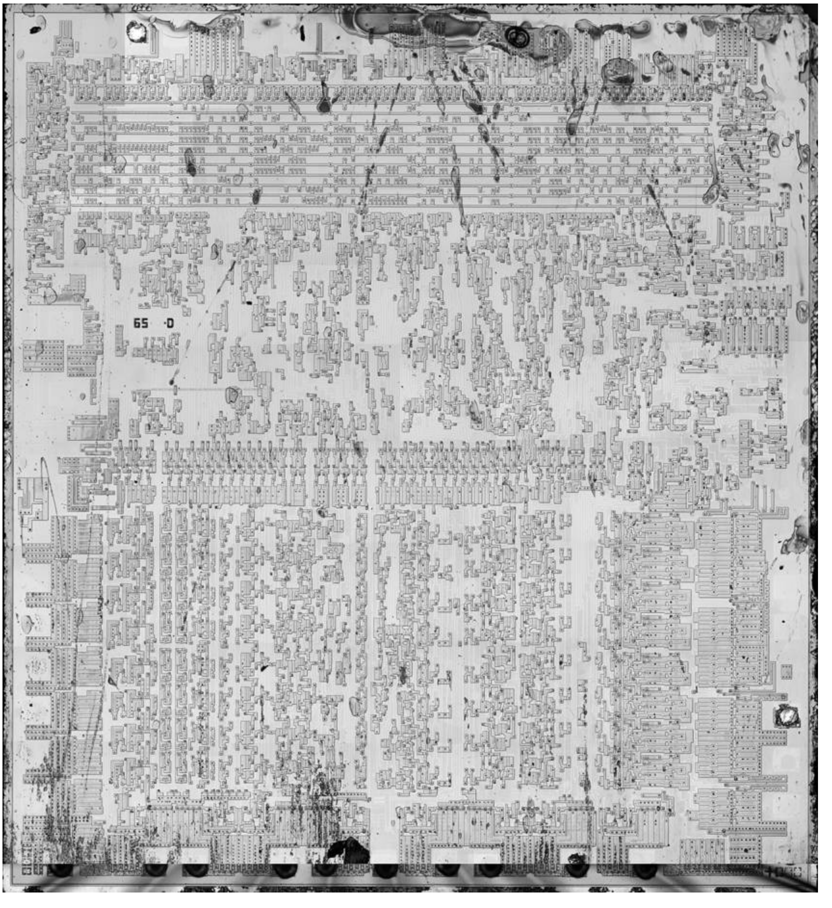

FIGURE 5. Composite microphotograph of the MOS 6502 microprocessor after stripping away the top layer of metal and polysilicon. Image courtesy of Greg James and the Visual 6502 project.

York in the 1860s, and in 1893 N. S. Amstutz of Cleveland made an enterprising attempt to use relief photographs, read in the way a stylus reads a phonograph, as a means of telephotography, later influencing the French inventor Édouard Belin, whose *téléstéréograph* wired the first photograph from Paris to Lyon in 1907.[29] On the basis of these and similar experiments, Friedrich Kittler has situated photography within the set of media possibilities opened up by mass print culture in the nineteenth century, where it

29. David A. Hanson, "A. A. Turner, American Photolithographer," *History of Photography* 10, no. 3 (1986): 193–211. See the accounts of Édouard Belin and N. S. Amstutz in D. W. Isakson, "Developments in Telephotography," *Transactions of the American Institute of Electrical Engineers* 41 (Jan. 1922): 794–801.

came to fill the role lithography once served in providing illustrations for rotary-press newspapers. Similarly, Gregory Wickliff argues that photography arose from a plurality of interests in reproducing physical reality in the nineteenth century, representing "a realization of some of the strongest latent desires in Western culture of this period: to produce photolithographs, to capture minutely detailed scenes from nature, to render economical and rapid human portraiture, and to scientifically study the nature of radiation itself."[30] The precise extent and breadth of this impulse toward the automatic sculpting of physical matter, however, and its role in the history of computing, deserves more attention.

Consider, for instance, the physical processes involved in manufacturing an integrated circuit, leaving to one side for the moment the significant research and development that goes into the circuit schematic and mask design. An integrated circuit begins with a thin disc of extraordinarily pure, defect-free crystalline silicon, called a wafer.[31] A single wafer, depending on its diameter, can contain several hundred individual circuits, or dies, to be cut using an extremely precise diamond dicing saw. The wafer takes one of two types, according to an initial doping process applied to the source ingot and used to introduce carefully determined impurities into the silicon to alter its conductivity. Adding phosphorus in infinitesimal quantities creates N-type silicon; adding boron creates P-type silicon. The doping process tilts the semiconductor from a slight insulator to a slight conductor, meaning that the substrate of the microchip begins with a finely tuned polarity. By adding new layers and new impurities, a process primarily achieved today by photographic techniques, this initial polarity conditions the flow of current through the eventual circuit.

An integrated circuit, such as the MOS 6502, grows out of a process applied to the entire wafer, but, for the sake of clarity and because transistors were initially produced individually, it makes sense to look at how the process creates a single transistor on an individual die. Three primary materials make up a silicon transistor—metal conducting lines, a thin film of silicon dioxide, and doped silicon—lending it the name metal–oxide–semiconductor field-effect transistor (MOSFET). Thin layers of oxidation occur naturally on silicon, in much the way layers of rust grow on iron or, in a similar process, patinas form on bronze and copper. Integrated circuit manufacture uses this naturally occurring oxide layer, while controlling its formation

30. Gregory A. Wickliff, "Light Writing: Technology Transfer and Photography to 1845," *Technical Communication Quarterly* 15, no. 3 (2006): 294.

31. For an excellent account of the history of silicon crystal growth, see Christophe Lécuyer and David C. Brock, "The Materiality of Microelectronics," *History and Technology* 22 (Sept. 2006): 301–325.

in prespecified ways, to protect the silicon and act as an insulator. As Michael Riordan has argued, the pivotal moment in the history of integrated circuits turned on Jean Hoerni's discovery, at Fairchild Semiconductor in 1957, that this oxide layer, which up until then had been stripped away, could be used to protect the positive–negative junctions at the surface of the silicon.[32] Prior to Hoerni's discovery, the most prevalent transistor had been the mesa type, so named because the geometry of its base was slightly raised in the form of a mesa. Mesa transistors required all contacts to be hand-painted using a camel's hair brush, making them exceptionally labor intensive and expensive. Additionally, the rising mesas left the contact points exposed to dust and moisture that could disrupt electrical performance. Rather than elevating layers on the transistor, as occurred with the mesa type, Hoerni's process used the oxide layer to lay out the entire circuit design on a flat topography. He wrote in an early report about his discovery: "It is obviously more convenient to deal with an integrated system having a planar surface than a collection of mesas and valleys."[33] The planar process, as the technique came to be called, extended the photographic method used to create part of the mesa transistor to the whole design, exploiting light and optical masks to create the entire pattern through etchings in the oxide layer.

Transistors had not always been photographic.[34] The first transistor ever, the point-contact transistor, for which John Bardeen and Walter Brattain won the Nobel Prize in 1956, used no photo-etching techniques at all, instead having all contacts placed by hand. In 1949, Jack Morton, who supervised transistor development at Bell Labs where the discovery was made the year before, modeled his idea of automating the manufacturing process not on photography but instead on the printing press. "Imagine a technique," he contemplated, "in which not only the connecting leads and passive elements . . . but also the active semiconductor elements are 'printed' in one continuous fabrication process."[35] That the eventual print-

32. See Michael Riordan, "The Silicon Dioxide Solution," *IEEE Spectrum*, 1 Dec. 2007, spectrum.ieee.org/tech-history/silicon-revolution/the-silicon-dioxide-solution

33. Jean A. Hoerni, "Planar Silicon Transistors and Diodes," 1960 Electron Devices Meeting, Washington, D.C., October 1960, s3.computerhistory.org/siliconengine/hoerni-planar-paper.pdf

34. Yet this should not be taken to mean that all computer hardware at the time was nonvisual. As Wendy Chun details, the necessary ephemerality of computer memory capitalized on the capability of the cathode-ray tube to write and rewrite information, as in the Williams-Kilburn tube; see Wendy Hui Kyong Chun, "The Enduring Ephemeral, or the Future Is a Memory," *Critical Inquiry* 35 (Autumn 2008): 148–71.

35. Quoted in David A. Laws and Michael Riordan, "Making Micrologic: The Development of the Planar IC at Fairchild Semiconductor, 1957–1963," *IEEE Annals of the History of Computing* 34 (Jan.–Mar. 2012): 20.

ing process for microelectronics mobilized photographic techniques rather than mechanical ones owes as much to the auspicious binary alternation at the basis of photography as to the legacy of photomechanical etching. If one wanted to produce diffusion areas with electrical properties opposite the properties in adjacent areas, it helped to be able to use a medium also capable of such alternation. As Kittler puts in perspective, negative–positive photography embodied the logic of modern computing long before the first photographically printed transistor:

> The consequences of unlimited copying are clear: in a series first of originals, second of negatives, and third of negatives of a negative, photography became a mass medium. For Hegel, the negation of a negation was supposed to be anything but a return to the first position, but mass media are based precisely on this oscillation, as it logically calculated Boolean circuit algebra and made possible nothing less than the computer.[36]

With the invention of photoresists in the 1940s, the technical potential of photographic reversibility returned to the ambitions of Niépce and Talbot. Extending Bazin's idea that photography and film emerged from the dream of reconstructing "a perfect illusion of the outside world in sound, color, and relief,"[37] we might call special attention to the aspect of relief, which, beyond its effects in the virtual space of the image and in the optical illusions of three-dimensionality, commanded a far more literal place in the contours and valleys carved by photolithography.[38]

The first step-and-repeat cameras to apply photolithographic techniques to the production of mesa transistors had a more prosaic connection with the history of photography. "For [Robert] Noyce and [Jay] Last to produce the first masks through which to expose photoresist," Gordon Moore relates, "they sorted through the inventory of 16-mm movie camera lenses in a San Francisco camera store to select the three that matched most closely in focal length. These were then mounted in a rigid frame and used to make a set of three masks by stepping the image over the surface of three photographic plates."[39] It was necessary to select three

36. Friedrich Kittler, *Optical Media: Berlin Lectures 1999*, trans. Anthony Enns (Malden, Mass., 2010), p. 134.

37. Bazin, "The Myth of Total Cinema," in *What Is Cinema?* 1:20.

38. In a sense, both photography and photolithography are three-dimensional processes, with each writing into the depth of the substrate to create two-dimensional effects, resulting respectively in images and in pathways for the patterning of information traffic.

39. Gordon E. Moore, "The Role of Fairchild in Silicon Technology in the Early Days of 'Silicon Valley,'" *Proceedings of the IEEE* 86 (Jan. 1998): 56.

lenses with the same focal length because the process required three steps. Photolithography was not a snapshot of the circuit design but instead a process of implementing it through layers. Mesa transistors consisted of three layers and thus required three masks. To fabricate a transistor solely through optical techniques, Hoerni's planar process required a more complicated photolithographic sequence using four masks.[40] The complication of adding masks to the lithographic process, to draw on Godfrey Reggio's juxtaposition between the grid of the city and the pathways of the microchip in *Koyaanisqatsi* (1982), was like trying to match up plumbing, drainage, and sewage across different stories of a building.[41] Nevertheless, combined with Noyce's concept of circuit integration, the planar process was more than worth the cost; it facilitated the mass production of not only transistors but also entire circuits and thereby fulfilled the dreams of Niépce and Talbot in another domain.[42]

The crucial photographic element prompting the Visual 6502 reverse engineering effort was this master mask set, which, by the time the MOS 6502 was being designed, consisted of six masks. Circuit masks were generally produced in Silicon Valley by skilled technicians. An image held at the Computer History Museum shows two operators at Intel in 1970 cutting the circuit design by hand onto Rubylith, a layer of red plastic film, in a process that an early designer described as "back-breaking," involving long hours standing over a light table with an X-Acto knife.[43] The mask design would then be photographed from above with a high reduction factor, the resulting photograph then rephotographed to reach the desired level of magnification. As circuit complexity increased in the 1970s, mask designs became increasingly unwieldy because technicians could not shrink the Rubylith

40. See ibid., p. 58.

41. Brian Bagnall provides an excellent explanation of this problem as it played out in Bill Mensch's design of the MOS 6502; see Brian Bagnall, *Commodore: A Company on the Edge* (Winnipeg, 2010), p. 21. Also, it should be noted that comparisons between the layout of cities and microchips abound. Allen A. Boraiko in an early popular account in *National Geographic*, for instance, writes, "Under a microscope the chip's intricate terrain often looks uncannily like the streets, plazas, and buildings of a great metropolis, viewed from miles up" (Allen A. Boraiko, "The Chip: Electronic Mini-Marvel That Is Changing Your Life," *National Geographic* 162 [Oct. 1982]: 421). Similarly, the analogy has formed the basis of legal claims for the copyright protection of semiconductor circuits; see Dorothy Schrader's statement as cited in Robert W. Kastenmeier and Michael J. Remington, "Semiconductor Chip Protection Act of 1984: A Swamp or Firm Ground?" *Minnesota Law Review* 70 (1985–1986): 435.

42. Noyce led circuit integration at Fairchild, but patent disputes in the 1960s arose concerning the priority of work by Jack Kilby at Texas Instruments; these were eventually resolved by a cross-licensing agreement.

43. Yannis Tsividis, "Designing Analog MOS Circuits at Berkeley in the Mid-70s," *IEEE Solid-State Circuits Magazine* 6 (Spring 2014): 23. For the image of Rubylith operators, see www.computerhistory.org/revolution/artifact/287/1614

patterns during the cutting stage and instead had to photograph them with ever higher reduction factors. The patterns increasingly sprawled out across the laboratory floor, which sometimes amounted to nothing more than a garage, and as Michael Feuer relates, eventually outgrew the space altogether, leading to the creation of automated mask design.[44]

The possibility of exact visual replication made microchips particularly susceptible to misappropriation because, as in the Visual 6502 project, unscrupulous manufacturers needed only to disassemble the chip to expose its constituent masks. In an intellectual property article from 1980, which would later be influential in extending copyright protection to software, John Craig Oxman notes that such practices of photographic reproduction have always made mask designs susceptible to reverse engineering because their surface representation is their meaning. In a passage that is especially apropos for a visual history of computing, Oxman makes the case that integrated circuit masks and reticles might be classified under the law as "audiovisual" or "pictorial" works.[45]

That computational structures were coextensive with their visual representation also meant that they could transition very easily to graphic design capabilities. As early as the introductory demonstration of Sketchpad at MIT's Lincoln Laboratory in 1963, Ivan Sutherland outlined the uses of computer graphics for defining electrical circuit connections. Later in the 1960s, precision plotters and computer-aided design systems came to form a tight system for importing handmade sketches into digital form and exporting digital designs for review and manufacturing, expressed nowhere more succinctly than in the Auto-trol Corporation's slogan "Graphics to computer to graphics to computer to graphics" (fig. 6).[46] To follow Peter Galison's insight, this also meant that computers capitalized on and operationalized a

44. See Michael Feuer, "VLSI Design Automation: An Introduction," *Proceedings of the IEEE* 71 (Jan. 1983): 5–9.

45. John Craig Oxman, "Intellectual Property Protection and Integrated Circuit Masks," *Jurimetrics* 20 (Summer 1980): 446.

46. Smithsonian Institution Archives Center, Gerber Scientific Instruments, Box 75, Folder 1, Aero Microplotter, Auto-trol Graphics. In a penetrating inquiry into the S-C 4020 microfilm plotter used at Bell Laboratories in the 1960s, Zabet Patterson makes the case that special-purpose image peripherals such as these played a more central role in the history of computing and in the development of graphics capabilities than has generally been recognized. Patterson focuses predominately on scientific visualization, or what she calls "synthetic cinematography," and computer art, but the insight can extend beyond the material influence of peripherals on graphics and interfaces and circle back along the feedback loop of computer manufacturing to include the influence of graphic design systems on circuit hardware development (Zabet Patterson, *Peripheral Vision: Bell Labs, the S-C 4020, and the Origins of Computer Art* [Cambridge, Mass., 2015], p. 11).

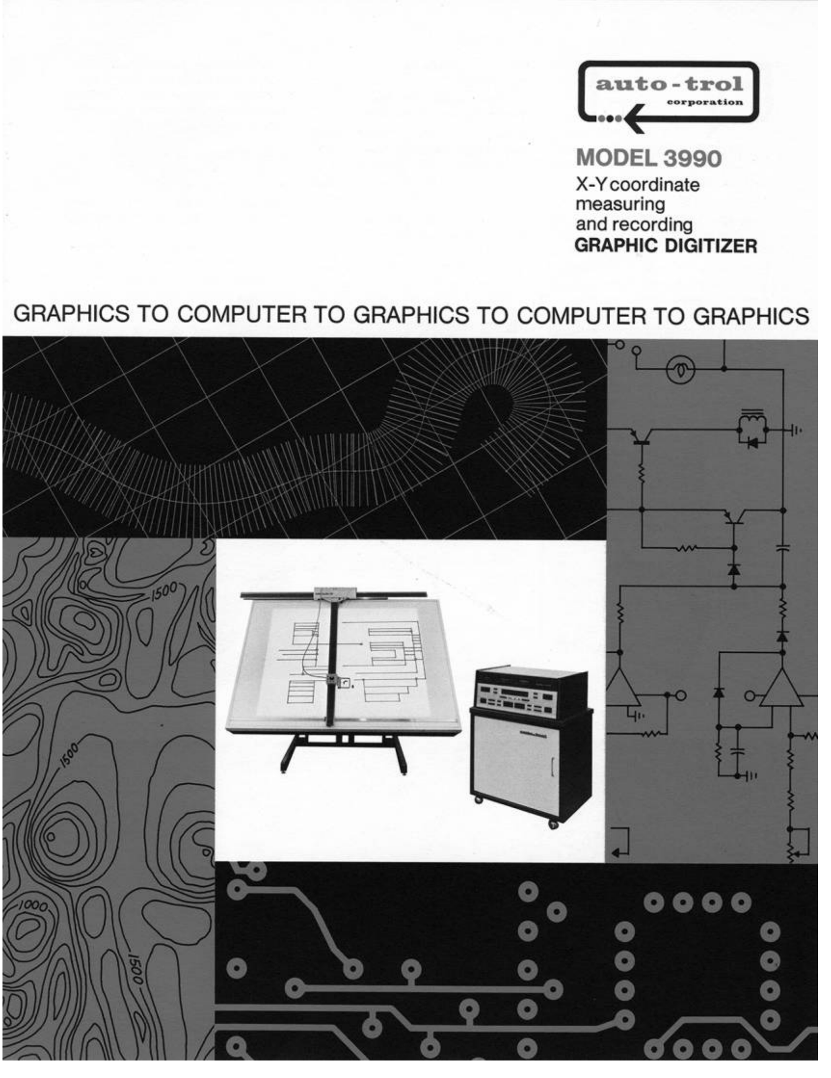

FIGURE 6. Auto-trol Graphic Digitizer, from trade catalogue. Image courtesy of the Smithsonian Archives Center from the ICE Integrated Circuit Collection.

reciprocal interchange that had long played out in the history of science: "Images scatter into data, data gather into images."[47]

47. See Peter Galison, "Images Scatter into Data, Data Gather into Images," in *Iconoclash: Beyond the Image Wars in Science, Religion and Art*, ed. Bruno Latour and Peter Weibel (Cambridge, Mass., 2002): 300–23. See also Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago, 1997).

Image and Data, Two Universalities

The MOS 6502, alongside other chips from the mid 1970s to early 1980s, was released at the threshold between large-scale integration (LSI) and very-large-scale integration (VLSI), an important historical shift that corresponded suggestively with the cultural shift from modernity to postmodernity. VLSI circuits, with transistor counts in the hundreds of thousands, stretched thin manual design processes and production techniques such as circuit layout and the placement of connecting wires and eventually confounded them altogether, necessitating computer-aided design and manufacturing systems. Kathryn Henderson, in her foundational account of computer-aided visual design practices, relates the story of a circuit designer who kept "a stack of paper printouts near his computer screen to help him keep a new chip's overall design in mind."[48] It is precisely this sort of visual aid that VLSI circuits, with their reliance on the automated eyes and hands of graphic design systems and fabrication techniques, would obsolesce. Similarly, increasing circuit complexity would soon outmode the processes of manual inspection, often called eyeballing, which Lisa Nakamura describes in her important article on indigenous electronics labor at the Fairchild Semiconductor plant in Shiprock, New Mexico, in the 1970s.[49]

Before this transition, Kittler notes wryly, even amateurs such as himself could tinker with a processor: "In the good old days when microprocessor pins were still big enough for simple soldering irons, even literary critics could do whatever they wished with Intel's 8086 Processor."[50] But after successive generations, this possibility was eliminated even for technicians. Human intervention was displaced to the periphery of circuit manufacture and relegated to specialized technical means of access. Inhumanly large and complex, VLSI circuits accelerated a process of enlisting chips to produce further generations of chips and by extension computers further generations of computers. Each time human-based design and manufacturing practices obsolesced, nonhuman optics took over a significant part of the work.

As Bernard Stiegler has long maintained, the method of deconstruction arose in the 1960s in the mirror reflection of a programmatic technicity unprecedented in its capabilities and dangers, "a technology that constitutes something like an 'objective'—that is to say, factual—'deconstruc-

48. Kathryn Henderson, *On Line and On Paper: Visual Representations, Visual Culture, and Computer Graphics in Design Engineering* (Cambridge, Mass., 1999), p. 1.

49. Lisa Nakamura, "Indigenous Circuits: Navajo Women and the Racialization of Early Electronic Manufacture," *American Quarterly* 66 (Dec. 2014): 919–41. See also Rachael Grossman, "Women's Place in the Integrated Circuit," *Radical America* 14 (Jan.–Feb. 1980): 29–50.

50. Kittler, "Protected Mode," trans. Stefanie Harris, in *Literature, Media, Information Systems*, trans. Harris et al., ed. John Johnston (New York, 2012), p. 156.

tion.'"[51] New information and communication technologies, as Marshall McLuhan similarly witnessed, effected radical new organizations of writing, from television programs to automatic stored programs, that exerted pressures on human language and threatened traditional forms of social organization, while at the same time awakening new understandings of human history and media systems. On the same basis, Gregory Ulmer has located Derridean thinking at the cusp of a profound epochal overturning: "If Plato marks the turn from a civilization based on orality (speech) to one based on alphabetic writing, Derrida marks a similar shift from alphabetic writing in its print stage to filmic writing."[52] With historical hindsight, Ulmer's observation appears modest in that filmic writing has receded to secondary importance behind vast new computational forms of writing so powerful they have redefined even cinema. Yet his insight about film's role in this epochal turnover should not be dismissed; it is really a matter of what type of *film* is at issue, what visual practices have organized this historic shift in media systems. From our current perspective, when databases have rendered available technical articles and lectures previously difficult to navigate for humanities researchers, all fully searchable and indexed by their interlinking citations—not to mention, fully made possible by integrated circuits—we are able to see that the most transformative visual practices in the last half-century have been developed in the areas of photolithography, interactive graphics, and machine vision. Derrida was not yet able to trace the history of these visual supplements, these automated exteriorizations in the adventure of interrelationships between hand and eye; however, that did not stop him from supplying the critical tools necessary to understand the technical constitution of this field of objective deconstruction.[53]

Derrida's annus mirabilis, 1967, witness to three career-defining books inaugurating the method of deconstruction, was also the year Fairchild Semiconductor released its first computer-designed integrated circuit. The 32-Gate Custom DTL Logic Array entered the market as part of the same Diode Transistor Logic family the company had been supplying to mil-

51. Bernard Stiegler, "Derrida and Technology: Fidelity at the Limits of Deconstruction and the Prosthesis of Faith," trans. Richard Beardsworth, in *Jacques Derrida and the Humanities: A Critical Reader*, ed. Tom Cohen (New York, 2001), p. 238.

52. Gregory L. Ulmer, *Applied Grammatology: Post(e)-Pedagogy from Jacques Derrida to Joseph Beuys* (Baltimore, Md., 1985), p. 303.

53. See Stiegler, "Derrida and Technology," p. 248. Similarly, although Stiegler has called for an understanding of this explicitly in terms of a "*history* of the supplement," he has remained largely at the level of philosophizing about them rather than tracing their lineage and their own internal disadjustments (p. 248). When Stiegler has taken up the question of deconstruction's objective materiality, he has, like Ulmer, largely focused on film; see, for instance, Stiegler, *Cinematic Time and the Question of Malaise*, vol. 3 of *Technics and Time*, trans. Stephen Barker (Stanford, Calif., 2011).

itary contractors and the space program for half a decade.[54] Its design was innovative for using a two-layer metal process, also the first of its kind, whose complexity and interconnections called for the precision of computer graphics over the then-prevalent process of designing by hand. In a year when NASA's ATS-3 satellite delivered the first whole-Earth image—the photographic data of which was collected through a series of passes captured by the satellite's Spin Cloud Camera and then transmitted back to ground where it was assembled and processed in both photographic and magnetic tape formats, the image being stored in both picture and data form, recording this Archimedean vantage in its photographic plenitude and also reducing it to the near-zero degree of signification as a series of data—it is striking to read Derrida settling on the same two universal languages of the image and computing in his deconstruction of Étienne Bonnot de Condillac's *An Essay on the Origin of Human Knowledge* (1746). These are, of course, the usual coordinates mentioned in the history of electronics: the quest for miniaturization through semiconductor computing and the attainment of a total world picture through space technology, the latter accelerated by the former. Derrida's insight was to think these "two epochs of universal writing" in terms of the pro-*gram* and the picto-*gram* forming a circuit.[55]

In his reading of Condillac, Derrida outlines a series of epochal transformations of the sign: from the earliest forms of pictography, as displayed in Paleolithic cave paintings, where each thing has its own unique sign; to hieroglyphs, which strip away at the image and gain in economy by using one sign to represent multiple things; to the alphabet, which pares down signifiers to abstract characters that refer not to things but to speech sounds that in their combination refer to things. The historical tendency of signification, along this path, tilts away from the plenitude of pictographic representation and toward formalization and abbreviation, as Derrida summarizes, ventriloquizing Condillac's theologically-inflected conclusions: "Separating itself from the origin, the signifier is hollowed and desacralized . . . and universalized" (*OG*, p. 285). Alphabetic characters reduce material and information to a minimum, economizing the expenditure of writing by requiring fewer brush strokes, drawn lines, or etchings. Reciprocally, "the first writing," "a painted image," strikes free from the weight of expressing the panoply of human communication to graze in other pastures of artistic wonder, which along one path will approach photorealism (*OG*, p. 283). The origin and terminus of the history of

54. See Christophe Lécuyer, *Making Silicon Valley: Innovation and the Growth of High Tech, 1930–1970* (Cambridge, Mass., 2006), p. 243.

55. Jacques Derrida, *Of Grammatology*, trans. Gayatri Chakravorty Spivak (Baltimore, Md., 1997), p. 285; hereafter abbreviated *OG*.

writing thus give birth to two possibilities: the image and the sign. And at a certain moment of closure of an epoch of writing, in 1967, Derrida grasps their kinship:

> The history of writing, like the history of science, would circulate between the two epochs of universal writing, between two simplicities, between two forms of transparence and univocity: an absolute pictography doubling the totality of the natural entity in an unrestrained consumption of signifiers, and an absolutely formal *graphie* reducing the signifying expense to almost nothing. [*OG*, p. 285][56]

Emerging from these remote figures in what Derrida, following an insight from the anthropologist André Leroi-Gourhan, calls "the history of the *grammè* as an adventure of relationships between the face and the hand," the integrated circuit maps out from the circuit of the human body an interplay extending from the face and the hand down to the precision of eyes and digits (*OG*, p. 91). In it image and data, as the arts of the eye and the hand respectively, have been abstracted to the point of nearly perfect functionality: the image has been reduced to a processor of data, and data (thought in the Latin sense of "things given") have been reduced to the simplest form of signification in either being given or not. Through such functional abstraction, the integrated circuit *operationalizes* and *couples* the two poles of signification that Derrida identified in "an absolute pictography" and "an absolutely formal *graphie*," its structural and optical configurations coinciding, reinscribing "the unity of gesture and speech, of body and language, of tool and thought" in another domain (*OG*, p. 85).

Trading in one of the most pervasive mythologies about the character of the divine entity, the architecture of computing is written in light, composed in images at scales beyond human handwork and beyond human seeing. This trajectory of technical operations beyond human perception, already underway when Derrida wrote *Of Grammatology*, should be understood to be that closure of an epoch of writing that reveals logocentrism for what it always was, a certain guarantee against the threat of *techné* that all writing in some way returned to the human. As long as written characters could evoke the fullness of voice, they covered over their more monstrous potential: the way that writing writes itself, how it subtly works through the human adventure to expand its own domain, displacing the work of the hand, the reading of the eye, and the movement of people along the way. Any history of computing today must in some way account for this visual history of computing beyond all human vision.

56. For the complete discussion on Condillac, see *OG*, pp. 280–95.