HOW ELECTRONS REMEMBER

In this essay I will argue that electronic images are the index, if not of an original object, then at least of a physical process. Without sounding too anthropomorphic, I want to suggest that electrons remember. There are two problems to be addressed. First, what is the material basis of electronic imaging? Second, is this material basis significantly different for analog and digital electronic imaging? I invite the reader to assume a subatomic empathy as we look at the life of the electrons in electronic imaging.

Electrons exemplify what Manuel De Landa calls nonorganic life. De Landa argues that supposedly inert matter, from crystals to the rocks and sand in a river bed, exhibits self-organizing behavior and even acquires experience, which entitle it to be considered nonorganic life.[1] In effect, De Landa is arguing not that rocks are like humans so much as that humans are like rocks. Yet the reverse is implicit: he effectively rearticulates life as something that is not the sole property of organic creatures. I suggest that the same nonorganic life exists at the level of subatomic particles. The memory that I attribute to electrons does not have to do with will or self-consciousness, but with an emergent self-organizing principle. Like De Landa, physicist David Bohm argued that the distinction between organic life and nonorganic matter is arbitrary. He gives the example of a tree: it grows from a seed, whose DNA molecule organizes matter into a tree; but Bohm says it doesn't make sense to say, for example, a CO_2 molecule is inorganic until it becomes part of the tree, then it's organic.[2] Bohm's example underscores an argument that all elements are part of a (nonorganically) living whole. For the electron, the living whole in which it partakes is the wave forms that unify all matter.

It is common for critics of digital media to note that in digital media the indexical link between image and represented object is irrevocably severed. In photography, film, and analog video it is possible to trace a physical path from the object represented, to the light that reflects off it, to the photographic emulsion or cathode ray tube that the light hits, to the resulting image. In digital imaging this path is not retraceable, for an additional or alternative step is added; namely, converting the image into data that can then be manipulated, and thereby breaking the link between image and physical referent. In the digital image, it

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2. Strictly speaking, chemical nomenclature says that an inorganic chemical such as CO_2 becomes organic when it is part of an organic chemical.

3. Gene Youngblood, *Expanded Cinema* (New York: Dutton: 1970).

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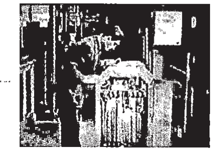
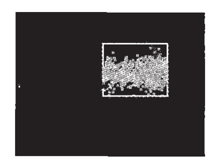


These concerns are accurate, though it is exaggerating to see the advent of digital media as a watershed between truthful and constructed imagemaking, as historians show that these media have been tinkered with since their inceptions. What I question in the current rhetoric about the loss of indexicality in the digital image is that it assumes a concurrent loss of *materiality* of the image. As a result it is assumed that digital images are fundamentally immaterial, and that, for example, to enter cyberspace or to use VR is to enter a realm of pure ideas and leave the "meat" of the material body behind. Digital and other electronic images are constituted by material processes no less than photography, film, and analog video are.

When we look at the physical process whereby electronic images are constituted and transmitted, we find that it is indeed possible to retrace the path traversed by the image. Electronic imaging is indexical in the broadest sense, in that the medium bears the physical mark of the object whose image it transmits. This can be argued if I can convince the reader not only that electrons exist (i.e., are not reducible to waves or to probabilities), but that because of particle-wave relationship, all matter is fundamentally interconnected. Basically, I will argue that the analog or indexical relationship is maintained insofar as the activity of electrons can be traced to a wave function. When the wave function is broken, the indexical bond is lost as well. Yet we can still trace the basis of digital information in interconnected matter.

LAURA U. MARKS

Certainly, the electronic image, both analog and digital, would seem to be a physical object insofar as it is constituted by a barrage of electrons. Gene Youngblood pointed this out back in the analog days: "On the most fundamental level electronic visualization refers to the video signal itself as a plastic medium, as the 'material' of electronic presence. . . . This isn't visual art or picture-making; it is the thing itself, the visible process of the electronic substance."[3] Yet, in my plunge into the world of



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3. Gene Youngblood, *Expanded Cinema* (New York: Dutton: 1970).

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physics, I have found that physics is still fraught with questions concerning the entity of the electron. Roughly put, is it a particle or is it a wave, is it a thing or merely a symptom, and does matter as such exist or can it only be approximated by equations?

DO THEY EXIST, AND CAN WE KNOW WHERE THEY ARE?

To trace the various electronic pathways through cathode ray tubes, silicon chips, copper cables, optical fibers and their other media, it is first necessary to look at the behavior of individual electrons. This means entering the world of particle physics. The excursion into theoretical physics that follows cleaves to the minority "realist" interpretation associated with Albert Einstein, Erwin Schrödinger to a degree, David Bohm, and John Bell, as opposed to the dominant "positivist" argument associated with Werner Heisenberg and Niels Bohr. This argument in physics is remarkably similar to semiotic arguments about the relationship of the sign to reality, and hence the question of whether reality is knowable in itself or only through signs. In a comparison between physics and semiotics, realists like Bohm are more like Charles Sanders Peirce, while positivists like Heisenberg are more like Ferdinand de Saussure. The former argue for a material connection between reality and the description of reality, while the latter argue that the connection between the two is entirely symbolic. A materialist myself, I choose to learn from Bohm's theories for the same reason that my semiotic loyalties lie with Peirce. I beg the indulgence of readers who have studied theoretical physics or electronic engineering, for whom the following will be annoyingly simplified.

It may surprise other readers, as it surprised me, that quantum physics is now considered not a radical theory but an orthodoxy among physicists, to the degree that an acronym, QUODS, has been coined for members of the quantum-orthodoxy-doubting subculture.[4] Since we humanities scholars are supposed to mistrust orthodoxies of all sorts, this news may invite us to look more sympathetically upon the continuing debates among this century's physicists.

Most physicists, following Schrödinger (as interpreted by Neils Bohr), Werner Heisenberg, Max Born, and others, believe that at a quantum level we cannot know matter as such.[5] Most quantum physics is non-objective, i.e., does not assume that its mathematical models have a physical counterpart in the world. They argue that at a quantum level the rules of classical physics, which do describe the behavior of matter at a macroscopic level, do not apply. In contrast, the pocket of "realists" represented most strongly by Einstein and Bohm posited an ontological the-

4. In David Wick, *The Infamous Boundary: Seven Decades of Controversy in Quantum Physics* (Boston, Basel, and Berlin: Birkhäuser, 1995). Compared to humanities scholarship, the sciences are less subject to fashionable breezes. In science, as in other disciplines, theories are accepted if they explain phenomena. However, science's orthodoxy often means that graduate students and post-docs only work on areas that they think have a good chance of being published and getting them jobs, established scientists do the kinds of work that are assured to receive grants, and in other ways the discipline renews the status quo. In science it's hard to get by on chutzpah. Passion and faith, however, are important ingredients in remaining a scientist, especially if one's work is not recognized in one's lifetime.

5. Schrödinger, who was not a positivist, "hated" Born's interpretation of his equation as merely a probabilistic one (Wick, 31), but the interpretation stuck.

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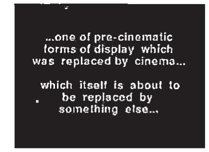
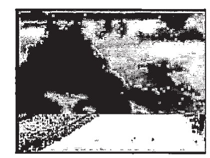
Quantum orthodoxy was established with the widespread acceptance of Schrödinger's wave equation. This equation (as interpreted by Born) gives the probability of where an electron will be observed at a given moment, if an observation of its position forces it to become localized. In 1905 Einstein demonstrated that light interacts like particles with energy $E = h\lambda$, where h is Planck's constant and λ is the frequency of light. His special theory of relativity argued that space and time must be treated similarly. From these two discoveries Louis de Broglie, in 1926, suggested that electrons must have wave properties, and that the wavelength can be given by $p = h/\lambda$, where λ is the electron's wavelength.

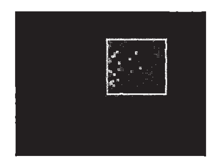
That same year Schrödinger suggested an answer to the question; if an electron was a wave, how could that wave change with time so that it satisfies these two equations and still move as a particle (which, according to Newton's laws, accelerates under an external force)? His answer, a differential equation for the wave of the electron that also works for systems of particles, is still the cornerstone of modern physics. To predict where an electron is likely to be, look at where Schrödinger's wave function has a large amplitude. Where the amplitude is small, electrons will be scarce. The equation was revolutionary because it combined particle and wave functions, making it possible to interpret the behavior of matter as both wavelike and particlelike. What takes the equation out of the realm of materialism (describing physical matter) and into positivism (describing only what can be observed) is that the electron's position remains unknown, and the wave equation can only predict the probability of where it will be seen if observed. (Similarly, matrix quantum mechanics explains quantum behavior in mathematical terms that cannot be expressed physically.)

In 1927 Werner Heisenberg took this development further in the direction of positivism with his uncertainty principle. When an electron that has been struck by a gamma ray emits a photon, whose momentum is designated p and position is designated q,

$$\delta p \times \delta q \geq h$$







– the product of the uncertainty or fuzziness in momentum and position always exceeds Planck's constant (h). Using this equation we can calculate the photon's momentum with great precision if we give up knowing anything about its position, and vice versa. Further, the equation implies that we can't know either of these quantities independently, just their statistical spread δ. (The same equation describes the relationship of time and energy.)

According to the Heisenberg uncertainty principle, the measurer of subatomic particles is part of the experimental situation and influences its outcome, for electrons behave differently when they are being "watched." It would seem that the wave only collapses into a single electron when it is being measured. If it's measured with a wave detector, waves are detected; if with a particle detector, particles are detected.[6] This finding by Heisenberg and Bohr supporting the emerging belief that said the electron is epistemologically unknowable.[7]

Heisenberg's uncertainty principle has filtered into popular culture in a slew of metaphors, for example the argument that people behave differently when they are observed by a camera than they would if the camera were not there. But physicists continue to debate how to interpret it, and whether to bother. Mathematician David Wick points out that quantum mechanics is unique in that its equations are known but not its principles.[8] In other words, quantum mechanics is a epistemological system, not an ontological one. Yet, for most physicists, the fact that quantum mechanics works "for all practical purposes" deterred them from investigating further. The quotable Einstein once compared the "'Bohr-Heisenberg tranquilizing philosophy' to a soft pillow on which to rest one's head"[9]: it cannot explain matter, but it successfully describes it. For the most part, quantum mechanics has gone on to other things, with this unknowability tucked away in its fundamental equations.

One of the fundamental paradoxes of quantum physics is nonlocality. This principle, first demonstrated in a thought experiment devised by Einstein, Boris Podolsky, and Nathan Rosen. Two charged particles (atoms or photons) are separated and sent to two devices that detect the particle's "spin."

After many runs,

detector 1 reads UUDUDDDU . . .
detector 2 reads DDUDUUUD . . .

– in other words, the particles continue to behave as though they are related. The experiment suggests that each particle "knows" what the other is doing. The direction of either

6. J.P. McEvoy and Oscar Zarate, *Quantum Theory for Beginners* (Cambridge, England: Icon, 1996).

7. John Bell joked about the famous measurement problem, "Was the wavefunction of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better-qualified system . . . with a Ph.D.?" (quoted in Wick, p. 145).

8. Wick, p. 169.

9. Einstein's letter to Schrödinger, May 1928, quoted in Wick, p. 139.

10. "*Spukhafte Fernwirkungen*"; this was Einstein's phrase for Max Born's interpretation of quantum mechanics. Born proposed that if one photon approaches a piece of photographic film, it must collapse from a wave to a particle when it is absorbed by a silver atom, in an impossibly great and instantaneous shift of magnitude. Letter from Einstein to Born, March 1947, quoted in Wick.

11. Nature 386 (30 November 1995), p. 449.

12. At the history-making Solvay conference in Brussels of 1927, de Broglie, supported by Einstein, proposed the pilot wave theory. However, at the same conference, Heisenberg and Max Born introduced their theory of quantum mechanics, a theory of particles that explains discrete or "quantal" properties observed on the quantal scale. Their theory was embraced, though Einstein complained that it did not fully explain the physical world, and became the hegemonic position in theoretical physics.

13. McEvoy Zarate, 93-99.

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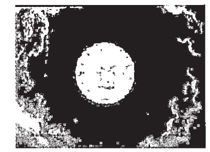
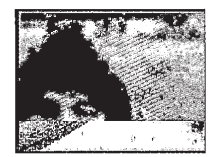
particle cannot be known until it is measured, that is, until the wave function is collapsed. In effect one particle must "wait" until the other particle is measured, and then take the opposite value accordingly. A classical explanation would require some local hidden variable to "tell" each particle what state to assume when it was measured and then to communicate it to the other, which would assume the opposite state. This is impossible because the particles would have to communicate at faster than the speed of light. The realist Einstein worried about this "spooky action at a distance"[10] that cannot be explained classically. Later thought experiments by John Bell determined quantum theory could explain nonlocality.

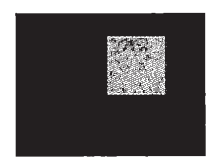


Nonlocality has been demonstrated experimentally. Most strikingly, in a recent experiment in Switzerland, photons separated by an EPR device have traveled over 10 km.[11] It works, whether the explanation is accepted or not!

Meanwhile, however, realist physicists were not satisfied with the mere practicality of quantum equations. They wanted to explain the nature of matter, and thus had to return to the wave-particle relationship. David Bohm argued, following the "pilot wave" theory proposed by Louis de Broglie in 1927,[12] that a single electron is a member of a whole of many electrons, joined in a common wave. This hypothesis follows from Schrödinger's equation, which although it is used to calculate the probability that the electron is doing certain things, also describes a relationship between electron and wave. According to Bohm, each electron on a given wavelength has the wave function encoded into it. It "remembers" where it came from, and thus remains linked to other electrons sharing the wave even when they are physically far distant. This means that the photons of sunlight that warm our faces are physically connected to the star that emitted them, arriving on a common wave.



Electrons also "remember" their more proximate relationship to their neighbors. Each electron in a single atom has its own distinct set of quantum numbers (the size of its orbit; the shape of its orbit; the direction in which the orbit is pointing; and the "spin" of the electron). Knowing its own address, it also knows not to enter other electrons' territory, for if it did the atom would implode.[13]



Bohm argues that electrons are connected by invisible forces. Electrons are like corks bobbing on waves in the sea. If one electron moves, the paths of the other electrons that are entangled with it on a shared wave will be modified. And we know from lakes and bathtubs that when waves cross each other they create interference. Matter, then, is composed of waves that are thoroughly and intimately interrelated. And electrons ride on them.

The above foray into quantum physics is all to argue that individual electrons, for example in a cathode ray tube, act as a whole in their connection with other electrons. Quantum theory's principle of nonlocality means that even distant objects affect each other as part of a single system. The whole cannot be reduced to an analysis in terms of its constituent parts. Not only electrons in proximity to each other – for example, those coursing to their demise on the video screen – but electrons as far apart as those in my hands typing in Ottawa and your eyes reading in Seoul, share a common wave.

Of course, this sounds "spooky" according to the classical way we think about space. Keep in mind that the categories Schrödinger, Heisenberg, and Bohr were using – position, momentum, time – are categories of Cartesian space. Schrödinger's probability and Heisenberg's uncertainty describe relationships in Cartesian space, with unsatisfactory results.[14] Quantum theory argues that we must accept these paradoxes because matter behaves differently at a quantum level than at a macro level. But could there be another order in which these relationships could be described with more certainty?

Bohm proposes that they can, in his theory of the *implicate order*, which explains nonlocal connections in terms of implicit patterns. He uses the terms explicate, or unfolded, for that which is apparent in a given system, and implicate, or enfolded, for that which is latent in the same system.[15] Bohm's elegant illustration is a model of two glass cylinders, one inside the other, with a layer of viscous fluid, like glycerin, between them, but otherwise airtight. When a drop of ink is put in the liquid and the inside cylinder revolves, the ink drop is drawn out into a thread or unfolded; when it is revolved in the other direction, the thread of ink is enfolded back to a dot.[16] The line is implicate in the dot. A more controversial example of implicate order is the idea that when I stick pins in a figure representing my enemy, my enemy, wherever he or she may be, suffers as a result. Voodoo might be explained in terms of nonlocal connections between the two of us. (Not to say that Bohm would have believed in voodoo.) What Bohm's principle of the implicate order means for physics is that we need not distinguish between particle and wave, saying we can measure only one or the other. According to the implicate order, the electron is enfolded in the wave that carries it, and unfolds or expresses itself when necessary – for example, when a light wave hits the surface of a cathode ray tube.

Bohm's ideas were ridiculed or dismissed by most physicists.[17] A few have developed them, notably John Bell. Einstein

14. Bohm and Hiley 1993, p. 350.

15. This may remind you of Leibniz's theory of the fold: see Gilles Deleuze, *The Fold: Leibniz and the Baroque*, trans. Tom Conley (Minneapolis: Minnesota University Press, 1993).

16. Bohm and Hiley, pp. 358-60.

17. Bohm's intellectual exile was partly due to political events. In 1949, while Bohm was developing his theory of "action at a distance," he was called before the House Un-American Activities committee. Because he refused to testify, he was kicked out of Princeton. With a recommendation letter from Einstein, he got a job in São Paulo. Thus Bohm was distanced from his intellectual community, but his intellectual death sentence was delivered when the U.S. State Department revoked his passport. Rendered stateless, Bohm was unable to participate in the discussions around quantum physics. He died, not exactly in obscurity (he was an Emeritus Professor at Birkbeck College, University of London), but having seen his life's work ignored by most physicists, in 1992 (Wick, 73). His books include *The Undivided Universe* (London and New York: Routledge, 1993), published posthumously with Basil J. Hiley.

18. Quantum Mind listserve, http://www.consciousness.arizona.edu/quantum-mind.html. Thanks to Jim Ruton for pointing this out.

19. James P. Crutchfield, "Appendix A: Video Physics," in *Eigenwelt der Apparatewelt: Pioneers of Video Art*, ed. David Dunn (catalogue for a show curated by Steina and Woody Vasulka). Vienna: Ars Electronica, 1992.

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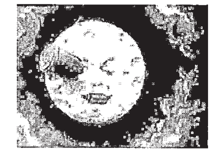
The above foray into quantum physics is all to argue that dual electrons, for example in a cathode ray tube, act as a in their connection with other electrons. Quantum theory's ple of nonlocality means that even distant objects affect other as part of a single system. The whole cannot be ed to an analysis in terms of its constituent parts. Not only ons in proximity to each other – for example, those cours- their demise on the video screen – but electrons as far as those in my hands typing in Ottawa and your eyes read- Seoul, share a common wave.

Of course, this sounds "spooky" according to the classical we think about space. Keep in mind that the categories dinger, Heisenberg, and Bohr were using – position, entum, time – are categories of Cartesian space. dinger's probability and Heisenberg's uncertainty describe onships in Cartesian space, with unsatisfactory results.[14] um theory argues that we must accept these paradoxes se matter behaves differently at a quantum level than at a level. But could there be another order in which these onships could be described with more certainty?

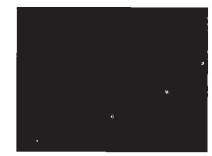
Bohm proposes that they can, in his theory of the *implicate* , which explains nonlocal connections in terms of implicit ns. He uses the terms explicate, or unfolded, for that which arent in a given system, and implicate, or enfolded, for that is latent in the same system.[15] Bohm's elegant illustration nodel of two glass cylinders, one inside the other, with a of viscous fluid, like glycerin, between them, but otherwise ht. When a drop of ink is put in the liquid and the inside der revolves, the ink drop is drawn out into a thread or ded; when it is revolved in the other direction, the thread of enfolded back to a dot.[16] The line is implicate in the dot. re controversial example of implicate order is the idea that I stick pins in a figure representing my enemy, my enemy, ever he or she may be, suffers as a result. Voodoo might be ined in terms of nonlocal connections between the two of Not to say that Bohm would have believed in voodoo.) What 's principle of the implicate order means for physics is that eed not distinguish between particle and wave, saying we neasure only one or the other. According to the implicate , the electron is enfolded in the wave that carries it, and ds or expresses itself when necessary – for example, when t wave hits the surface of a cathode ray tube.

Bohm's ideas were ridiculed or dismissed by most physi-[17] A few have developed them, notably John Bell. Einstein himself remained a realist to his death in 1955. It appears to this non-physicist that the field is beginning to entertain the idea of non-locality again, for example on the Quantum Mind newsgroup.[18]

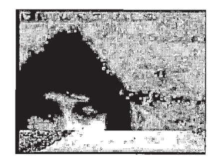


ELECTRONIC PATHWAYS

If all matter is intimately interconnected by wave-surfing electrons, then all electronic images have an indexical or analog connection to – matter. But to what degree do they keep an indexical or analog connection to the object of which they are images? In this section, taking a tip from Youngblood's materialist enthusiasm, I trace the electronic pathway for an analog video image and then for its digital counterpart.



Say we have a camera, any camera. The light that reflects off an object and is focused on the camera lens is composed of waves. Light waves are only reflected if they are the same wavelength as that of the "object" that reflects them; so, of all the light waves that bombard a blue flower, only those of the same blue wavelength will be reflected. So we might say (not yet distinguishing between particles and waves) that "blue" photons, photons with wavelength blue, will hit the camera lens at the appropriate point. But, of course, millions of electrons of all wavelengths will converge upon the lens, producing an image that is the analog of the object. Note that a wavelength is an index, in this case of the color of light.



Inside the vidicon tube of an analog video camera, the image is focused not on a lens but on a photoconducting layer (made of a semiconductor like selenium).[19] Incident light "excites" electrons in the photoconductor, dislodging them at wavelengths that continue to correspond to the colors of the object being recorded. Then the electron beam from the vidicon's cathode scans the surface of the photoconductor (at the rate of 525 lines per second in NTSC format). To "recognize" the wavelength of blue, the beam takes on the charge of the electrons/waves ejected by the photoconductor, restoring the photoconductor to its previous charge.[20] The electron beam sends an electronic signal of the same wavelength to the monitor. This means that individual electrons travel all the way from the cathode to the screen, where they crash and die a brilliant death in the release of thousands of photons, forming the light patterns on the phosphor-coated surface of a video monitor. At 250 pixels per scanline times the same number of lines (in a consumer video camera), this means that each video frame is composed of 625,000 electronic pulses. That's 625,000 electrons crashing on the screen, 60 times a second. So in a conventional analog video

20. We can speak of charge interchangeably with wavelength, since $E = hf$, or energy equals frequency times Planck's constant.

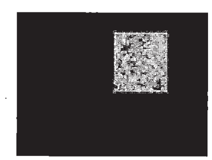


image we know that 37,500,000 electrons are giving up their existence every second in order to bring us an image. In broadcast, the same set of waves disperses into the ether, perhaps to be received by a satellite transponder. The point of this analog map is to show that a calculable number of electrons move along a set of common wavelengths all the way from the object to the image. When an image is broadcast, its indexical likeness undulates to the ends of the universe on the waveforms that compose it.

Images may also be transferred along wires or optical cables. When energy is applied to a wire, a wave populated by hordes of electrons conducts electricity by equilibrating the changing pressure of electrons pushed to one end of the wire. Here their motion is governed by the wave function, as foot traffic in Grand Central Station is governed by the arrival and departure of trains. In all these forms of transmission, the images retain an indexical relationship to the object they represent, thanks to the particle-wave relationship.

Now let us imagine an alternative electronic path, this time for an image produced by a digital video camera, stored on a hard disk, and digitally projected. We will see that this activity continues in large part to be wave-driven, that is, constituted by streams of electrons and thus as indexical in the analog situation. But there are two important differences, based on the fact that most computers, being digital, rely on approximations.

What happens when an image is digitized? First, we must keep in mind that digitization is only one way of encoding information. Since currently we use digital computers more than any other encoding system for complex information, "digitization" has come to mean encoding. Say we have a still, color image. To digitize the image, a program divides the image surface into small areas (also called pixels) and calculates for each a set of numerical values. These correspond to the intensity, or number of photons per second, for the frequencies of red, green and blue. The resulting values are translated in turn to a string of 0s and 1s. In this process there are two ways that the richness of the analog information is diluted. One is in the number of pixels assigned to the image. The other is the amount of memory devoted to calculating the intensity per pixel. When you set your monitor to calculate "256 colors" or "thousands of colors," you are assigning how long those memory strings are allowed to be.

Loss of Indexicality 1

This simple step is the first crucial challenge to both the indexicality of the image and the individuality of the electrons. It is here that the image loses its indexical or existential connec-

21. These properties of silicon, as well as the scarcer and more heat-volatile germanium, were discovered in World War Two radar research; see Electronic Genie: The Tangled History of Silicon by Frederick Seitz and Norman G. Einspruch (Urbana and Chicago: University of Illinois, 1998). Military support was, of course, crucial to transistor research: from 1953 to 1955, half the money for transistor development at Bell Labs was military. During the Korean War, Bell's brilliant William Shockley had the bright idea that a mortar shell driven by a microwatt junction transistor could be detonated just above the ground, raining shrapnel upon the heads of the Communist enemy. The first fully transistorized digital computer was developed for the Air Force in 1954 by Bell's Whippany lab, to command guided missiles (Michael Riordan and Lillian Hoddeson, Crystal Fire: The Birth of the Information Age [New York: Norton, 1997], pp. 187-88, 203-04).

22. Developments in molecular physics at such research centers as Bell Labs, Texas Instruments, and Dupont in the 1950s appear mostly to have been due to mastering combinations of doped silicon. See Riordan and Hoddeson, chapters 6 and 7 (which amount to an oral history of Bell Labs) and 10, and the more sober Electronic Genie: The Tangled History of Silicon by Frederick Seitz and Norman G. Einspruch (Urbana and Chicago: University of Illinois, 1998), chapters 11, 13 and 14.

23. Seitz and Einspruch, p. 55.

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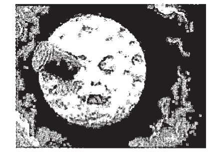
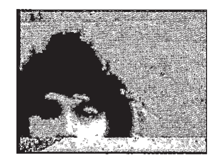


However, within digital circuits, electrons continue to exert themselves in analog ways. To demonstrate this, let me trace the electron's path in the most workaday medium of digital calculations, the silicon chip. Silicon, which is cheap and can be highly refined, is the most popular medium for digital calculations in applications from coffeemakers to smart weapons. Like other elements in the fourth column of the periodic table, silicon is indifferently promiscuous: the four electrons in its outer valence allow silicon atoms to form an extensive network of electromagnetic bonds (compare the "noble gases" such as neon, which have the full complement of eight electrons, allowing these atoms to remain imperiously alone). Silicon's four-electron bonding produces a crystal structure that is both stable and ductile. While the metals are conductors, meaning that metal atoms catch and pass electrons with the energy of a high-speed unidirectional soccer game, silicon, which moves electrons more sluggishly, is termed a semiconductor (as is its heavier fourth-column cousin germanium, as well as oxides such as copper oxide).[21] Molecular chemists learned to control the purification process whereby silicon is "doped" with a few atoms per billion of boron or phosphorus (among other elements) to produce a slight under- or overpopulation of electrons, respectively.[22] These impurities cause electrons to flow in only one direction through the material. Where negative, there are more free-floating electrons than can be held by the silicon atoms in the crystal lattice, which rush to distance themselves from a charge; where positive, there are a few "holes" to which electrons eagerly migrate when a charge is applied. Fusing micron-thin layers of positive- and negative-charged silicon produces transistors (chips) which sophisticatedly control the flow of electrons.



Here, Schrödinger's equation returns to explain why semiconductors are so susceptible to even the smallest charge, yet, unlike metals, do not produce much heat. Quantum statistics dictates that in a given assembly, be it a single atom or a large crystal, only one electron can possess a given wave function.[23] Put otherwise, an electron can occupy only a given band in the "orbit" of an atom. When voltage is applied to silicon doped with phosphorus, the extra electrons are only too eager to make the quantum jump to a higher state of excitation–chemistry's anthropomorphic term for electrons with no place to go but up.[24] The energy thus produced can be measured in terms of electrons per unit per second, where the unit is a gate in a silicon chip or a pixel. Such a calculation would establish the individual contributions of our hard-working electrons.

Within the silicon chip, then, electrons continue to ride waves in a micro-indexical way. In any transistor-reliant device, hordes of excited electrons are speeding through gates and causing other hordes of electrons to get excited and seek a wavelength of their own, in a ceaseless, frantic relay race. Digital computers, by definition, work with the binary difference of on and off signals or positive and negative signals. Its OR, AND, NOT and NAND circuits are operated by combinations of these signals. These circuits are themselves electron pathways. For example, the OR circuit has two or more inputs and one output, and it emits a pulse if any of the inputs receives a pulse.[25] In other words, the OR circuit is designed so that if a herd of excited electrons surges (through a wire of gold, copper, or aluminum) into any of its inputs, it will release a herd of excited electrons in turn. it would seem from this description that the behavior of electrons in silicon chips continues to index their associated wave.

Loss of Indexicality 2

The crucial characteristic of digital computers that breaks the indexical relationship is the same characteristic that makes computers accurate. Digital computers cannot tolerate intermediate states between 0 and 1. Every circuit contains a "flip-flop" circuit that eliminates intermediate states by ignoring weak signals. Only a strong signal, the cumulative behavior of masses of electrons, registers a change in the circuit. It is at this point that the wave-particle relationship is overriden. The flip-flop circuit pays attention only to huge hordes of electrons and quashes the efforts of the few. In this herd behavior, any change in the state of an individual electron is obviated by changes in the whole. Thus, in digital computers, quantum non-locality, or the shared properties of electrons on a common wave, is not observable. Our friend, the electron, gets lost in the herd.

Just for fun, let's say that the final image is digitally projected using one of the new projectors designed by Texas Instruments and Hughes-JVC. This requires a rectangular array of 1.3 million mirrors, each .016 mm wide. Each mirror has a corresponding microchip cell that emits pulses of 1 or 0 which

24. Similarly, vacuum tubes, the precursor to the transistor, provided vacuums or no-electron's-lands which the electron could only jump when at a state of higher excitation.

25. Seitz and Einspruch, p. 198.

26. "Curtains for celluloid," *The Economist*, March 27, 1999, pp. 81-82.

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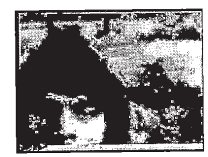
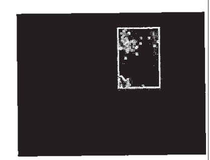
In each pathway I have described, analog and digital, the transmission of electronic data can be traced to the actions of electrons, or, depending on your point of view, to the wave pattern that organizes them. These road maps show that an electronic image, *whether it is analog or digital*, is implicate, or enfolded, in the interconnected mass of electrons that transmit it along common waves. In digital imaging, however, two steps intervene to break the indexical bond: one that approximates analog information to a symbolic number, and one (repeated in every circuit) that obviates the wave-particle relationship.

THE ENFOLDED IMAGE

In the analog electron pathway, if we believe Bohm's theory of the implicate order, the image remains enfolded in the waves that carry it from source to transmission. In the digital pathway, *information* is enfolded in the pulses that travel through the computer, but the initial indexical relationship is lost. Yet, one does not have to agree with Bohm's principle of nonlocality to argue that a digital image is enfolded in its code. In digital computers the image is doubly enfolded: once, when it is encoded as strings of 0s and 1s, and again, when this information is enfolded in the charge of particles or the length of waves. Analog electronic imaging involves only the second process of enfolding.



To explore the difference between encoding in a language (such as a computer code) and enfolding in a wave, let me digress briefly to describe an artwork for computer by Thibaud Beghin, a Muslim artist who lives in Lille, France. His work *Virtual Prayers* represents Islamic prayers in the abstract and decorative Arabic script typical of traditional Islamic (iconoclastic) visual art. But this is only the visible aspect of the work, as manifest on a computer screen or printout. Here, the image is the explicate form of an implicate order, the computer code. Beghin also transmits these prayers in encoded form over the Internet or in digital files. In this version the prayers are "enfolded" in ASCII code and thus inscrutable. A religious person would say that the digital code is itself the explicate manifestation of an implicate order, that of prayer.



This encoding seems an appropriate means of transmission for a religious message that is subject to censorship and tends to spread clandestinely. One can imagine these prayers being received by a Muslim in a secular state or one where Muslims are persecuted. As an image their status is very tentative–they are virtual prayers, potential prayers, prayers that the code retains even when they are not manifest in an image legible to humans. Beghin does produce them as ink-jet prints, where each dot represents a translation of the electronic memories. But these are merely manifestations of the prayer, they are not the prayer itself. Encodement or enfoldment is this work's most typical state. I would suggest many digital works exist typically in a state of latency, and when they are visible to us, this is a rare case of unfoldment.

QUANTUM INDEXICALITY, OR, SUBATOMIC MIMESIS

The example of Beghin's work emphasizes the distinction between the role of the electron and the role of the code in electronic imaging. The former is physical, but the latter has an aspect that is purely virtual, because it approximates physical reality into symbolic information.

Note, however, that not all computers are digital in the usual sense. Quantum computers, which are now being developed theoretically, would use a minimum number of electrons, instead of the millions herded into formations of 1 and 0 by digital computers. Quantum computers would work with the superposition of the discrete states, such as orbit or polarization, of single particles. Thus, they could make calculations based on the controlled excitation of ions in an ion trap. They could also use nuclear magnetic resonance (NMR) to detect the nuclear spin of atoms in small organic molecules.[27] In quantum computers the role of particular particles matters very much. If digital computers are like herders of sheep, quantum computers are like flea circuses: they rally a very few, very tiny actors whose individual behavior, though somewhat limited,[28] makes a perceptible difference in the whole.

It is my indexical fantasy to witness an image produced by a quantum computer, perhaps an animated image produced from the varying combinations of two or four electrons in varying states of excitement. Such an image would not be a simulacrum or a mathematical model, but the index of a physical referent, the tiny dance of subatomic particles. Of course, quantum physics tells me that such an image cannot be produced, because observing or measuring a quantum system renders the objects mere statistics, destroying the indexical relationship. But nanotechnology is already producing quantum objects, such as the "quantum corral" produced at IBM's Almaden Research Center. A scanning

27. See Gilles Brassard, Isaac Schuang, Seth Lloyd, and Christopher Monroe, "Quantum Computing," *Proceedings of the National Academy of Sciences* 95:19 (15 September 1998): 11,032-11,033. http://www.pnas.org/cgi/content/full/95/19/11032?

28. As artists and flea-circus director Maria Fernanda Cardoso has told me, fleas do not learn per se, but they become more lively when stimulated with oxygen, as when she blows on them; electrons exhibit four quantum states of excitation and "spin."

29. B.C. Crandall, "Molecular Engineering," in *Nanotechnology: Molecular Speculations on Global Abundance*, ed. B.C. Crandall (Cambridge, MA and London: MIT Press, 1996), 31.

30. Walter Benjamin, "On the Mimetic Faculty," trans. Edmund Jephcott, in *Reflections* (New York: Harcourt, 1978), 333-336. Max Horkheimer and Theodor W. Adorno, "The Concept of Enlightenment," in *Dialectic of Enlightenment*, trans. John Cumming (New York: Herder, 1972), 3-42.

31. See, for example, Richard Hall's "Cosmetic Nanosurgery" and the fantasy of a seamless nanotech environment in J. Storrs Hall's "Utility Fog: The Stuff That Dreams Are Made Of," both in *Nanotechnology: Molecular Speculations on Global Abundance*, ed. B.C. Crandall (Cambridge, MA and London: MIT Press, 1996), 61-80 and 161-184.

32. See Brassard.

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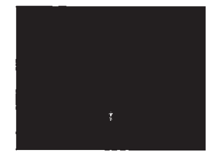
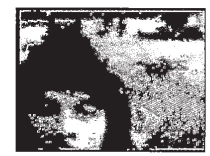
Finally, let me suggest that, since subatomic particles are connected by mutual physical bonds, it is possible to speak of *electronic mimesis*. Mimesis, according to Frankfurt School theorists Walter Benjamin, Max Horkheimer, and Theodor Adorno, is a form of representation that is mediated physically rather than symbolically.[30] The mimetic faculty is usually superseded by symbolic means of representation in modern society (we are more likely to represent an airplane with a word or a drawing than by zooming around with our arms outstretched). Nevertheless, mimetic representation still at least partially underlies abstract representational systems, such as language. Similarly, the physical interrelationships between subatomic particles underlie the symbolic transmission of digital information.



I have argued that in the analog electronic image, because of the enfolded wave-particle relationship, a strongly indexical or mimetic relationship is maintained between object and image through all stages of recording, transmission, and reception. Moreover, even the digital image remains a physical object. Although it no longer bears an analog relationship to its initial object, the digital image relies for its existence on the fundamental interconnectedness of subatomic particles. Electronic images, like all of us, owe their material being to electrons and their associated wave forms. We are physically implicated in the virtual realms we inhabit, and far from divorcing ourselves from the world when we enter electronic spaces, we may be more connected than we imagine.



POSTSCRIPT: ANALOG LEAKS FROM DIGITAL STREAMS

I do not wish to end this materialist essay on such an idealistic note, given that the technologies in which I have traced the marvelous interconnected life of electrons have been largely developed for military and commercial applications that enslave as well as liberate. At a time when all of space and all objects of vision are claimed as corporate property, we must note that certain encodings are occurring at practically the subatomic level. Nanotechnology is being developed as an applied science by military and biotech companies, and some of their first experiments have been to sculpt atoms into corporate logos.[31] The first applications of quantum computing will likely be bank security and espionage.[32] We look to the subatomic level for evidence of a new uncharted territory or a new sublime only at the risk of ignoring how all that is perceivable may be or has already been

encoded as a proprietary interest. The electrons can play all they want, but we aggregates may find ourselves seduced by the apparent immateriality of electronic media.

In this cautionary tone I adopt Sean Cubitt's notion of digital aesthetics,[33] which emphasizes the materiality and vulnerability of the medium. A digital aesthetics remembers that any technology is social, and looks for the social and utopian potential of technologies. To pursue the radical materialism of my argument above, I want to suggest that the interconnected universe of electrons offers more than just a metaphor for social interconnection.

33. Sean Cubitt, *Digital Aesthetics* (London: British Film Institute, 1998).

The materiality of electronic media is most often evident to us not when everything is running smoothly but during the breakdowns and failures, the anomalies of low and obsolete technologies, and the ways electronic media are actually used as opposed to how they are imagined in the software manuals. A well-running platform, for those who can afford such a thing, has a false transparency that makes it quite easy to believe we are operating in a virtual realm.

When, due to low bandwidth or small hard drives or lack of fancy plug-ins or lost phone links, our digital media "fail" us, they are closest to reminding us of the physicality of the electronic medium. When a digital operation fails at the machine (as opposed to programming) level, it is usually because its switches, rather than falling nicely into the on/off positions, register a "maybe." That "maybe" is the product of electrons that abandon their regimented paths, attracted to impurities in the silicon like workers to a bar. This produces dire results for networked computers and guided missiles, of course. But the noise of a failed Internet connection, for example, is a declaration of electronic independence. It grabs us back from virtual space and reminds us of the physicality of our machines. They remind us not only of the wave-hugging electrons that interconnect all matter, organic and nonorganic, but also of our connections with other humans and our shared less-than-perfect, less-than-virtual circumstances.

This paper was developed through many head-spinning conversations, involving fevered drawing of diagrams on napkins and laptop-tapping telephone calls, with my father, neuroscientist and amateur physicist Bill Marks. I also thank computer scientist and amateur physicist Gilles Brassard, who helped me take my quantum foot out of my classical mouth. Any errors are mine! Finally, I am most grateful to Grahame Weinbren, thanks to whose demanding editing this essay expanded exponentially.