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From Heat Engines to Digital Printouts: A Tropology of the Organism from the Victorian Era to the Human Genome Project

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LAUREN RABINOVITZ AND ABRAM GEIL, EDITORS

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Letters, Martin’s Electricity & Watson’s first Part and Sequel. We are, as we always have been, extremely [sic] obliged to you for your kind Care in sending us from Time to Time, what is new and curious, tho’ not wrote for” (from the Bowdoin Ms., quoted in Cohen, Experiments, 1781).


David Depew

FROM HEAT ENGINES TO DIGITAL PRINTOUTS

Machine Models of the Body from the Victorian Era to the Human Genome Project

The Human Genome Project and the Digital Image of the Body

It is not news to say that our insight into ourselves, into other sorts of living things, and indeed into nature as a whole penetrates no further and no deeper than what our current technologies can afford us by way of models. *Verum et factum convertuntur*, the eighteenth-century rhetorician Giambattista Vico famously wrote: our ideas can be said to be true only when we have used art to produce the made objects to which these ideas primarily refer. Nor was Vico alone in thinking that we can only understand things we have put together ourselves. Several decades after Vico published *The New Science*, Immanuel Kant proclaimed: “Reason has insight only into what it produces after a plan of its own.”

By this standard at least, our knowledge of biology has lagged well behind our knowledge of physics and chemistry. Physics found its first exploitable technological models in the seventeenth century.
While it is true that theoretical physics contributed much to the perfection of the art of ballistics, it was the art of ballistics—the technological practices that sprang up around siege and artillery warfare—that in no small measure gave rise to modern physics in the first place. Many early modern “natural philosophers” worked as part-time defense contractors. Chemistry, for its part, acquired its theoretical basis hand-in-hand with the development of chemical engineering in the second half of the nineteenth century. Nor was the connection with the art of war any less marked in this case than in mechanics. Bismarck’s Germany was as aware as its bellicose successors that its ability to project its power was limited by access to natural resources. It sought to make up some of the difference through industrial chemistry. Arguably, however, it has only been in the last several decades that humans have begun to acquire abilities to manipulate living systems in ways that are quantitatively and qualitatively analogous to our skills in manipulating physical, chemical, and even biochemical systems. This quite recent transition has been accompanied, as all such sudden changes are, by extravagantly utopian hopes and equally extravagant fears. Talk about genetically engineered plants evokes visions of the end of hunger (a claim advanced by Archer Daniels Midland [ADM] in its television advertising) as well as of “frankenfoods.” Talk about biotechnology as well as tirades against “backdoor eugenics.”

What technologies, we may ask, and what discourses centered around sites of technological innovation, have constituted the condition of the possibility of the biogenetic revolution in the sense that ballistics once constituted the condition of the possibility of physics? Certainly, the massive expansion of techniques for making the body visible, and intervening in its workings, has had a lot to do with it. In this essay, however, my attention will be focused on biogenetic engineering proper, an array of technologies that goes no further back than the development of restriction enzyme techniques in the 1970s. Restriction enzymes are complex molecules found in bacterial cells. They have the ability to cut up pieces of foreign DNA and RNA at specific, recognizable sites. Because bacteria multiply very fast, this technique provides experimental platforms by means of which genes can be sequenced and the effects of different genetic combinations, which can be inserted into the genomes of the same or different species between the points where restriction enzymes cut, can be rigorously explored.

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“Over the next ten years,” Gilbert continued, “we will understand how we are assembled in accord with dictation by our genetic information.” It is noteworthy that eight years later, in a newspaper article reporting the earlier-than-predicted completion of the mapping phase of the project in June 2000, Elizabeth Neus of Gannett News Service duly reported, “By the end of June, scientists hope to have reached a biological Holy Grail.”

Seldom, I suspect, has rhetoric designed to acquire funding flowed so smoothly down a single channel from senders to receivers over such a protracted period of time. If anything, the puffery has been enhanced by casual misinterpretations of what authors like Gilbert actually said. Gilbert thought of the Holy Grail as a distant prospect in which medicine would have transformed the human condition, not as the outcome of the mapping phase of the Human Genome Project itself. This remarkable rhetorical success leads to the first assertion I will put forward in this essay. The rhetoric of the Human Genome Project, I claim, could not have been as successfully deployed as it has been (and probably will continue to be) if the lived body had not already come widely to be seen as a computational system running on a genetic program. The mere fact that transgenics is generally thought of as a matter of uploading and downloading information from one hard drive to another, thereby construing genes as discrete packets of information, testifies to the truth of this judgment. (A recent cartoon features a young boy saying to his mother, “I know how I was downloaded, but I don’t understand how I was uploaded.”)

The relevance of computation to the rise of genetic biotechnology is not limited, accordingly, to the relatively trivial fact that high-powered computers and programs are needed to keep track of the information about where variant genes are in the chromosome, and how they differ from individual to individual, population to population, species to species. The Viconian themes announced above support a more contentious and more interesting claim: if computational machines had not been used to interpret organisms as printout from a genetic program, the swift transformation of transgenic technology from an experimental aid to abstruse theoretical inquiry into a growing plethora of biotechnological industries might not have occurred so quickly or effortlessly. Nor, I suspect, would the diffusion of the rhetoric of the Human Genome Project have been put in such a positive light. Nothing like this, as I have already men-

tioned, has happened in the field of agricultural biogenetics. It is hard to resist the conclusion that a conception of the human body (indeed of the mind, too) as printout from a digital program running on a hydrocarbon-based rather a silicon-based computer has not only preceded and to some extent guided the reception of the Human Genome Project, but has more or less silently justified it as well.

How, we may go on to ask, did this figuration of the body arise? The digital tropology of the body that now shills for the Human Genome Project is quite recent; in its full-blown form, it extends no further back than the enthusiasm for computer programs that characterized the personal computer revolution of the 1980s. At the same time, however, this rhetoric is clearly the culmination of a series of rhetorical framings of the body that first began to take shape when scientists in the late 1950s and early 1960s tried to determine the relationship between DNA and protein. Scientific mythology suggests that the “coding problem,” as the effort to link ribonucleic acids to protein assembly was known to those working on it, was solved almost as soon as Francis Crick and James Watson discovered the structure of the DNA molecule in 1953. The fact is, however, that this effort was characterized by many false starts; a decade and a half passed before it was definitively worked out. Eventually, it was determined that a redundant code transcribes the four bases of DNA into RNA and then translates RNA into the twenty amino acids out of which proteins are made. This “code of codes” was worked out by what historian of science Lily Kay has presented in her 2000 book Who Wrote the Book of Life? as a somewhat fortuitous conjunction of three overlapping but nonetheless distinct discourses: molecular genetics, which was busy attempting to supplant classical genetics during this mid-century period; cybernetics, or the study of devices, whether analog or digital, for assuring that systems, both artificial and living, homeostatically maintain themselves in their environment by way of feedback, generally negative; and information or computer science, which emerged from the wartime experience of a group of talented mathematicians and electrical engineers who had been commandeered to crack codes (and solve problems connected with nuclear fission) by building, programming, and using first analog, then digital, computers.

According to Kay, the trope of the Book of Life was deployed to allow this array of heterogeneous discourses to coalesce into
a single, seemingly integrated tropological system. This has been achieved by recycling an old metaphor: Galileo’s and Descartes’s idea that scientists read the Book of Nature in the same way that sacred Scripture has, by a gift of God, allowed us to read the Book of History. This trope reached an early peak in Newton’s heady idea that in discovering the calculus he had stumbled on the language in which God had written the Book of Nature, by which he meant inanimate astrophysical nature. It was to be several centuries before the same image was brought to bear on living systems. When at last that came to pass, however, it gave new resonance to the Old Testament notion that our deeds, and our fate, are written in a Book of Life. Only at the end of the 1950s, Kay argues, did biochemists begin to recast their chemical representations of heredity as “scriptural,” thereby bringing the “age-old metaphor” of the Book of Life to bear on a historically specific and culturally contingent problem: how to state the relation between genes and proteins.

Francis Crick was a continuously important source for the coding-decoding conception of the relationship between DNA, RNA, and protein. Throughout the 1960s, he and other influential scientific middlemen—James Watson, George Gamow, Robert Sinsheimer, Jacques Monod, and others—used the language of communication and information theory as a sort of pidgin in order to forge links between disciplines such as molecular biology, protein biochemistry, and immunology, all of which had important roles in the experimental work on which success in solving the coding problem depended, but whose native tongues were mutually unintelligible. The problem of communication among research communities was perhaps more responsible for the construction of a common object of inquiry in terms of the language of information theory than has been acknowledged. However that may be, by the time Sinsheimer reported the solution of the coding problem to the public in his widely disseminated 1967 work, The Book of Life, the DNA-RNA-protein link was presented unambiguously as an informational, indeed a linguistic, bond. According to Kay, Sinsheimer’s book did more than any other to turn what had been a facultative and pragmatic lingo, designed to facilitate communication between different research communities, into the obligatory “scriptural” image of DNA that has prevailed ever since. Writing in the New Yorker in the week preceding Clinton’s and Blair’s announcement in summer 2000, Robert Preston was doing little more than recycling Sinsheimer’s title when he wrote, “The Book of Life is now opening, and we hold it in our hands.”

The connection between Sinsheimer’s book and the Human Genome Project, it should also be noted, was far from merely journalistic. When Sinsheimer became chancellor of the University of California at Santa Cruz, he sought consciously to reverse his new university’s persistently nonscientific image by teaming up with Charles DeLisi, an administrator at the Department of Energy and a former official at Los Alamos National Laboratory, to propose the Human Genome Project to an at first skeptical biological and medical community. For his part, DeLisi was betting that the genetic information that had been collected and stored at Los Alamos ever since the survey of the results of the Hiroshima bombing might help the laboratory negotiate its way into a future in which there might be less call for atomic weapons design. In view of Sinsheimer’s earlier exercises in figuration, it should not be surprising that he and DiLisi pitched their project as one in which the genetic structure for a human being was figured as “The Code of Codes.” In using this phrase as the title of their 1992 anthology, Daniel Kevles and Leroy Hood (the latter of whom is a molecular geneticist who took a hand in the highly profitable work of developing automated gene sequencers) were merely following Sinsheimer’s lead. The phrase has circulated more or less uncritically ever since in both expert and lay communities.

Having reported on the role of scriptural tropology in articulating the notion of the lived body as printout from a code, in this essay I will as the first order of business project Kay’s excellent historical work somewhat further back in time than the mid-twentieth century world on which she so diligently reports. Kay is fully aware that there was a time when it was still possible to talk about the relationship between genes, proteins, and traits without invoking scriptural imagery about this relationship, or indeed without invoking the notion of information transfer that this imagery was designed to capture. She declines to note, however, something that has been noticed by N. Katherine Hayles, who in her 1999 book How We Became Posthuman recognizes that the cybernetic-informational-scriptural image of the body that emerged in the last quarter of the twentieth century was not created out of whole cloth, but rather
supervened on an older conception of the body as a thermodynamic engine or heat machine. Thus my next order of business, after pushing the tropological history of the body as far back as the Victorian era where this thermodynamic image has its roots, will be to project the story Kay tells about the mid-century origins of the scriptural figuration of the body into the 1980s and 1990s, where this imagery began for the first time to be interpreted in explicitly digital ways. I will argue that the conception of the lived body as printout from a digital computer program arose from a technical, indeed philosophical, question about what biological information means rather than from any new empirical knowledge, and the central effect, if not the function, of its dissemination is to give ideological cover to the biotechnological revolution that is now upon us. The digitalization of the body, I wish to suggest, has pushed out of sight, by way of what rhetoricians (following Kenneth Burke) call “terministic screening,” aspects of living things that are no less well established and important to our understanding than genetics, and no less relevant to the prospective successes and limitations of genetic medicine. I will argue that this result has been achieved by a series of slippages, silencings, and screenings that occurred precisely at the historical juncture when the discourse of a feedback-controlled or cybernetic body was recast, for quasi-theoretical reasons, in terms of digital information.

Seen in this light, Kay’s implication that the cybernetic and digital conceptions of the body form a coherent line of development stands in need of qualification and disruption. There is little, I suggest below, that is biologically realistic or theoretically perspicuous about the notion of a digital body. By contrast, the older notion of a cybernetic body, which guided mid-century efforts to solve “the coding problem,” is realistic enough. But, as Hayles has suggested, the notion of the body as a negative feedback system is realistic only to the extent that it was still tied by its mid-twentieth-century advocates to the energetic model of the body that had its roots in the mid-nineteenth-century technology of steam engines. The rhetoric of digitalization has cast this older image adrift. By attracting the cybernetic image of the body into its orbit, that is to say, the digital image of genetics has expunged the energetic, and ecologically embedded, view of the body on which cybernetics is actually based. The reasons for this erasure remain to be seen—and, if truth be told, its practical consequences deserve to be worried about.

In the middle of the nineteenth century, modern physics, which had for some time been organized in terms of the notion of force, was busy rearticulating itself in terms of the new architectonic concept of energy. It was in this context that a tropology of the body as an energy-using and entropy-dissipating system—a heat engine—began to displace earlier mechanistic conceptions. The most accessible technological model for this purpose was the water wheel, but only insofar as the water wheel was used to understand the workings of the steam engine. “We get mechanical effect,” James Thompson wrote to his soon-to-be-more famous brother William, who became Lord Kelvin, “when we let water fall from one level to another, as well as when we let heat fall from one degree of intensity to another, lower intensity.” In both cases, and indeed in all cases where work is produced, energy itself is conserved, as Rudolf Clausius had stipulated in the first law of thermodynamics. Because of statistical considerations, however—disorder is more probable, ceteris paribus, than order—there is always at least some energy that cannot be captured into work: some waste, some dissipation, or, when it was given a mathematical measure by Boltzmann, some entropy. So says the second law of thermodynamics. As M. Norton Wise and Crosbie Smith have argued, Kelvin’s primary interest in this law, which was to minimize dissipation and maximize efficient work in steam engines, was also of help to him in expressing his moral indignation at the dissipation of the lower classes, which had not yet been efficiently integrated into the industrial order. By the same token, however, it is likely that the latter concern, and the language associated with it, entered into the social construction of thermodynamics itself.

In view of these technological tropings, it soon became obvious to biochemists, biologists, and medical scientists that the equilibrium or homeostasis of the lived body is not the result of a balance between four bodily secretions, or humors, as the Hippocratic and Galenic tradition had it, or between opposed centrifugal and centripetal forces, as Newtonians saw it, but between phases of a cycle in which the body takes in energy at one level, breaks it apart to do work, exports it in a degraded state to the environment, and begins over again by taking in more energy-containing matter. The con-
stanty of this anabolic and catabolic cycle, which is itself modeled on the phases of a steam engine, is measured by temperature. By reiteratively asking how the organism staves off, however temporarily, the inevitable consequences of the second law, and how it manages to maintain itself in such a remarkably steady state, the energetic conception of the body frames much of what we now know about medicine. It undergirds, for example, the insistence of physicians that before they do anything else they must take a patient’s temperature. It also marks the contested boundary between traditional anatomy, with its stress on inert morphology, and the more process-based physiology that is focused on the cell, which is conceived as a miniature factory for the efficient creation and dissemination of matter and energy.

The control of energy flows is as essential in the body as it is in industry, for without control it can be very violent and very inefficient indeed. The cell would incinerate itself unless its energetic work were not distributed over millions of very small reactions, each of which releases only a minuscule amount of heat. Although evolution has solved this problem for the cell, solutions to the analogous problem in industrial applications are hampered by the fact that control cannot be achieved by direct human intervention alone. Our visual and other sensory monitors, and indeed our brain itself, cannot quickly enough, precisely enough, or safely enough observe the process of energy release and direct its transmission. Thus automatic control systems are required.

In the case of external combustion or steam engines, this need was met by means of flywheels and mechanical governors. Governors are, quite literally, steering devices; the term comes from the Greek word *gubernates*, steersman. The little flywheel governor invented by the Scotsman James Watt is paradigmatic of the mechanism. One can see the tropological application of this conception to the body in such phrases as “blowing one’s top.” A more fruitful application of this energy-and-control conception to the specific case of organisms did not occur, however, until external combustion or steam engines evolved into internal combustion engines. This development imported electricity into the energetic image of the body, both as a form of energy and as a means of control. In an internal combustion engine, electricity is used to release energy in the cylinders by sparking off an explosion of pressurized gas. Electricity is also used to control this energy release, transmitting it by means of on-off switches in the distributor. This model can be, and has been, readily superimposed onto the thermodynamical conception of the body that I have sketched above. For the form of energy on which organisms run is largely electrical energy generated by chemical gradients, for which nerves serve as conduits and switches. On this view, the brain can be portrayed as a sort of central switchboard that receives and sends on messages and, in order to maintain the body’s characteristic homeostasis, distributes the overall load appropriately at peak times and down times, as in an electrical grid. Before the identification of DNA as hereditary material within the cell nucleus, it was even imagined that life itself might have begun when bolts of electricity “galvanized” the presumably undifferentiated protoplasm of the protocell into life. (Many a quaint feature film provides fevered images of this Promethean idea, which mirrors the role of energy release and control in the “lifelike” images afforded by the technology of moving pictures themselves.)

An electrified body using chemical gradients emerges, accordingly, from the assimilation of organisms to heat engines. Yet as Erwin Schrödinger recognized in his influential 1944 essay *What Is Life?*, living things do more than merely exchange matter. They do even more than exchange energy. For unlike physical and chemical systems, which do both of these things, organisms have a remarkable ability to avoid the precipitous fall toward thermodynamic equilibrium that we call death by maintaining themselves in a homeostatic state far away from thermodynamic equilibrium. An ascription of agency to living things in expressing this sort of goal orientation is well-nigh unavoidable. In addition, unlike merely physical and chemical systems, organisms have a capacity actively to reduce the entropy production within their boundaries, which would otherwise take its toll far more quickly than we observe. “The essential thing in metabolism,” Schrödinger wrote, “is that the organism succeeds in freeing itself from all the entropy it cannot help producing while alive.” Animals can do this without offending the second law by actively increasing the entropy of their surroundings, degrading it faster than would otherwise happen, by identifying prey, moving through space to get them, and using other organs to extract their energy by destroying and ingesting them. Plants, for their part, do this when they extract energy from soils that they deplete. In this sense, all organisms “suck order,” as Schrödinger memorably phrased it, or “positive entropy,” or what he called “negentropy.”
from their surroundings, especially from high-energy, organic components of their surroundings.

The conception of an organism as a peculiar sort of energy-using and entropy-dissipating system that can maintain itself far from thermodynamic equilibrium by means of internal feedback and external coupling to its environment informed the discourse of cybernetics that self-consciously emerged in the 1940s in the now famous Josiah Macy conferences. The term “cybernetics” is merely a variant on the Greek word for a steersman, *gubernates*, which we have already encountered. According to early cybernetic theorists like Norbert Wiener, whose 1948 book *Cybernetics: Control and Communication in the Animal and the Machine* was an influential development of Schrödinger’s ideas of a few years earlier, cybernetics is a way of automating the task of determining, and in this sense knowing, when and in what quantities energy should be released or acquired in order to restore imbalances that would otherwise disturb the homeostatic end point that any goal-seeking system, by its very nature, is intended to attain and maintain, but which is constantly being threatened by the thermodynamic activities of the system itself.

For their parts, however, Schrödinger and Wiener could not imagine how organisms could stave off the disordering tendencies of the second law unless their ordering tendencies came from something that was already ordered. This is so because both men, trained as classical physicists, were still haunted by the Victorian image of the prospective heat death of the universe, which notoriously troubled such turn-of-the-century amateurs as Henry Adams. Thus, even physicists as advanced as Schrödinger and Wiener failed to recognize that organisms, like other complex systems that maintain themselves far away from thermodynamical equilibrium, have self-organizing or “autopoietic” properties that rely much on positive as on negative feedback and, more importantly, do not depend for their functioning on a central control system. It is these self-organizing properties that are more important than anything else, including allegedly coded information, in maintaining a living system far from thermodynamic equilibrium.

The first inklings of this thought emerged in the 1950s in the work of Nobel laureate Ilya Prigogine. His insights have been developed by the so-called second-order cybernetics of Humberto Maturana and Francisco Varela. Even now, however, this alternative paradigm is highly contested—largely, I suspect, because many (techno)scientists, with their eye on both theoretical and technological control, are loath to give up the analogy between organisms and centrally controlled (and highly decomposable) industrial systems and machines. It is both true and interesting that Wiener himself was inclined to think of cybernetic machines as like organisms rather than the reverse; he was, as Hayles has argued, an anxious humanist. It is no less true, however, that the digitalization of cybernetics (which began with the “numerical control” of machine tools) but reached the figuration of genetic mechanisms only quite recently) has done more than anything else to reverse the direction of this analogy. We now commonly think of organisms and persons as like machines, carrying out instructions that are coded either in genes or neurons, and not the other way around. In view of the steady drift of both popular and expert thought in this direction, the so-called second-order cybernetics expressed in the work of Prigogine’s followers, including Maturana and Varela, has taken upon itself the difficult task of making plain precisely the *disanalogy* between organisms and machines.

To follow this body of thought toward the more ecologically embedded and interpretive framework in which living things are placed, however, lies well beyond the scope of this essay. Here I can merely note that, although an alternative path lay open, the assumption of (and demand for) central control of systems that are regarded more as assemblies of replaceable parts than as organic totalities passed, by way of the idea of a coded program, from the cyberneticists of the 1950s to today’s theorists, technologists, and propagandists of the Human Genome Project. Even if its medical successes eventually prove to be more limited than anticipated, it should be recognized that digital discourse about the body has already succeeded, perhaps irreversibly, in publicly legitimating the idea that the body is a complex machine made of subassemblies that can in principle be taken apart and put back together again. The risks and difficulties of genetic medicine are played down by the circulation of this system of imagery. Changing one’s genes can appear in its light as no more difficult than replacing the logic board of one’s computer. Unfortunately, however, the blithe dissemination of this very imagery may create or exacerbate some of the problems for which this tropology envisions a metaphorical, and to that extent fantasized, solution.
How, we may now ask, did the digitalization of the cybernetically construed body come about? Again, we must begin with Schrödinger. In *What Is Life?*, Schrödinger, unable as we have seen to break with classical thermodynamics, predicted that “the nucleus of the fertilized egg would contain an elaborate code-script involving all the future development of the organism.” This code-script was to provide a source of “order from order” that would guide the development of organisms and direct their ongoing attempts to beat the second law. Memorably, Schrödinger also predicted that this code-script would be inscribed in an “aperiodic crystal” that would serve as a template for organic reproduction in the same way that ordinary crystals, working on much simpler algorithms, serve as templates for new ones.

The search for the genetic material, which was first imagined as a contest between the two basic materials of the cell nucleus—proteins and ribonucleic acids—was explicitly and actively guided by a reading of this prediction; Crick and Watson, when they finally showed how DNA could do the job, literally thought that they had found Schrödinger’s “aperiodic crystal.” I say that this research program was guided by a reading of Schrödinger’s speculation, however, because, while Crick and Watson blithely used the notion of *coded* information, Schrödinger himself was merely thinking of a template copying mechanism, albeit one more mathematically complex than that of a periodic crystal. Nonetheless, this reading stood. It guided the efforts that went on throughout the 1960s to link the four bases of DNA and RNA (adenine, guanine, thymine, and cytosine) to the twenty amino acids out of which protein is made. Until the amino acid sequences of particular proteins were known, this problem was well-nigh impossible to solve. For in the absence of sequence information about proteins, the problem, as one researcher noted, would be a little like trying to decode the Rosetta Stone without knowing anything about any of the languages, Greek, Egyptian, and Hebrew, that were interrelated by the stone. Things got a lot better, accordingly, when the amino acid sequence of the tobacco mosaic virus was fully analyzed. That was in 1960. In the following year, Marshall Nirenberg and Walter Matthaei, working at the National Institutes for Health, established by very clever experimentation how three RNA bases specify a particular amino acid, phenylalanine, in the bacteria *e. coli*. On the one hand, this result confirmed the speculation of George Gamov and other “code crackers” that amino acids would be specified by a nonoverlapping code of triplet bases, or codons, such as AAT or GGC. On the other hand, it set off a race to verify the larger hypothesis about the role of DNA in protein assembly by completing the correlation between codons and all twenty amino acids. This took some years.

During this time, the project of decoding “the code of codes” was universally framed by those participating in it as matter of communication—of sending a coded message down a channel in such a way that the message sent would be accurately picked up by the receiver. There can be little doubt that the most important consideration in fixing this representational matrix was the fact, also established in the early 1960s, that DNA specifies proteins by way of one form of RNA, “messenger” RNA, which carries information to a ribosomal site where protein is manufactured. The notion that a message had to be sent from place to place by way of an intermediary in turn reinforced the notion that this message had to be written in some sort of code. This link was readily forged in large part because throughout the 1960s the DNA-RNA-protein relationship was explicitly guided by Claude Shannon and Warren Weaver’s 1949 book *The Mathematical Theory of Communication*, which promulgated the conception of communication as quantifiable bits of information moving down a channel by way of more or less efficient codes (such as Morse Code). It was during this period that the four bases of DNA first came to be thought of as letters: A, C, G, T. They are, of course, not letters at all, any more than amino acids are words or proteins are sentences. They are merely chemicals with a certain specificities for bonding with other chemicals.

It is of great importance to notice at this point that the well-nigh universal acceptance of mathematical communication theory as a guide to unraveling the DNA-RNA-protein relationship was not yet equivalent to the notion that an organism is a readout from something like a computer program. During the period in question, in fact, computers and computer programs were not yet widely known. As a gesture toward explaining why this further transformation took place, I will point to four crucial, if insufficient, moments...
in this process. At each of these moments the energetic view of the body on which the coherence of the cybernetic image is based was thrown deeper and deeper into the shadows.

The first consideration takes us back once more to the cybernetic pioneers of the late 1940s. All of them, as we have seen, viewed information as a matter of feedback control of energetic processes, whether natural or artifactual. Precisely because they presupposed this energetic framework, they were all impressed by how little energy is needed to run an organic control mechanism. Wiener clearly acknowledges in Cybernetics: Control and Communication in Animal and Machine that "the living organism is above all a heat engine." He quickly goes on to note, however, that "the bookkeeping which is most essential to describe organic function is not one of energy." The books are kept, Wiener says, in informational terms: "The information fed into the central control system of the body very often contains information concerning the functioning of the effectors themselves." 27

In retrospect it is easy to see in this text Shannon and Weaver's claim, put forward the following year, that information can be quantified into discrete bits. It is no less easy to see in it an acknowledgment of the work of the code crackers and engineers who were beginning to build computers based on digital programs. It is even easy to see in it an anticipation of the molecular geneticists' notion, in the wake of Crick and Watson's triumph in 1953, that organic information is "encoded" into pieces of DNA. When one looks directly at Wiener's text, however, there is no mention, or even inkling, of any of these things. Information is not quantified or localized in any of Wiener's text, however, there is no mention, or even inkling, of information as a matter of feedback control of energetic processes, whether natural or artifactual. Precisely because they presupposed this energetic framework, they were all impressed by how little energy is needed to run an organic control mechanism. Wiener clearly acknowledges in Cybernetics: Control and Communication in Animal and Machine that "the living organism is above all a heat engine." He quickly goes on to note, however, that "the bookkeeping which is most essential to describe organic function is not one of energy." The books are kept, Wiener says, in informational terms: "The information fed into the central control system of the body very often contains information concerning the functioning of the effectors themselves." 27

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This reading of Wiener's text leads to a second crucial moment in the emergence of the digital image of the body. The solution of the coding problem in biology—the use of the paired bases of DNA to specify the twenty amino acids from which protein is assembled—was put in place by means of what came to be called the "central dogma" of molecular biology, which forbade the reinsertion of amino acid sequences, and hence the information in proteins, into RNA and DNA sequences. It was Crick who formulated the central dogma. 28 It conveys, as we now know, a decidedly inadequate sense of what goes on in the cell nucleus. Our coevolution with viruses, for example, depends on their wicked ability to insert their DNA sequences into our cellular machinery by means of what is called reverse transcription; as much as 40 percent of the genome, it is currently estimated, may consist of mechanisms for blocking, containing, or otherwise controlling this sort of invasion. In taking up genetic biotechnology, we are, from this perspective, doing nothing other than aping nature's profound ability to plug the DNA of one organism into another. The extent of which this process goes on in a competitively coevolving world is only becoming clear to us now that we are acquiring mastery of the techniques of gene transfer that mimic it; such is the power of the Viconian epistemology evoked at the outset of this essay.

At the time, however, there were good reasons for insisting on the central dogma. Failure to abide by it would, in the first instance, open up living systems to the inheritance of acquired characteristics. This leakage from "nurture" into "nature" would not only bring down the wrath of decidedly anti-Lamarckian evolutionary biologists on the new community of molecular geneticists but would undermine their own markedly reductionist ideology, which aimed explicitly at absorbing the anti-Lamarckian genetical theory of natural selection into molecular biology rather than at contesting it. (Watson has acknowledged that his personal motives for working on the structure of DNA, in addition to the glory of winning the Nobel Prize, included a burning desire to prove that life is nothing
but chemistry; other pioneers of molecular biology, such as Jacques Monod, held similarly reductionistic views.\textsuperscript{39} There were, moreover, practical reasons for insisting on the central dogma in addition to theoretical ones. Without the central dogma in place, it would be difficult to maintain the boundaries of a research program that was single-mindedly focused on the coding problem, and in consequence studiously indifferent to (and in some cases ignorant of) many other phenomena going on in the cell, even in its nucleus. In many of these processes, there is indeed massive feedback between the environment, the organism, the cells, and the nucleus. Even if they cannot inscribe the information they bring directly into the genome, environmental signals tell cells when to turn genes on and off. It is just here that the practical demands of sealing off a research program from complexities and disturbances resulted in something more dubious—an erasure of complex cellular and environmental processes by exclusive concentration on the one-way “transcription” and “translation” of allegedly information-containing genes into proteins. From this perspective, the multidirectional flow encoded in the energetic-cybernetic image of the body projected by Schrödinger and Wiener was, in spite of its limitations, far more biologically realistic than the unidirectional image that emerged among molecular biologists, which continues implicitly to dominate the rhetoric of the Human Genome Project.\textsuperscript{30}

I come now to a third moment in the emergence of a digitalized version of the cybernetic body. It was pointed out by many people in the 1960s, including Shannon and Weaver themselves, that, if mathematical communication theory has anything at all to do with it, genes and genetic programs can be said to store, call up, and transmit information only in a formal sense.\textsuperscript{34} Quantified information does not, literally, make sense. It contains merely a syntax, not a semantics. To be afforded a more biologically realistic interpretation, genetic information had to be given a semantics, and indeed something analogous to a pragmatics, that would determine its uses. What did the job was the evolutionary concept that variant genes or alleles code for slightly variant forms of proteins in organisms, families, and populations just because variation within the amino acid sequences of proteins is the very stuff out of which adaptive traits have been made by natural selection. In other words, genetic “information” came to be regarded as meaningful in a semantic sense because, from a pragmatic point of view, it was adaptively functional in the same way that a machine’s construction is adapted to uses to which it is put. Molecular biologists and evolutionary biologists all signed on to this interpretation. It was by means of this evolutionary interpretation, in fact, that the central dogma of molecular biology was converted from a heuristic tool for policing the boundaries of a particular research program into what, by the mid-1960s, was taken to be a fundamental law of nature.

The selectionist interpretation of the meaning of genetic information certainly gave substance to the evolutionary biologist Theodosius Dobzhansky’s famous maxim that “nothing in biology makes sense except in the light of evolution.” Nonetheless, there arose throughout the 1960s and 1970s considerable anxiety among many evolutionary biologists about the prospective assimilation of genetic Darwinism, whose fundamental principles had already been worked out in the 1930s, to molecular biology. For one thing, in spite of their common agreement on the central dogma, there was no love lost between these disciplinary communities. During the entire period we are studying, molecularists were busy taking over biology departments at universities by calling into question the scientific credentials of “whole organism” biologists, including ecologists and evolutionary biologists. Even E. O. Wilson, whose proposal for a gene-based sociobiology would later cause him to be painted as highly reductionistic by the standards of many other evolutionary biologists, was heard to refer to James Watson, his colleague at Harvard during the 1960s, as “Caligula.” (Wilson claimed that Watson was the most unpleasant human being he had ever met.)\textsuperscript{32} Evolutionary biologists, moreover, seconded by many philosophers of science who came to their defense, were doubtful that the Mendelian notion of genes on which genetic Darwinism was founded could ever be reduced to the molecular gene. Certainly there is a tie between protein and adaptations. But that tie is complicated, indirect, and many-to-many. There are so many levels to go through that, except in cases where variation in one codon of a particular amino acid leads directly to physiological failure, as in the case of phenylketonuria, it is well-nigh impossible to infer any direct and exclusive route between a given gene and a given adapted trait.\textsuperscript{33} Many well-informed genetic Darwinians would agree with Richard Lewontin, an eminent population geneticist who is no friend either to the selfish gene theory or to the overblown medical promises associated with the Human Genome Project, that it is impossible to “compute
the organism" from its DNA sequences: “Even the organism does not compute itself from its DNA. A living organism is at any moment in its life the unique consequence of a developmental history that results from the interaction of and determination by internal and external forces; and the external forces, what we usually think of as the "environment," are themselves partly a consequence of the activities of the organism itself as it produces and consumes the conditions of its own existence.”

Nevertheless, by the 1980s a growing number of influential Darwinians began to be converted to the view that the Mendelian gene, on which genetic Darwinism had hitherto been predicated, is identical to the molecular gene, and to a presumption that the tie between DNA, protein, and adaptive traits—including behavioral traits—is more straightforward and potentially unravelable than had been assumed. The most influential theorist in leading this *volte face* has been Richard Dawkins of Oxford University. Dawkins’s conception of “the selfish gene” was designed to reformulate genetic Darwinism in such a way that adapted traits come into existence just because they are the means whereby coding sectors of DNA get replicants of themselves represented in greater numbers in successive generations. Those chunks of DNA—genes, by Dawkins’s lights—that succeed best in building the adapted traits that fight their battles with other organisms become, to the extent of this success, “immortal replicators.” In spite of the loud, but largely ineffective, protests of figures such as Lewontin, this DNA-centered conception of natural selection, in which organisms and their traits serve as mere “vehicles” for the self-perpetuation of self-replicating DNA, had become, under the influence of the sociobiological and evolutionary-psychological research programs that have been framed in its terms, so dominant by the last decade of the twentieth century that it had monopolized the name “Darwinism.”

I come by this route to the fourth and final moment in the process by which genetic programs, already scripturalized in the way described by Kay and rendered linear by the central dogma, began to be construed as digital printout. Until recently at least, organism-centered (as distinct from gene-centered) Darwinians have not been opposed to construing the genome as containing a genetic program. Ernst Mayr, for example, professor at Harvard’s Museum of Comparative Zoology and a founding father of the Modern Evolutionary Synthesis, has long spoken of genomes as containing “genetic programs.” Eager to burnish the credentials of genetic Darwinism by extruding from it any lingering elements of Lamarckism, Mayr’s ascent to the central dogma has been sealed by his construction of the genome as guiding the development of an embryo by means of such programs. In saying this, however, Mayr was not thinking either about a linear, one-to-one relationship between genes and adapted traits, or about a digital program running on computers. The latter had barely been developed when Mayr first started using the phrase “genetic program.” Instead, Mayr was thinking of the genome in good mid-century cybernetic terms as a goal-oriented, feedback-driven “teleonomic” (rather than the more suspiciously Lamarckian “teleological”) process. In this cybernetic conception of the relationship between genes and organisms Mayr was at one with the cybernetically oriented researchers at the Institut Pasteur—Monod, Francois Jacob, and Andre Lwoff—who first discovered how structural genes are turned on and off in the process of development by regulatory sectors of the genome. Mayr’s thinking also accorded, in this respect at least, with the work of developmentalist Darwinians such as C. H. Waddington, who since the 1940s had been appropriating cybernetic conceptions of feedback to explain the way in which embryos, as they slide down “epigenetic landscapes,” can push a restart button to compensate for the many contingencies, some induced by insults, others due merely to chance, that a fertilized egg must encounter as it differentiates. Waddington went out of his way to insist that “the traffic is certainly two way.” Mayr would have agreed.

It is precisely not this conception of “genetic program,” however, that has been projected by Dawkins in books such as *The Blind Watchmaker* (1986) and *Climbing Mount Improbable* (1998), which followed *The Selfish Gene* (first edition, 1976). In these works the assimilation of genetic programs to computer programs—and in particular to so-called genetic algorithms that mimic the sheep-and-goats process of natural selection, in which only adapted combinations of genes are allowed to “reproduce”—is presented as a way of adumbrating, protecting, and even empirically confirming the selfish gene hypothesis, which was first put forward without any analogy to computational software or hardware. In this approach, Dawkins has been seconded by the philosopher Daniel Dennett, who in his 1995 monograph *Darwin’s Dangerous Idea* construes natural selection itself as an “algorithm” in which various genetic combinations

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66 DAVID DEPEW

FROM HEAT ENGINES TO DIGITAL PRINTOUTS 67
or “macros”—stable, even immortal, units of genetic structure and phenotypic function that can be recycled into new combinations whenever adaptive utility requires—are submitted to a process in which inefficient combinations are programmatically weeded out by a recursive decision procedure. This “algorithmic” conception of natural selection inscribes computer imagery into the very process of natural selection itself. “The capacity of computers to run algorithms with tremendous speed and reliability,” writes Dennett, “is now permitting theoreticians to explore Darwin’s dangerous idea in ways heretofore impossible, with fascinating results.”

Fascinating as it may be, this “algorithmic” conception of natural selection—Darwin’s “dangerous idea”—is foreign to anything in the earlier history of Darwinism. In its disturbance of the delicate balance between the chancy and the necessitated aspects of the process of natural selection, this tropology gives the impression that the evolutionary process is more orderly, more programmatic, more oriented toward adaptive efficiency than the main line of Darwinism has hitherto assumed. This effect is rhetorically enforced by the projection of the language of engineering design onto the statistical process of natural process. Dennett even speaks of natural selection as a designer, whereas Darwin, and the majority of Darwinians after him, have merely claimed that selection achieves what design produces without a designer. This rhetorical performance is underwritten by the belief that we have finally built the right kinds of machines to make sense out of living nature, and to show that natural selection is, as Dennett puts it, “the best idea anyone ever had.”

The assimilation of the notion of a genetic program to a digital readout is, no doubt, largely the product of a pretheoretical public enthusiasm for seeing the world through the eyes of a new technology. For journalists, computer programs provide an inviting source of metaphors useful in translating technical results into terms that various publics can readily understand. Taking this system of imagery seriously, however, is a different matter. Dennett’s reasons for using it to make a theoretical case are, from one point of view at least, innocent enough. He wishes to give aid and comfort to Dawkins’s conception of natural selection, to back up the central dogma, and implicitly, at least, to extend the scriptural imagery that, as Kay has shown, has come to constitute genetic discourse. At the same time, when it is disseminated into the wider public sphere in which genetic and other forms of biotechnology are being harnessed to capitalist production, Dawkins’s and Dennett’s digital tropology gives a tacit blessing to biogenetic engineering by conceiving of natural selection as a machinelike process with an efficient testing and management system, as ruthless in its decision making as any downsizing post-Reagan capitalist enterprise. This rhetoric celebrates the cyborgian notion that there is no distinction in principle between organisms and machines that can be programmed to perform various tasks. It supports the view that, in a reversal of the words of the Nicene Creed, organisms are made, not born, factum, non genitum. It thereby pushes into the background the populational, statistical, and chance aspects of Darwinism that have enabled it during the twentieth century to become a mature science.

As widespread as digital imagery of the gene now is among both expert and popular audiences, it is nonetheless a markedly imprecise representation of the relationship between genes and traits. Even if we insist on seeing the relationship between nucleic acids and protein as a coded and programmed one, still there is no “machine language”—no binary system of zeros and ones—lurking beneath the correlation between the base pairs of nucleic acids and proteins. To be sure, a tropology that construes genes as “macros,” which are recycled by both evolution and human ingenuity when occasion demands, has been useful in recording and expressing one of the most salient discoveries that has arisen from sequence data generated by the various “model organism” programs—mouse, fruit fly, flatworm, bacterium—that have gone on concurrently with the Human Genome Project. Genes, it seems, are highly conserved across very distant lineages. Nonetheless, it is by no means clear that the genes that are conserved across distant lineages make sufficient contact with the conception of genes that figures in Darwinian population genetics, with its stress on quite subtle differences among the alleles that are distributed statistically in populations, to contribute to the further development of evolutionary theory.

Precisely this suspicion has been voiced by Darwinians and philosophers who, like Lewontin, tend to see in the Human Genome Project, with its inflated and utopian rhetoric about curing diseases, enhancing reproductive choice, and intervening benevolently in social policy by identifying genes for “homelessness” and a “propensity for violence,” a worrisome underestimation of genetic diversity.
and epigenetic complexity, and a revival of quasi-eugenic political and social fantasies that are deeply, if sometimes unwittingly, embedded within the checkered history of the Darwinian tradition. Even when advocates of the Human Genome Project insist that the sequence data they put down as "the gene for X" are no more than a point of reference for comparison among individuals and populations, population geneticists like Lewontin suspect that the very idea of calling a single sequence the gene for some species-specific trait serves as a terministic screen behind which the natural diversity that exists within populations—which, in its struggle to overcome its eugenic past, the Darwinian tradition recognized only with great difficulty—disappears from view and is replaced by the homogenizing "quality control" tendencies on which genetic engineering depends and at which it is explicitly aimed at producing. Digitalized rhetorics of the gene have the effect of minimizing this conceptual dissonance, at the expense of the gene concept that is built into evolutionary population genetics. If properly diagnosed, however, this conceptual dissonance may in the end serve to show that genetic variation and selection cannot be reduced to molecular machinery, and that Dawkins's selfish gene, which was designed to hybridize the Mendelian gene with the molecular gene, subtracts more from good science than it adds.

Whatever its relation to the larger contours of the Darwinian tradition, the moral of this essay is that the digital tropology of the body has obscured ecological and energetic facts that, in spite of its limitations, had been brought to light by cybernetics with its link to the heat machine. When considered as a formal algorithmic process analogous to the reiterated running of a computer program, natural selection must be presented as "substrate neutral"; that is, as indifferent to the kinds of material on which it operates—carbon based, silicon based, and so forth—and to the unique sorts of processes, structures, and properties that may inhere in particular materials. Dennett is explicit on this very point: "Darwin's dangerous idea is reductionism incarnate ... Its being the idea of an algorithmic process makes it all the more powerful, since the substrate neutrality it thereby possesses permits us to consider its applicability to just about anything." This formalized conception has obscured, however, not only the statistical nature of population genetics, but the complex physiology of the cell and the organism as energy processing, cybernetically controlled, goal-seeking, homeostasis-maintaining systems that are coupled deeply to energy flows in their environment through the specificities of the materials on which they are based. What has replaced this notion is the idea that genes specify functional modules that can be taken out of and inserted into the organism in the same way they are taken out of and into machines.

To be sure, few contemporary biologists or biochemists will deny that bodies use genetic information precisely in order to efficiently process energy so that it does work. Even a newspaper report in May 2000 about progress in the Human Genome Project concedes that "proteins, not genes, do the work. They build tissues, digest food, store memories, process waste, and tell cells when to die." Enthusiasts for treating the organism as a collection of "macros," moreover, continue to speak of the ways in which living things "beat" or "stave off" the second law are any distinction registered between closed and isolated thermodynamic systems, such as those whose "heat deaths" Lord Kelvin and Henry Adams worried about, and the open, far-from-equilibrium systems that are actually presupposed by a robust and realistic cybernetic discourse of living systems. As a result, the current apotheosis of the digital body, by tending to drop out the cybernetic middle term, has led to conceptions of biogenetic engineering that minimize and misconstrue the structuring and constraining roles that energetics actually plays in living things. Digital imagery also assigns a far greater degree of agency to genes, which after all are relatively inert molecules, than they can possibly exercise in a complex system in which nothing happens without feedback, both positive and negative. This exaggerated sense of the agency of the genes is an effect of the erasure of everything that stands between a gene and the organisms in which it is, after all, only a minute part. This erasure, which began with the scripturalization of DNA, has been considerably enhanced by the recent digitalization of the gene.

A digitalized image of the body is probably necessary if a conception of the organism favorable to unrestricted biotechnology
and utopian medical technoscience is to be legitimated. Industrial genetics demands a body that is a manipulable collection of genetic-physiological-behavioral modules that can be taken apart and reassembled like so many “macros.” Anything more holistic would be technically intractable and morally suspect. Nonetheless, the systematic erasure of the distinction between the natural and the artifactual that is implied by the digital image of the gene-protein-organism relationship cannot help but create a discursive framework within which unrestricted genetic technology and overly optimistic genetic medicine can flourish without a just appreciation of the difficulties, both physiological and ecological, that these new technologies, however useful and inevitable they may be, must encounter. The dissemination of the digital image can, accordingly, lead to misperceptions on the part of the public, and perhaps on the part of professionals themselves, about just how complicated and messy genetic medicine and genetic agriculture are likely to be. Precisely because we will be, and even should be, engaging in these practices and techniques, it is desirable to have an accurate, and ideologically uncontaminated, conception of what we are and will be doing.

Notes

4 In this essay I leave out of consideration a parallel development in which the coalescence of various disciplinary strands into “cognitive science” has been predicated on a conception of the mind as a printout from software that runs on the hardware of the brain. Key to this idea is the so-called functionalist interpretation of the mind-body relationship, which was initially set forth by Hilary Putnam, according to which mental functions are distinct from, but not independent of, bodily states because, although every mental function must be realized in some material or another, the same function can be realized in different materials. This doctrine, which skirts both traditional materialism and Cartesianism, is built on and gives added support to the notion that the relationship between mind and brain is like the difference between computer software and hardware. It thus illustrates clearly the marked dependence of our conceptions on our technologies that is the leitmotif of this essay.
7 A similar thesis has been defended in a different idiom in Richard Doyle, On Beyond Living: Rhetorical Transformations of the Life Sciences (Stanford: Stanford University Press, 1997).
11 Kevles and Hood, eds., The Code of Codes.
15 Maxwell’s demon, who pushes molecules one way or another by inspecting them, affords an image of the problem of control by inspection. Maxwell’s conclusion is that there is no such demon in nature. The process of the distribution of energy states in molecules is purely statistical, random, and chancy.
17 For deeper reflections on how film, as a modernist medium, inscribes the conditions of its own production, see Garrett Stewart, Between Film and Screen (Chicago: University of Chicago Press, 1999).
For a detailed account of the history and proceedings of the Macy conferences, see Hayles, How We Became Posthuman, 50-83.


Hayles, How We Became Posthuman, 84-100.


Kay makes this point in Who Wrote the Book of Life?

As Kay shows, the Rosetta Stone image was common among researchers during the 1950s; it adumbrates the Book of Life metaphor.

Wiener, Cybernetics, 41–42.


A full inventory of the complexities of cellular replication is presented by Eve Jablonka and Marion J. Lamb in Epigenetic Inheritance and Evolution: The Lamarckian Dimension (Oxford: Oxford University Press, 1995). Jablonka and Lamb characterize their project as “Lamarckian” because they wish to ferret out aspects of this process that defy the central dogma. This rhetorical choice, which can easily backfire, testifies implicitly to the hegemony of the central dogma over contemporary Darwinians, who have signed on to the central dogma with few reservations, and who in consequence have given the impression that to defy the central dogma is to make oneself over as a non-Darwinian.


For a recent summary and defense of the antireductionist consensus among philosophers of biology, see Kim Sterelny and Paul Griffiths, Sex and Death: An Introduction to the Philosophy of Biology (Chicago: University of Chicago Press, 2000).


For an account of the French school of molecular biology, see Kay, Who Wrote the Book of Life? chapter 5.


Ibid., 51.

Ibid., 60–71.

Ibid., 21.


For a vivid summary of these objections, see Lewontin, “Dream of the Human Genome.”


Dennett, Darwin’s Dangerous Idea.

On the claim that the selfish gene and the digitalization of genetics has ascribed to genes much more agency than they can conceivably exercise, see Evelyn Fox Keller, Refiguring Life: Changing Metaphors in Twentieth-Century Biology (New York: Columbia University Press, 1995); Ruth Hubbard, Exploding the Gene Myth (Boston: Beacon, 1997); and Lewontin, Biology as Ideology.