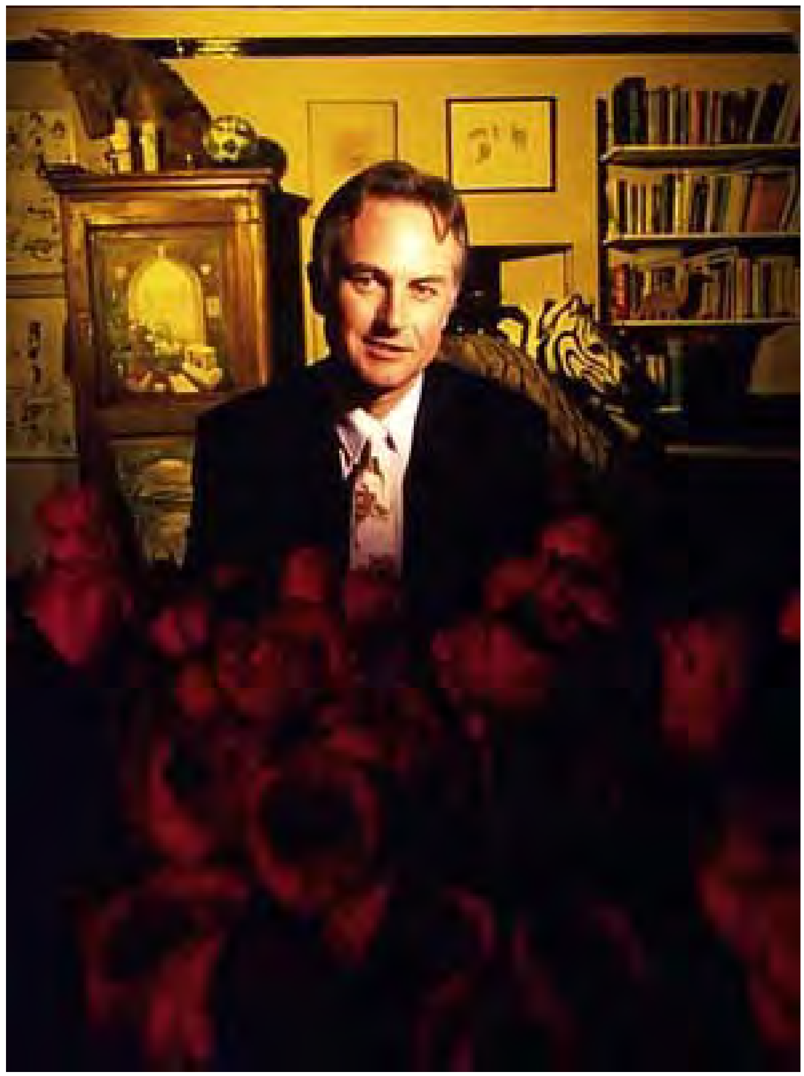
# Revolutionary Evolutionist

*For Richard Dawkins, genes are selfish, the watchmaker is blind, and the mystery of life is no mystery - it's digital.*

By Michael Schrage (July 1995)



In the cluttered back room of Richard Dawkins's Oxford flat, a Macintosh morphs through the image of a human skull evolving. Over and over, the huge prognathic jaw shrivels as the cranial cavity swells to grotesquely large proportions: tiny brain, monster brain.

"This is what our skulls might look like in thousands of years," Dawkins remarks, glancing at the screen, "should we be around that long." That same trend applied to Dawkins's own skull produces the image shown on the cover of this magazine.

But even without futuristic morphing, Dawkins's head holds more provocative ideas than most. Two decades ago, Dawkins presented a radical evolutionary perspective in a small book called The Selfish Gene, a disturbingly persuasive essay arguing that living things are little more than corporal vessels impelled to heed the primal dictates of selfish genes hellbent on their own replication and propagation. Much as the English philosopher and novelist Samuel Butler observed a century ago that a chicken is just a way an egg makes another egg, Dawkins proposed that we are nothing but expressions of our selfish genes in the process of making more selfish genes. Taking that idea even further, Dawkins proposed that genes themselves are expressions of particularly elegant code manipulating the world around it to its own reproductive end. He extended these notions into culture and described ideas as competing, self-replicating entities he called memes. Dawkins's most recent book, River Out of Eden (see excerpt), extends his life's work into a unified evolutionary theory arguing that all life, at its core, is a process of digital-information transfer.

These ideas are intriguing, even a little outrageous, but - most importantly - they have proven astonishingly influential. When a Dawkins meme smacks into your neurons, your neurons obediently repattern themselves around it. You might resist their explicit message, but they are difficult to ignore and impossible to dismiss. They're quite fit - in the Darwinian sense.

Dawkins's revolutionary evolutionary rhetoric has particularly inspired researchers of artificial life. Indeed, Dawkins's work has created new contexts for exploring genetic algorithms and has sensitized the growing community of artificial-life researchers to the evolutionary dynamics of their software creations. Much as Herbert Simon and Marvin Minsky framed the agenda for artificial intelligence, Richard Dawkins has effectively defined the evolutionary agendas for artificial life. If you want to understand the future of natural and synthetic evolution, you have to read Richard Dawkins.

The morphing skulls are just a taste of Dawkins's designs on synthetic evolution. Other randomly selected signs of digital Darwinism are strewn throughout Dawkins's apartment. The seat cushions for the wooden chairs are immaculately embroidered with images of color biomorphs - polychromatic representations of progeny that Dawkins first bred a decade ago with his own home-brewed artificial life program. So, don't sit on them. They were lovingly sewn by Lalla Ward - Dawkins's third wife - best known in Britain as Romana, the comely assistant to the BBC's Dr. Who but perhaps more proud of her role as Ophelia in a BBC production of Hamlet. She and Dawkins were introduced at a party by Douglas Adams, author of the science fiction classic The Hitchhiker's Guide to the Galaxy. Small world.

The biomorphs are reminiscent of the musings of D'Arcy Thompson, the British biologist of natural forms. Completely aware of the innate ability of computers to replicate data patterns, in 1984 Dawkins decided to play God and write a simple program to generate treelike structures on his Apple II. He called them biomorphs - living structures. He determined the "fitness" of the image and tried to breed aesthetically charming virtual trees. But the program birthed much more than stately elms or magnolias. Dawkins described the excitement of his discovery of synthetic life forms in The Blind Watchmaker: "When I wrote this program, I never thought that it would evolve anything more than a variety of treelike shapes. I had hoped for weeping willows, cedars of Lebanon, Lombardy poplars, seaweeds, perhaps deer antlers. Nothing in my biologist's intuition, nothing in my 20 years experience of programming computers, and nothing in my wildest dreams prepared me for what actually emerged on screen. I can't remember exactly when in the sequence it first began to dawn on me that an evolved resemblance to something like an insect was possible. With a wild surmise, I began to breed, generation after generation, from whichever child looked most like an insect. My incredulity grew in parallel with the evolving resemblance.... I still cannot conceal from you my feeling of exultation as I first watched these exquisite creatures emerging before my eyes. I distinctly heard the triumphal opening chords of 'Also Sprach Zarathustra' (the 2001 theme) in my mind. I couldn't eat, and that night 'my' insects swarmed behind my eyelids as I tried to sleep."

Perhaps the most amusing pastiche of synthetic biology to grace the Dawkins household is the beautifully carved wooden horses. Most are charming refugees from carnival carousels. A few of the weathered animals go back to the '50s. Are these simply a charming Dawkins eccentricity? Not at all. By sheer happenstance, it turns out, Lally's mother had been collecting them for decades. Now they're stabled - along with the biomorphs and the simulated skulls - in the Dawkins home. It all seems quite natural. Really.

In the living room, Dawkins picks up a scrapbook and flips through it to read from a letter written to him about The Blind Watchmaker, his pop explanation of natural selection. The letter, from a New Zealand academic, reads: "One of my most capable students confessed that she had been reduced to tears by your book. She felt that any religious belief was now impossible to her, as it had been logically disproved."

The academic was kind enough to enclose his reply to the student, which Dawkins reads aloud: "When Lenin traveled through Germany earlier this century, the Germans permitted him only to travel in a sealed, locked train - on the condition that he proceeded nonstop from the one border post to the other. They clearly recognized his persuasiveness and power of his ideas and their capacity to produce unhappiness. I respectfully request that you don't lend Dawkins's book to anybody for the same reasons."

While his tone skids teeteringly close to the brink of smugness, Dawkins never quite makes it over the edge. His is more the pride of craft than ego. The letter writer is, of course, absolutely correct. Dawkins is a dangerous man. Without question, Richard Dawkins is the most brilliant and compelling propagandist of Darwin today. His rhetoric inspires even as it provokes. He is a veritable Tom Paine of evolution, an uncompromising champion of the brute force of natural selection, ruthlessly dismissive of those who question evolution's essential truth. Creationists who believe in the divinity of natural design, of course, might think him more a Goebbels.

But for Dawkins there is nothing left to argue: genes are selfish; the watchmaker is blind. To say otherwise, he insists, betrays the truth. Cherished concepts like "free will" and "spirituality" live in the dark, helical shadows of our genes. He has roused the ire of England's religious communities by publicly expressing his view that theology is nothing other than a pseudo-intellectual grab bag of charming myths. Dawkins is a fiery evangelist for atheism.

His metaphors, his prose, and his ideas burn with a rational passion that simultaneously overwhelms and disarms. He is not a scientist haunted by self-doubt. There are moments in his speech, manner, and texts when he comes across as completely uncompromising in all of his firmly held beliefs as any Bishop Wilberforce. Even Harvard's well-known evolutionist and Darwin booster, Stephen Jay Gould, is a Darwinian softie by Dawkins's hard standards.

And Dawkins has been extremely effective in probing the boundaries between natural evolution and artificial evolution as created in computers. Indeed, Dawkins's thought suggests that the distinctions between natural evolution and artificial evolution are themselves artificial. Evolution is truly transcendental, he argues: Darwin's dynamics are as universal, as profound, and as potentially explosive as E=mc2.

This transcendental nature of evolution has bred several new fields of computer science that have a biological feel to them. One of these fields is called computational biology; it focuses on using genetic algorithms and other formulas that imitate genetic breeding for replicating the effects of evolution in ordinary computer chips. The stronger form is artificial life; it attempts to simulate all the essential traits of life - not just evolution - using silicon (and other substrates) instead of carbon. A-life researchers believe life is an information process that can be ported from one matrix to another.

In fact, computational pioneers like Danny Hillis and Stanford University's John Koza now actively explore software that breeds other software. Instead of software engineering as the paradigm of software design, they want to apply Darwin's theories to grow software that grows solutions. The rise of cheap processors and parallel architectures creates the ideal digital ecosystems to spawn software rather than build it. Nature - not rational cognitive planning - becomes the guiding force for the next generation of software solutions.

With his skillful articulation of evolutionary issues - combined with his digital breeding of biomorphs - many researchers consider Dawkins a conceptual godfather of the artificial life movement. He is as comfortable with digital media as with the genetics of fruit flies. He hacks software as readily as he hacks zoology. He wrote his own word processor for the old Apple II and documented the decision processes of baby chicks. With his multimedia, multispecies fluency, Dawkins knows that artificial life has as many insights to offer biology as biology does artificial life.

A shy man with quick movements, Dawkins circles questions warily - almost distrustfully. He is cautious and disciplined. Conversation is not a game. He first pokes at ideas rather than plays with them. He is almost the caricature of the Oxford don - extraordinarily well read with a command of language that moves easily between forcefulness and nuance, with a dry wit that tends toward the droll.

Leon Lederman, the physicist and Nobel laureate, once half-jokingly remarked that the real goal of physics was to come up with an equation that could explain the universe but still be small enough to fit on a T-shirt. In that spirit, Dawkins offered up his own T-shirt slogan for the ongoing evolution revolution:

Life Results from the Non-Random Survival of Randomly Varying Replicators.

Expect to see it on grad student T-shirts everywhere from Oxford and MIT to the Santa Fe Institute.

Although whimsically done, Dawkins's T-shirt slogan is at the center of his powerful manifesto. The message nattily packages the essential insight that makes Dawkins far more than just an evolutionary propagandist and provocateur. In many ways, what Dawkins is saying about evolution is as bold for our time as Darwin's tenets were for his. Dawkins has redefined the fundamental doctrines of "natural selection" in ways that transform the vocabulary of evolutionary biology into the new realms of digital media.

What distinguishes Dawkins from most of his evolutionary peers is his passionate embrace of digital technologies as an appropriate medium for testing Darwin. Dawkins doesn't have to go to the Galápagos Islands to test hypotheses about genetic diversity; he can go to the keyboard. Unlike the life scientists who treat the personal computer as a calculator, Dawkins intuitively sensed that the computer should be viewed as a medium for evolution. If genes are really all about the transmission of information, what better medium than the computer to simulate how information might evolve?

Born and raised in East Africa, Dawkins grew up amid one of the most irresistible bioscapes on Earth. Dawkins came to Oxford in 1959 as an undergraduate, and eventually came under the spell of Niko Tinbergen, the eminent Danish biologist. Author of The Study of Instinct and winner of the Nobel Prize in biology for his pioneering work on animal behavior, Tinbergen was one of the first of the modern ethologists (biologists who explore and explain the nature of animal behavior). What is instinct? Tinbergen would ask. What behavior is learned? How can we truly know the difference? How does behavior change? How do animals communicate? How do animals behave differently in groups than they do as individuals? Why do animals cooperate? How do they compete?

Ethology, as Tinbergen constantly stressed, was a highly interdisciplinary biological science, requiring insights into psychology, physiology, ecology, sociology, taxonomy, and evolution. Tinbergen focused on the eternal tension between the breadth of behaviors observed in nature and a scientist's need to reduce these behaviors to a set of fundamental principles. "My own dominant recollection of his undergraduate lectures," Dawkins recalls, "was that I was particularly taken with two phrases of his - behavior machinery and equipment for survival. When I came to write my first book, I combined them into the brief phrase survival machine."

Dawkins developed a special protégé/mentor relationship with Tinbergen. After a stint at the University of California at Berkeley, Dawkins returned to his alma mater, where he ultimately became a fellow at New College (he still teaches there).

Dawkins's dual interest in the nature of machines and the machinery of nature took place amid the rise of molecular biology. Just a few years after Francis Crick and James Watson's 1953 discovery of the double helix, the molecular biologists - not the naturalists, zoologists, or ethologists - began calling the intellectual shots in biology. The increased ability to track and explain what the genome was and what it was doing - classic reductionalist science as opposed to mere descriptive taxonomies - radicalized the way nature was observed. Centuries of animal breeding had, of course, created an explicit awareness of links between genetic endowment and behavior. The double helix became the new scaffold for erecting theories of evolution.

For the young Dawkins, the ethology of Tinbergen quickly became the conceptual lens through which he viewed the world. Behavior, say of the chicks he studied as a graduate student, was the empirical observation that Dawkins sought to identify and explain. At the same time he was observing chicken processing, Dawkins was busy processing his data with a clunky punch-tape Eliot 803. The machinery metaphor - the machinery meme - that resonated with and reinforced Tinbergen's ideas ultimately welded itself to Dawkins's strong notions of the primacy of the gene. What happens to scientific thinking if the survival machine is defined by the machinery of the genes?

Amid this primordial soup of new paradigms, Richard Dawkins the ethologist rapidly mutated into an evolutionary biologist. In 1965, he hit upon an idea breathtakingly simple to understand but extraordinarily powerful in its implications. In essence, Dawkins argued for an ethology of the gene: How do genes communicate? How do genes behave differently in groups than they do as individuals? Why do genes cooperate? How do genes compete? The same questions ethologists ask about chicks and geese and chimpanzees are virtually identical to the sorts of questions they should be asking about the genome and its genes.

Others had played with this notion before, but Dawkins made it his own and aggressively pushed it into the mainstream of science culture.

As the first true ethologist of the gene, Dawkins de facto became an evolutionary biologist. How genes behave over time - which ones dominate, which ones die off, which ones cooperate, which ones compete, which ones change, which ones remain the same - is the very definition of an evolution based on the flow of information.

When Dawkins published The Selfish Gene in 1976, the book further heated the debate over whether humans were ruled more by nature or nurture, a debate refueled by the emerging sociobiologists - notably Harvard biologist Edward O. Wilson in his 1975 book Sociobiology. By proposing an ethology of the gene, Dawkins shifted that debate away from the individual animal as the unit of evolution to the nature, nurture, and behavior of the genes. With The Selfish Gene, Dawkins offered scientists a conceptual bridge between the reductionist imperatives of molecular biology and the taxonomies of zoology, psychology, and sociology. In other words, the metaphor of the selfish gene not only created an important context to explain human and animal behavior - it also created a framework for molecular biologists to examine the organic interactions of genes. The metaphor scaled from double helices to human interactions.

But looking at the richness and complexity of life on Earth, Dawkins freely acknowledged that an ethology of the gene alone was simply not robust enough to explain evolution. So he applied a Darwinian view of culture, as well. Dawkins argued for the concept of memes - ideas that are, to use the felicitous phrase of William Burroughs, "viruses of the mind." Memes are to cultural inheritance what genes are to biological heredity. A meme for, say, astrology, could parasitize a mind just as surely as a hookworm could infest someone's bowels. Ideas - like genes - could compete and cooperate, mutate and conserve. They, too, are operated on by natural selection. Human evolution, Dawkins postulates, is a function of a co-evolution between genes and memes.

Even that was not enough. Dawkins's intellectual adventure went well beyond the ethology of genes and memes to explore an even more radical insight into the nature of evolutionary dynamics. This idea, too, was astonishingly simple, but it offers a powerful intellectual framework for a new understanding of life as an information process.

What do genes and memes have in common? Dawkins asked. They are replicators. Through various but distinct coded systems, they reproduce; they effect change in their world so they can propagate, just like viruses in either digital or organic form. Dawkins's most powerful paradigm is that the unit of evolution is not the individual - the gene - or the meme, but the replicator.

This was apostasy to Darwinian evolutionists, who took it as dogma that the dynamics of natural selection cared only for the fitness of individual organisms and absolutely nothing else. But here was Dawkins saying that what really counted in "nature tooth and claw" was the replicating code beneath the organism. Evolution is really the story of replicators über alles.

Dawkins aggressively evolved this replicator concept. He noted that discussing the evolution of birds without looking hard at the evolution of their nests, or at beavers without considering the evolution of their dams would be prima facie ridiculous. Each is essential to the survival of the other. It is the combination of bird and nest, the combination of beaver and dam, that gives a competitive edge to the animals who build them. Not only does the body of an organism march to the orders of its genes, but so do the artifacts the organism builds or uses. In this sense, the egg uses both a chicken and a nest to make another egg, and so the nest, too, is an evolutionary extension of the egg.

In biology, the genes in the egg would be called its genotype, while the physical expression of those genes - the chicken - would be called its phenotype. Dawkins called this marriage of organism to artifact The Extended Phenotype - the title of his second book, published in 1982. Still extending the outer limits of his replicator idea, Dawkins used this "extended phenotype" construct to look beyond the individual and artifact to embrace the family of the organism, its social group, the tools and environments it created. These are part of the physical "readout" of the genes, the extended phenotype of the replicating code. The invisible code in genes are therefore, in a very real sense, manipulating large chunks of the visible world to their selfish advantage.

Of course humans - with our massive and complex array of technologies - have extended our phenotypes more than any other living species. Just like a bird's nest, a beaver's dam, or a groundhog's intricate set of underground tunnels, our technologies are now an integral part of our evolutionary fitness. In light of Dawkins's work, to be a scientist today and talk about human evolution divorced from technological evolution no longer makes sense. In the truest and most fundamental sense, human evolution is now inextricably bound with technological evolution. Taken to its natural conclusion, Dawkins's idea suggests that humankind is really co-evolving with its artifacts; genes that can't cope with that new reality will not survive into future millennia.

What happens to life - to artificial life - when our unit of evolutionary observation becomes the replicator? By framing life and its evolution in the context of replicators and networks of replicators, Dawkins has forced all of biology to reexamine its assumptions of the fundamental mechanics of living things. Is technology just what our genes want, or is it a cultural conspiracy of our genes and memes? Does human DNA control the technosphere we've created and live in and around? What does it mean to say that nerve gas and microprocessors are extensions of selfish genes? These questions - as much as the genetic underpinning of embryology and neurophysiology - are the sorts of questions that evolutionists must now address, posits Dawkins.

So essential is Dawkins's work to redefining life that he might have fairly titled one of his books On the Origin of Replicators and expected it to revolutionize science in the most radical fashion since Darwin. But Dawkins is not the sort to run the risk of parodying Darwin in this way, because of his respect for the principles of natural selection. Already, however, this transforming view is proving to be an extraordinarily robust meme that is rapidly replicating in human minds.

When Dawkins spoke at the first artificial life conference in Los Alamos, New Mexico, in 1987, he delivered a paper on "The Evolution of Evolvability." This essay argues that evolvability is a trait that can be (and has been) selected for in evolution. The ability to be genetically responsive to the environment through such a mechanism as, say, sex, has an enormous impact on one's evolutionary fitness. Dawkins's paper has become essential reading in the artificial life community. His multidisciplinary, interdisciplinary fluency in fields ranging from ethology to software has made him someone who is closely watched not only by fans of his popular books but especially by his scientific peers, who range from Stephen Jay Gould to Marvin Minsky to Roger Penrose.

Now 54, Dawkins has few students of his own. He quietly confesses that he wouldn't mind becoming Oxford's first professor of synthetic evolution. (He is seriously on the lookout for an intellectually adventuresome benefactor to endow such a chair for him.) Dawkins likes tossing around a semi-serious idea of awarding prize money to spur innovation and ingenuity in artificial life. (A decade ago, when his Biomorph program came out, he offered US$1,000 of his own money to anyone who could find the exact image of a chalice, or Holy Grail, he had come across in his own explorations. To Dawkins's surprise, a Caltech software jock claimed the prize within a year.) Dawkins detailed his new idea in an exchange of e-mail: "My prize would be for a visually appealing world in which the life-forms have a visible, and preferably 3-D, morphology on the computer screen. They must evolve adaptations not just to 'inanimate' factors like the weather (which would produce essentially predictable, not emergent evolution) but to other evolving life forms (which is a recipe for emergent properties)."

Ingenious, and yet there seems to be something vital missing from Dawkins's venture into multimedia evolution: the hard math. In his recent autobiography, Edward O. Wilson, every bit as much the ethologist as Dawkins, describes a lifetime odyssey of intellectual collaboration. Wilson recognized that he was woefully deficient in mathematical skills, so he proceeded to forge close ties with a number of biostatisticians and mathematicians to help him build accurate models of population biology.

By contrast, Dawkins evinces some remorse but no particular desire to go beyond his amateur programming and formidable rhetorical skills to formalize his revolutionary evolutionary ideas into elegant algorithms that might win the respect of great mathematicians in the science community. He has had collaborators, none of whom ever really brought the rigor of quantitative formalism to his work. Dawkins's métier is metaphor - not mathematics.

Indeed, in an e-mail exchange, Dawkins is positively testy about discussing what might be the new math of replicators. He writes: "Equations are not my language. They are yours, and it was you that repeatedly brought the conversation back to equations. I'm not saying that this is not an important way to look at life. Just that it isn't my way, and I'm not equipped to answer questions on it."

That's not to say Dawkins needs to become expert in cellular automata or the new math of nonlinear dynamics to continue being a thought leader in the rapidly evolving field of artificial life. But, just as fields like physics and chemistry have increasingly become reified into mathematical representations, it seems inevitable that artificial life will mutate along similar dimensions.

Perhaps because of this, the lovely color biomorphs and color mollusks that he has bred on his Macintosh look, umm, a little anachronistic compared with the new artificial life menageries and terraria created by artificial-life breeders like Karl Sims and Tom Ray, who have a superb sense of computationally intensive algorithms. While Sims, working on a Connection Machine, can breed a digital 3-D creature that shimmers with lifelike dynamism, Dawkins's own virtual mollusk looks much like the sort of mollusk you find in a museum.

Dawkins will not be the intellectual adventurer who creates a set of artificial-life algorithms comparable to, say, Newton's calculus. But it would be a fitting tribute if, once they are created, those algorithms carried the name of the man whose memes made their discovery possible.

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## There is a river out of Eden, and it flows through time, not space. It is a river of DNA, a river of information.

An excerpt from Richard Dawkins's new book.

*All organisms that have ever lived - every animal and plant, all bacteria and all fungi, every creeping thing, and all readers of these words - can look back at their ancestors and make the following proud claim: Not a single one of our ancestors died in infancy. They all reached adulthood, and every single one successfully copulated. Not a single one of our ancestors was felled by an enemy, or by a virus, or by a misjudged footstep on a cliff edge, before bringing at least one child into the world. Thousands of our ancestors' contemporaries failed in all these respects, but not a single solitary one of our ancestors failed in any of them. These statements are blindingly obvious, yet from them much follows: much that is curious and unexpected, much that explains and much that astonishes.*

*Since all organisms inherit all their genes from their successful ancestors, all organisms tend to possess successful genes. They have what it takes to become ancestors - and that means to survive and reproduce. This is why organisms tend to inherit genes with a propensity to build a well-designed machine - a body that actively works as if it is striving to become an ancestor. That is why birds are so good at flying, fish so good at swimming, monkeys so good at climbing, viruses so good at spreading. That is why we love life and love sex and love children. It is because we all, without a single exception, inherit all our genes from an unbroken line of successful ancestors. The world becomes full of organisms that have what it takes to become ancestors. That, in a sentence, is Darwinism.*

*There is a river out of Eden, and it flows through time, not space. It is a river of DNA - a river of information, not a river of bones and tissues: a river of abstract instructions for building bodies, not a river of solid bodies themselves. The information passes through bodies and affects them, but it is not affected by them on its way through.*

*I speak of a river of genes, but I could equally well speak of a band of good companions marching through geological time. All the genes of one breeding population are, in the long run, companions of each other. In the short run, they sit in individual bodies and are temporarily more intimate companions of the other genes sharing each body. Genes survive down the ages only if they are good at building bodies that are good at living and reproducing in the particular way of life chosen by the species. But there is more to it than this. To be good at surviving, a gene must be good at working together with the other genes in the same species - the same river. To survive in the long run, a gene must be a good companion. It must do well in the company of, or against the background of, the other genes in the same river. Genes of another species are in a different river.*

*The feature that defines a species is that all members of any one species have the same river of genes flowing through them, and all the genes in a species have to be prepared to be good companions of one another. A new species comes into existence when an existing species divides into two. The river of genes forks in time. From a gene's point of view, speciation, the origin of new species, is "the long goodbye." After a brief period of partial separation, the two rivers go their separate ways forever, or until one or the other dries extinct into the sand. Secure within the banks of either river, the water is mixed and remixed by sexual recombination. But water never leaps its banks to contaminate the other river. After a species has divided, the two sets of genes are no longer companions. They no longer meet in the same bodies, and they are no longer required to get on well.*

*There are now perhaps 30 million branches to the river of DNA, for that is an estimate of the number of species on earth. It has also been estimated that the surviving species constitute about 1 percent of the species that have ever lived. It would follow that there have been some 3 billion branches to the river of DNA altogether. Today's 30 million branch rivers are irrevocably separate. Many of them are destined to wither into nothing, for most species go extinct. If you follow the 30 million rivers back into the past, you will find that, one by one, they join up with other rivers. The river of human genes unites with those leading to other major groups of mammals: rodents; cats; bats; elephants. After that, we meet the streams leading to various kinds of reptiles, birds, amphibians, fish, invertebrates.*

*Francis Crick and James Watson, the unravelers of the molecular structure of the gene, should be honored for as many centuries as Aristotle and Plato. Their Nobel Prizes were awarded "in physiology or medicine," but this is almost trivial. Our whole understanding of life has been revolutionized as a direct result of the ideas that those two young men put forward in 1953. Ever since Watson-Crick, molecular biology has become digital.*

*Watson and Crick enabled us to see that genes themselves, within their minute internal structure, are long strings of pure digital information.*

*What is more, they are truly digital, in the full and strong sense of computers and compact disks. The genetic code is not a binary code as in computers, nor an eight-level code as in some telephone systems, but a quaternary code, with four symbols. The machine code of the genes is uncannily computerlike. Apart from differences in jargon, the pages of a molecular-biology journal might be interchanged with those of a computer-engineering journal. Among many other consequences, this digital revolution at the very core of life has dealt the final, killing blow to vitalism - the belief that living material is deeply distinct from nonliving material. Up until 1953, it was still possible to believe that there was something fundamentally and irreducibly mysterious in living protoplasm. No longer. Even those philosophers who had been predisposed to a mechanistic view of* *life would not have dared hope for such total fulfillment of their wildest dreams.*

*The following science fiction plot is feasible, given a technology that differs from today's only in being a little speeded up. Professor Jim Crickson has been kidnapped by an evil foreign power and forced to work in its biological-warfare labs. To save civilization, it is vitally important that he should communicate some top-secret information to the outside world, but all normal channels of communication are denied him. Except one. The DNA code consists of 64 triplet "codons," enough for a complete upper- and lower-case English alphabet plus 10 numerals, a space character, and a full stop. Professor Crickson takes a virulent influenza virus off the laboratory shelf and engineers into its genome the complete text of his message to the outside world, in perfectly formed English sentences. He repeats his message over and over again in the engineered genome, adding an easily recognizable "flag" sequence - say, the first 10 prime numbers. He then infects himself with the virus and sneezes in a room full of people. A wave of flu sweeps the world, and medical labs in distant lands set to work to sequence its genome in an attempt to design a vaccine. It soon becomes apparent that there is a strange repeated pattern in the genome. Alerted by the prime numbers - which cannot have arisen spontaneously - somebody tumbles on the idea of deploying code-breaking techniques. From there it would be short work to read the full English text of Professor Crickson's message, sneezed around the world.*

*Our genetic system, which is the universal system of all life on the planet, is digital to the core. With word-for-word accuracy, you could encode the whole of the New Testament in those parts of the human genome which are at present filled with "junk" DNA - that is, DNA not used, at least in the ordinary way, by the body. Every cell in your body encodes the equivalent of 715 Mbytes of information, reeling off digital characters via numerous reading heads working simultaneously. In every cell, these tapes - the chromosomes - contain the same information, but the reading heads in different kinds of cells seek out different parts of the database for their own specialist purposes. That is why muscle cells are different from liver cells. There is no spirit-driven life force, no throbbing, heaving, pullulating,* *protoplasmic, mystic jelly. Life is just bytes and bytes and bytes of digital information.*

*Genes are pure information - information that can be encoded, recoded and decoded, without any degradation or change of meaning. Pure information can be copied and, since it is digital information, the fidelity of the copying can be immense. DNA characters are copied with an accuracy that rivals anything modern engineers can do. They are copied down the generations, with just enough occasional errors to introduce variety. Among this variety, those coded combinations that become more numerous in the world will obviously and automatically be the ones that, when decoded and obeyed inside bodies, make those bodies take active steps to preserve and propagate those same DNA messages. We - and that means all living things - are survival machines programmed to propagate the digital database that did the programming.*

*With hindsight, it could not have been otherwise. An analog genetic system could be imagined. But it would resemble a Xerox of a Xerox of a Xerox. After 800 photocopying "generations," all that's left is a gray blur. Boosted telephone systems, recopied cassette tapes, photocopies of photocopies - analog signals are so vulnerable to cumulative degradation that copying cannot be sustained beyond a limited number of generations. Genes, on the other hand, can self-copy for 10 million generations and scarcely degrade at all. Darwinism works only because - apart from discrete mutations, which natural selection either weeds out or preserves - the copying process is perfect.*

*Only a digital genetic system is capable of sustaining Darwinism over eons of geological time. Only a digital river of genetic code could have carried us out of life's Precambrian Eden and into the present day.*

(July 1995) GL