CHAPTER ONE

Life by Design: Evolution and Creation Tales in Synthetic Biology

"Them?"
"Nature and God."
"I thought you didn't believe in God," said Jimmy.
"I don't believe in Nature either," said Crake. "Or not with a capital N."
—Margaret Atwood, *Oryx and Crake*, 206

The perfect match, you and me
I adapt, contagious
You open up, say welcome
. . . . . .
The perfect match, you and I
You fail to resist
My crystalline charm
. . . . . .
My sweet adversary, ooh
My sweet adversary, oh
My sweet adversary
—Björk, "Virus," *Biophilia*

I had a virus I couldn't kick. Feverish and congested, I hurried from the MIT walk-in clinic to listen to Drew Endy lecture to the Department of Biological Engineering. On this overcast day in November 2005, Endy was one year into a tenure-track professorship at MIT (he had first arrived at MIT in 2002 as a research scientist). He looked young—about ten years younger than I knew he could possibly be, given his academic trajectory. The only aspect of his appearance that betrayed his age was his hair color, which had, in just the few months since the summer we had met, begun to fade from light brown to gray. He wore wire-rimmed glasses and kept his hair close-cropped, but photographs reveal that as a graduate student

at Dartmouth in the mid-1990s, he had sported an abundant beard that suggested a previous incarnation as an outdoorsman. When not busy with teaching, researching, and preaching the gospel of synthetic biology, Endy blew off steam by whitewater rafting, hiking, and kiteboarding and would organize semiannual lab field trips to get his students off campus and outdoors.

Despite the intervening decade between earning his PhD and arriving at MIT, Endy continued to dress like a graduate student, a quirk that was tolerated, if not embraced, by the laid-back sartorial culture of MIT.[1] On any given day, Endy would wear a T-shirt advertising some aspect of his work in synthetic biology: shirts emblazoned with logos of the BioBricks Foundation, MIT, or Creative Commons, and one that merely promoted "DNA." Today was no different.[2] Perhaps some of Endy's persona was self-consciously constructed to incarnate a social type, even a caricature: the enthusiastic inventor, the youthful and magnetic leader of a new movement in scientific research. By 2005 he had become such a high-profile spokesperson for the field that his persona had already triggered backlash, with an editorial in *Science* noting obliquely: "Some of his peers privately complain that Endy is a larger-than-life self-promoter."[3] No wonder the room that day was packed, with students sitting cross-legged on the floor and overflowing into the hallway on the first floor of MIT's building 68, running along Ames Street.

After a superlative introduction by fellow professor Penny Chisolm, Endy launched into a lecture that was equal parts autobiography and research report: "So, to get started, this is how I got into molecular genetics and biology . . ." Over the next hour, Endy revealed that he too had a virus he couldn't kick. Indeed, he had been living with it for over a decade. This one, a bacteriophage named T7, didn't infect him (it feeds only on bacteria). It had, however, infected his thinking, spurring him to understand biology differently.

In this, as in many of Endy's talks, his style betrayed a tension between the logical and rigorous approach of an engineer, in which discipline he had trained, and the starry-eyed naïveté sometimes projected by scientists when presenting their work to a wider audience. Endy reported to the assembled faculty and students the origins of his current research: how, as a graduate student in the 1990s, he had developed a software model that, using data from sixty years of molecular biology research on bacteriophage T7, computed the complete intracellular developmental cycle of the bacteriophage, focusing on the infection of a single *E. coli* bacterium by a lone

phage.[4] But his model, he told us, was lousy—it didn't work; it couldn't predict the behavior of T7.

Reflecting on his thwarted doctoral and postdoctoral work, Endy told his audience that those years were "pretty depressing to me, because now I'm coming back to this problem, where I want to *understand* how this thing works, and I want to *understand* how this thing works when I shuffle up all the [genetic] elements, right? And if I've got 72 elements, then I've got 72 factorial permutations, right? More than the number of protons in the universe, probably. And so it's not clear if I can build out a computer model that's going to let me explore this space, that I'm ever going to be able to get traction on this problem." Simmering down his question to a bullet point, he snapped, "What's *wrong* with the T7 genome?" I had been observing in Endy's lab for three months when I attended this lunchtime lecture, but his question shocked me nonetheless. I had never before heard a life scientist ask what was *wrong* with a living system. What sort of question was this—ontological? Normative? Ethical? Wrong to *whom*? Wrong by what metric? It was "wrong," I would learn, because it was disorganized and cluttered with genetic junk. It resisted Endy's best efforts to simulate, model, or understand it. The virus was wrong, in short, because it was a bad design. So he set about redesigning it.

Making Life Better

The MIT Synthetic Biology Working Group's self-described mission was to "mak[e] life better, one part at a time." The two labs constituting the group, led by Endy and Tom Knight, posted this slogan on their website when they founded the working group in fall 2002. If this book queries what synthetic biologists mean by "life," then this chapter draws upon ethnographic fieldwork among MIT synthetic biologists to ask what they mean by "better." Synthetic biology was—and remains—a diverse assemblage of interests, agendas, and research programs. Yet despite vast differences in academic background and wide variation in research agendas, these researchers are united by the philosophy that biology is a substrate amenable to the same engineering strategies employed by mechanical, electrical, and computer engineers to build the nonliving world, and they approach their engineering projects accordingly. Further, they are confident that building new living systems will advance their understanding of how biology works at a more fundamental and profound level than

discovery-based experimental science can uncover: that manufacture will heighten understanding.

In this chapter I narrate the T7.1 project, one research agenda that dominated MIT's Synthetic Biology Working Group during my first years there. This was an effort to synthesize a "better" version of the genome of the T7 virus. In telling this story, I trace two lineages mirroring one another. First, I track how Drew Endy moved from a background in structural engineering into life sciences research, how he became the Principal Investigator of the lab in which I conducted much of my fieldwork, and how he reached the conviction that life can and must be understood by *simplifying it*. Second, I follow the career of a simple biological agent that drew Endy away from structural engineering and pushed him to think about questions of evolution and biological complexity. This humble bacteriophage (a virus that infects bacteria; literally, "bacteria-eater") both piqued Endy's curiosity and frustrated him. T7 is a bacteriophage that either replicates within or bursts bacteria (cycles scientists respectively call lysogenesis and lysis). Endy's encounter with T7—his "sweet adversary," to borrow a verse from Björk—encapsulates a constellation of concepts and terms that are central to MIT synthetic biologists' thinking about life and that will recur throughout this book: simplicity, minimalism, simulation, design and evolution, nature and artifice.

When these synthetic biologists set about to manufacture simpler forms of life, their thinking is animated by two altogether different understandings of "design." One construes their efforts as improving upon natural selection by "rationally" engineering living things in a goal-oriented manner. Such thinking, I show, is animated by a belief that evolution renders genomes that are cluttered, "junky," and poorly organized. The other takes design to be synonymous with "creation." As such, they imagine themselves to be both objects and agents of evolution.

In the early 2000s MIT synthetic biologists cast themselves in three very different roles. They simultaneously saw themselves as *unnatural*, building artificial organisms that are "fit" to thrive only in the artificial environment of the laboratory; as *natural*, doing the work that comes to them "naturally"; and as *supernatural*, effecting feats of biological engineering that render them divine. I arrive at the conclusion that these stories are animated by a religious discourse, which I evaluate using ethnographic examples culled from lab meetings, private conversations with graduate students, and published material. In invoking this language, MIT synthetic biologists slip between ideas about biological design, anxieties and hopes

about "intelligent design," and Judeo-Christian accounts of creating life. Such stories cast MIT synthetic biologists as both godlike agents of biological evolution and unwitting participants in or targets of an evolutionary impulse.

Slouching Away from Bethlehem

How did Endy come to be delivering this lecture before MIT's Department of Biological Engineering? And what were the origins of his idée fixe with T7? Raised in Valley Forge, a small town in southeastern Pennsylvania, Endy, like many of the engineers with whom I spoke, remembered fondly youthful inclinations toward engineering, fueled by playing with Legos, Erector Sets, and Lincoln Logs.[5] Endy studied civil engineering at Lehigh University, a small college in Bethlehem, Pennsylvania, a postindustrial steel town less than two hours by car from his parents' home. The blast furnaces of the Bethlehem Steel Plant, now shuttered, still roared when Endy lived there, a symbol of American industrial manufacture. "The Steel," as it was called, forged iron for railroads, skyscrapers, and guns used during World War II.[6] Endy spent the summer of 1991 working for Amtrak, fixing bridges servicing the railroad between Washington, DC, and New York City. The shadow cast by Bethlehem Steel on Endy's early education struck me as especially formative when he explicitly compared—even denied any difference between—structural and biological engineering. As he rhetorically asked in his lecture, "What's the difference between building a bridge and designing a genome?" Such thinking denies any meaningful difference between the living and nonliving worlds, at least when it comes to their use as engineering substrates.

Bethlehem Steel is also the plant where Frederick Winslow Taylor first formulated his principles of scientific management,[7] a manufacturing philosophy some synthetic biologists also hope to build into biological engineering, making it faster, more streamlined, and less error prone by "standardizing" parts and protocols and setting up "assembly lines" for manufacturing engineered microbes.[8] After receiving his undergraduate degree, Endy remained in Bethlehem for two years to earn a master's degree in environmental engineering.

He next headed to Dartmouth, where he embarked upon a PhD in biochemical engineering and biotechnology. It is here that he first encountered T7. As he recalled for his audience, as a graduate student at

Dartmouth, his doctoral research involved building a software model that would simulate and predict the behavior of T7. Could biologists, he hypothesized, use fifty years' worth of experimental data to predict growth rates of viral plaques (infected bacterial cells grown in culture)?

To understand the stakes of this question, we must pause Endy's trajectory into the synthetic biology lab to trace the history of bacteriophage T7, asking how it too became an object of synthetic biology. Bacteriophages are some of the best-understood and well-characterized infectious agents in biology laboratories. Milislav Demerec and Ugo Fano, working at Cold Spring Harbor in 1944, are widely credited for isolating bacteriophage T7 from a standard anticoliphage mixture prepared by bacteriologist Ward J. MacNeal. T7 was the last virus isolated from a series of seven phages that were numbered in the order in which they were discovered (T for "type").[9] Experiments with T7 demonstrated in 1952, just one year before Watson and Crick elucidated the structure of the double helix, that bacteriophages were near-perfect parasites—they assimilated and converted all host DNA into viral DNA.[10] A few years later, researchers reflected on the role of RNA by studying the behavior of T7, concluding that it was "possible that the specific kind of RNA synthesized by the host under the influence of the infective phage may serve as the proper functional unit for the synthesis of phage specific protein."[11] This observation helped midcentury biologists to lay down the "Central Dogma," the tenet that "DNA makes RNA makes protein."

A slim genome, T7 was in 1983 one of the first living things to be sequenced, as it comprised fewer than forty thousand base pairs.[12] It was simple enough and short enough for its sequencing to be tractable by 1983's standards. Although T7 first snuck its way into molecular biology labs, smuggled within the bacterial Trojan horse it had infected and whose DNA it slowly converted into its own, by the time Endy began studying it as a graduate student fifty years later, it had become a workhorse of molecular biology and genetics, arguably one of the most comprehensively understood objects of biological experimentation. Hence, Endy was curious as to whether T7 could be modeled computationally—as he put it in his lecture, "whether or not our understanding of this relatively well studied natural biological system is good enough to support analysis."

In his 1997 doctoral thesis, Endy writes that his work was "motivated by the desire to develop the coupling between the information database and reductionist tools of the biologist and the synthetic tools of the engineer. . . . To improve our understanding of biological systems and through

such understanding better apply them."[13] He used his programmed model to try to predict what would happen in mutant versions of the same virus. If you moved around chunks of viral genetic material called coding regions (the "seventy-two elements" Endy would mention in his lecture) to make viruses that, for example, expressed RNA polymerase in a different order than they had before, would the computer model still be predictive? Building a model, on his reasoning, should effectively verify the sum total of the data molecular biologists had gathered about bacteriophage T7 during its long tenure in research laboratories.

But this was not as simple a doctoral research project as Endy had hoped. It would stretch beyond his graduate work to animate his postdoctoral work (and later would be taken up by his graduate students at MIT). Splitting his postdoctoral work between the University of Wisconsin at Madison and the University of Texas at Austin, Endy began studying genetics and microbiology, thinking that because he had trained outside the life sciences, perhaps he had missed some crucial information about the virus in programming his model.

During these years, Endy compared the predicted growth rates of his computer-modeled mutant bacteriophages with the actual growth rates of the mutant viruses, which as a postdoc he modified and cultured in the lab. But the results, he found, did not square: the computational model was an awful predictor of actual viral growth. What, he asked us, does it mean when the sum total of molecular biology's published data on bacteriophage T7 fails to predict how the virus reacts to perturbations and modifications of its genetic material? Endy took it as a failure of experimental "discovery-based" biology: all the knowledge painstakingly gathered from classical genetics, molecular biology, and virology, everything life scientists had learned about T7 from 1944 to now, was *not enough* to predict the behavior of an infectious agent so simple it is arguably only marginally alive.

Because the software simulation of phage intracellular infection did not agree with the observed experimental reality of phage infection, Endy (and, later, his students) chose not to modify the rules and parameters of the simulation but to modify the genetic material of the bacteriophage itself, in hopes of building a virus simple enough that it could be modeled computationally. Let me repeat: because the model did not work, instead of scrapping the model, Endy decided to modify the *virus*.

In their history of objectivity, Peter Galison and Lorraine Daston suggest that what they call mechanical objectivity strove to achieve a naturalism

so detailed that it mimetically approximated that which it was meant to represent, until this naturalism was superseded by trained judgment and artistry: "the whole project of nineteenth-century mechanically underwritten naturalism suddenly seemed deeply inadequate. For the image to be purely 'natural' was for it to become, ipso facto, as obscure as the nature it was supposed to depict: a nightmare reminiscent of Borges's too-lifelike map."[14] But Endy's work with T7 and its computational doppelgänger demonstrates not a striving toward naturalism, or even anything that might be termed objectivity, realism, or trained judgment. Rather, it betrays a lack of any real interest in "Nature . . . with a capital N."[15] Instead of the model explaining how the virus works, the virus now would explain how the model works.

For Endy and the synthetic biologists who would later continue to pursue this project, the collision of efforts to describe and to rebuild, to observe and to simulate, made life an unstable category—unable to understand how a living thing works, they remade it in order to render it more comprehensible. Historians and anthropologists of science have recognized how models materialize theories—they are both representations of scientific thinking and tools that guide research.[16] But in this case, the model functions not to guide the researcher in thinking about an external phenomenon "as it is" but as a blueprint with which to mold it "as it should be."

Debugging the Bugs

To understand what MIT synthetic biologists thought was "wrong" with T7, one must first ask what evolution is to a synthetic biologist. For those with whom I spoke and worked at MIT, it is both nature's greatest design principle and its worst flaw. Evolution, they say, makes living systems flexible and adaptive, yet it can also render them error prone, incomprehensible, and somewhat baroque, genetically speaking. Synthetic biology got under way at the end of the twentieth century and in the first years of the twenty-first, the same years that the Human Genome Project (HGP) wrapped up. HGP ways of thinking about the genome influenced synthetic biology's project.

Early detractors of the HGP complained that regions of noncoding or so-called "junk DNA" would be pointless to sequence; molecular biologists worried that tax dollars better spent on HIV research would be wasted sequencing genetic material that did not contribute to the human phenotype

and that therefore lacked meaning.[17] Twenty-three professors (representing "virtual unanimity of the . . . faculty")[18] of the Department of Microbiology at Harvard Medical School published a letter urging their colleagues *not* to sequence the human genome.[19] In the letter, they ask "whether identifying the last nucleotide in a human genome really has deep scientific value" and question "how a complete sequence could be useful for understanding the organization of the huge human genome: the magnification is wrong, like viewing a painting through a microscope." They conclude that "to sequence the genome because it is there" is a pointless, even potentially fiscally disastrous, enterprise.[20] And once the human genome was sequenced, it produced something of an epistemic panic attack—*now what*? Even the coding regions of DNA were then and remain today, admit Francis Collins and Craig Venter (who competitively sequenced the human genome), of little experimental or technical use.[21] On the tenth anniversary of the day on which Venter and Collins joined hands with President Bill Clinton, who declared the sequenced genome "the most important, most wondrous map ever produced by humankind,"[22] the only positive outcome of the HGP that biologists and biotechnologists could agree upon was that sequencing technology had vastly improved—it was faster, cheaper, and under control.[23]

At both the start and the finish of the sequencing race, the genome was haunted by its own density, complexity, and overwhelming *meaninglessness*. And evolution was always to blame: junk DNA was assumed to be the accumulated detritus of evolution, every obsolete bit and bob of every preceding organism, every strange cul-de-sac on the wandering path toward "fitness," every scar of viral infection, piled up, stuffed in, and overflowing the genetic "code." Such thinking—of genomes as massive, incomprehensible, noisy, and buggy molecular ciphers—would make its way into MIT synthetic biology, along with a healthy dose of software developers' enthusiasm for debugging.[24]

Intentional Biology

After completing his postdoctoral work, Endy took a position in 1998 as a fellow of the Molecular Sciences Institute (TMSI) in downtown Berkeley, California. TMSI had been founded two years earlier by Sydney Brenner, a geneticist best known for his Nobel Prize–winning work on the roundworm *Caenorhabditis elegans.* He developed a fate map of this simple worm that tracked its cellular development and differentiation across

its life cycle. Brenner would say of his worm, an organism he (and others) likened to a software program, "You can look at it and say 'that is all there is.'"[25] This statement could also be read as Endy's inspiration in its most distilled form: to be able to write a genetic code for T7 simple enough to be wholly transparent, legible, and predictable.

I would later hear Brenner lecture at the 2008 annual synthetic biology conference, held that year in Hong Kong. He was in town for a day, a brief stop between Japan and Singapore. He spoke of biology, the fantasy of its simplicity, the frustration of its evolved complexity, and the consequences of engineering new living systems. Unlike Endy, Brenner suggested that perhaps engineered organisms should make use of complexity, not tame it: "Complexity [in the animate world] has been achieved not by *design* but by a process of natural evolution achieved by selection. And I think we have to ask ourselves whether we want to give that up as an engineering principle. . . . Math is the art of the perfect, physics is the art of the optimal, and biology is the art of the satisfactory."

Brenner wanted to build an institute in which scientists could pursue their own research without the pressures of an academic career or the oversight of a private laboratory. With an initial infusion of $10 million in a five-year grant from the Philip Morris Company, he founded TMSI.[26] By 1998 geneticist Roger Brent had left a professorship at Harvard, frustrated by the way his academic position hindered his interest in annotating parts of the human genome as the HGP spat out reams of data. Brenner had left his post at the Scripps Research Institute, and the two converged upon downtown Berkeley, deciding to build TMSI in proximity to the University of California, Berkeley. Brenner stepped down as director in 2001, the same year that funding from Philip Morris dried up, and Brent took the reins. He would serve as president, CEO, and director of the independent and nonprofit institute until 2009. One of the topics around which TMSI scientists converged was "simplifying" and "quantifying" biology, a project the institute's mission statement termed "Intentional Biology." TMSI was a place where scientists from multiple disciplines—cell biology, mathematics, engineering—could trade ideas, rub shoulders, and collaborate on shared questions.

Endy would remain at TMSI as a research fellow for three years, leaving only to take up his position at MIT. While at TMSI, Endy and Brent began studying T7 together. Applying TMSI's principle of "intentional biology," they compared the growth rates of wild-type to modified phage, finding that the simulated models did not agree with their physical counterparts. As Endy recollected before the assembled audience at his MIT lecture in

November 2005, "The things we believe to be true, they go into the computer, and then we [did] the comparison . . . [and it] isn't lining up at all." In a paper they coauthored and published in *Nature*, Endy and Brent write that "in biological systems (and simulations), too much depends on chance interactions among small numbers of interacting molecules to yield behavior that is completely determined over time."[27] They posit that such biological complexity (which Endy would soon aim to eliminate via biological design) is to blame for rendering computational models inaccurate.[28]

Form and Function, Deformed and Reformed

When he arrived at MIT in 2002, Endy still had not settled his score with bacteriophage T7. Endy joined forces with Tom Knight to found the Synthetic Biology Working Group. Knight had already been at MIT for over forty years, having arrived in the early 1960s at the age of fourteen. With a graying Lincoln beard and eyes that suggest he is laughing at a joke that you are not in on, he describes himself as "your basic geek." Knight learned computer science in artificial intelligence researcher Marvin Minsky's lab at a time when immense computers used punch cards and batch processing. He made his name among the first generation of computer hackers by working on ARPANET and helping to develop the Lisp machine, one of the first single-user workstations. Turning in the 1990s to biology, Knight thought about living material as indistinguishable from computer code. One of his favorite catchphrases was "the [genetic] code is 3.6 billion years old; it's time for a rewrite." Such thinking infected Endy's ongoing struggle with T7.

Endy assigned the T7 project to his first graduate students and summarized in his 2005 lecture the last three years of work on the virus. The hypothesis he set out to test, as he put it, is whether "it's possible to produce an engineered surrogate genome encoding a viable organism whose behavior is easier to predict [than that of the wild-type genome]." Sriram "Sri" Kosuri, a doctoral student in biological engineering who had an undergraduate degree in biology from Berkeley, set to work redesigning T7 with Leon Chan, a graduate student in MIT's Department of Biology. Their project, which, following software nomenclature, they named T7.1, was funded by grants from the US Office of Naval Research, the Defense Advanced Research Projects Agency, and the National Institutes of Health. Leon Chan had already graduated when I arrived in the lab, but I learned much from Kosuri, a charmingly gregarious West Coast

transplant with a shaggy head of hair and taste for lo-fi indie pop who was never too busy to sit down with me to talk about synthetic biology.

Over the course of several years, Chan and Kosuri used new sequencing technologies to begin to sort out some of T7's "clutter." Endy projected slides mapping out the viral genome of wild-type T7 alongside maps of the modified and streamlined genome. The first step that they took, he explained, was separating out overlapping genes that coded for separate proteins, so that genes could be manipulated independently of one another. The virus that had hitched a ride into molecular biology by multiplying inside *E. coli*, that had been one of the first semiliving agents to be sequenced, and that had lured and foiled Endy was being decluttered and rebooted.

In the paper reporting on their work, published two months before Endy's lecture, the questions the authors posed echoed those now asked by Endy: "should we also expect that the 'design' of an evolved organism would be further optimized for the purposes of human understanding and interaction? Evidence drawn from fields outside biology suggests that the answer is no."[29] As evidence, they cite the fact that T7 bears fifty-seven genes coding for sixty proteins, only thirty-five of which have any known function. Perhaps, they asked, could we "safely ignore" the remainder?[30] Note that the word "design" appears in quotation marks while "evolved" does not. "Designing" a virus still functions as a metaphor for the authors, while "evolving" hardware or software using algorithms (a technique they describe in the next paragraph) has sunk into generalized common sense, losing its scare quotes. Evolution is not limited to biotic media, nor is it understood as being a way of describing the relationship between populations of living things in a dynamic environment. Instead, it here simply means modification over time.

The call to "ignore" anything about the viral genome that is incomprehensible is not unprecedented in biology. Certainly, the form and function of life-forms have, for life scientists and philosophers, oftentimes paralleled social, historical, and political forms of life. Hence, the impulse to purge variation and embellishments from living things is tethered to a modernism that simultaneously seeks to eradicate the foibles of human history. For example, an 1830 debate between zoologists George Cuvier and Etienne Geoffroy Saint-Hilaire over the anatomy of mollusks bled into contemporaneous debates among French architects about design, social reform, and the future of urban society. Proponents of "architectural rationalism" proposed that design types, following anatomical types, should be the "basis for

a utilitarian approach to architectural design, offering a modular method that was 'scientific' in its ahistorical extraction of a built object from contextual considerations."[31]

A century later, as Peter Galison reconstructs, a similar endeavor was under way in Austria. The logical positivism of the Vienna Circle infused the design principles of the Bauhaus in the interwar period. In this regard, "transparent construction" was a rationalist, functionalist "modern 'form of life'" espoused by philosophers and architects alike. In both philosophy and design, Galison demonstrates, logical positivists and *Bauhäusler* sought an "elimination of the superfluous" by logically assembling theories and principles out of simpler elemental units, whether of perception, color, or geometrical shapes.[32]

Synthetic biologists also seek to excise historical exigencies from T7—not social or political history but evolutionary history. Despite similarities in their modernist aesthetics to their precursors in the 1830s and 1930s—designing things undecorated, modular, transparent, simplified, and rationally arranged—they conceive of the relation of function to aesthetics in reverse. If Bauhaus designers like Gropius understood functionality as arising from aesthetics,[33] here simplification and the elimination of evolutionary "ornament" promote biological utility, which MIT synthetic biologists equate with comprehensibility. Biological simplicity is aesthetically pleasing *because* it is transparently intelligible, rather than vice versa.

To drive home his point that good genetic design should lend itself to human comprehensibility, Endy next compared T7 to two different electrical circuits with the same function: both circuits take the square root of an input voltage. An engineer designed the first circuit. The second, like T7, is an "evolved artifact." A research group headed by John Koza at Stanford University ran a series of simulated evolutionary algorithms on a computer to "evolve" a new design for an electrical circuit. Such "genetic programming" (which, unlike actual evolution, is teleological) begins with a list of criteria for an end product. A program generates legions of possible designs, then allows the more robust (or "fit") designs to continue to "mutate" toward some desired end.[34] Endy reported that he had shown both circuit designs—the designed and the evolved—to fellow MIT professor Gerald Sussman, a researcher whose work focuses on automating scientific research and reasoning.[35]

Endy said that Sussman "refuses to explain to me how this [second circuit] works. It's not that he couldn't figure it out, but it *isn't designed for it to be easy for him to figure it out*, and so he chooses not to do it." The

first circuit, however, is "easier to understand; if you wanted to change it, it would be easier to change. . . . And so now if you come back to this representation of an evolved piece of DNA, is it optimized for purposes of human understanding? . . . The hypothesis we [in the lab] got interested in testing was the answer might be 'no.'" Endy elicited laughs from his audience when he said, "we're all familiar with Darwin and the idea that evolution is cool, and it is. You know, but there's the other view of evolution—that it's a tyrant, giving us mutation without representation." By this he meant that nucleic acids, unlike software code, are not annotated to provide clear signposts or instructions for future engineers or programmers. The problem with evolution, on this view, is that while it may (putatively) maximize functionality, it is not easily legible on a genetic level. Such reasoning privileges genotype over phenotype, going so far as to erase phenotypic characteristics as criteria by which to assess evolutionary adaptation.

Similarly arguing by reference to Koza's electrical circuits, Chan and Kosuri write in their published paper that "so-evolved systems lack human readable descriptions and are difficult to understand, fix, and modify for new applications. By contrast, a structured design process produces systems that, in addition to functioning, are designed to be *easy to understand* and extend."[36] They explicitly based their approach not on the prior work of genetic engineers but on the practices of computer engineers and software designers, declaring that they were "inspired by the practice of 'refactoring,' a technique typically used to improve the design of legacy computer software."[37]

Endy, Chan, and Kosuri's overarching comparisons of T7.1 to John Koza's evolved electronic circuits complicate the relation of design to evolution. For Koza, the application of evolutionary algorithms to design problems is a means of seeking elegant solutions to difficult engineering problems (with mixed results). Here, evolution is a designer whose creativity is supposed to surpass human ingenuity, not the other way around. Yet Endy and his students treated natural selection as *opposed* to design—nature does not optimize, improve, or otherwise maximize itself, they were saying, but merely randomly accumulates modifications that may or may not be functional to the organism or "rational" to the engineer.

On Bad Design

Endy's description of phages as "evolved artifacts" rather than designed ones and his explicit alignment of a virus with an electrical circuit erase

the distinction between viruses and circuits, taking them both to be "evolved artifacts." In so doing, he rejects any meaningful distinction between the organic and the inorganic. But more to the point, the parallelism asks how, if at all, evolution is related to design, as well as reanimates dusty ruminations on the relationship of organisms to machines. Thinking about living things mechanistically—imagining that organisms operate like machines, or that living systems, organs, limbs, and tissues function like machine parts—historically led thinkers such as William Paley and others to assume a Mechanic and to understand design as both the fitting of form to function and the fitting of means to ends.[38]

Design in nature has been a long-standing concern in biology, predating the discipline by several millennia, and many philosophers have cut their teeth on evidence of design found in nature. Evolution and design have not always been treated as mutually opposed. From the ancient Greeks to Thomas Aquinas, philosophers believed the natural world to be both ordered and purposive. Immanuel Kant, in providing an early definition of "organism," differentiated between organization and self-organization, specifying living things according to their internal or self-possessed organization. The difference, on this view, between organisms and artifacts is that artifacts are actually designed, whereas organisms can be understood only metaphorically "*as if* designed."[39]

English philosopher and theologian William Paley argued in *Natural Theology* (1802) that "the adaptation of each species to its environment indicated that it was designed by a benevolent Creator."[40] Elaborating on the analogy of God to a "divine watchmaker," Paley posited that merely observing a watch (and comparing that watch to a stone) made clear that "the watch must have had a maker; that there must have existed, at some time, and at some place or other, an artificer or artificers who formed it for the purpose which we find it actually to answer; who comprehended its construction, and designed its use."[41] Design, for natural philosophers, was evidence of a divine hand shaping nature and assembling parts such that the whole would function purposively.

Indeed, natural theologians of Paley's day, in thinking of body parts as mechanical devices, were led to theorize "God as an engineer."[42] And by 2005 the engineers reversed the analogy when they began casting themselves as godlike artificers. The question of design in nature has paired investigations into life's form with faith in Providence's role in molding that form. Thinking about life as already artificial—as either analogous to machines or indistinguishable from them—makes such analogies tick. Watches presuppose watchmakers, and the watchmaker is always divine.

Questions of perfection and error, of good design and bad design, haunt this discourse. Charles Darwin worried terribly about eyes, which, historian Jessica Riskin reminds us, "philosophers and physiologists from Aristotle and Galen onward had considered . . . to represent divine craftsmanship."[43] Here, the suiting of means to ends, the complexity of a living system, and the analogy of the eye to a mechanical device (often, the telescope) all suggested a divine designer rather than natural selection, a force that lacks teleology and intentionality. Yet Darwin was torn when it came to questions of design—sometimes, useless features constituted a design flaw, yet at other times, they were beneficial. In 1847 he noted that "all allusion to superintending providence [is] unnecessary. . . . [*R*]*ather, expressly mention the design displayed in retaining useless organs for further modifications as proof of supervisal.*"[44] If natural theologians imagined a designer who crafted each organ and organism to a specific purpose and niche, here Darwin takes the "designer" to be one who sets good design principles in motion, including (especially) the retention of "useless" parts that might serve some unforeseen future purpose.

The question of "what is wrong" with a living thing would not have been thinkable or articulable to Darwin and his contemporaries—even "useless" parts must serve some later, as yet undefined, purpose. Such thinking also raises the specter of "intelligent design" theories, a term that in fact predates *On the Origin of Species* by at least nine years, when political philosopher Patrick Edward Dove wrote a treatise on intelligent design that questioned the use of both the terms "design" and "designer."[45]

Much more recently, theoretical biologists have taken up notions of biological design in opposition to neo-Darwinian theories, as, for example, in the work of Stuart Kauffman, who claimed that "organisms are *ad hoc* solutions to design problems [and] the answers lie in the specific details wrought by ceaseless selection."[46] Twentieth-century evolutionary biologists have also taken up the question of good and bad design, arguing over the place of bad design in nature, and what bad designs suggest about teleology, purpose, and the force of evolution. One of the most widely read examples of such thinking is the work of Stephen Jay Gould, who took an impish pleasure in pointing out just how nonoptimal nature could be, as evidence that evolution lacked any intelligent operator. His widely read essay "The Panda's Peculiar Thumb" argued precisely against intelligent design by pointing out that the panda makes do with an inefficient and awkward thumb-like protrusion to strip its bamboo—any reasonable celestial engineer would have built something much more suitable.

T7.1

MIT synthetic biologists, as engineers bending their design principles to living form, set about to do just that—to build biological systems more suitable, and in particular more suited to human understanding. To return to Endy's initial question: what is *wrong* with the T7 genome? The question suggests that something was made right by separating overlapping genetic elements. But what? As Endy showed the audience photographs of bacterial plaques infected by phage that had been grown in his laboratory, he explained that the reengineered virus, when transfected into *E. coli* and plated on petri dishes, resulted in reduced plaques. T7.1 was *much worse* than its predecessor at doing exactly what phage has evolved to do—infect bacteria, copy itself, burst open its host, infect more bacteria, repeat. The photographed plated cultures looked puny and sparse compared with the robust cultures of wild-type T7 that Kosuri and Chan had used as experimental controls.

If evolution is understood as the modification of an organism to be better suited to its own environment, then what characterizes evolutionary fitness or "good design" when "better" genomes make worse viruses? When MIT synthetic biologists bring their design principles to bear on living organisms, when they modify living things to conform to ideas about form and function imported from engineering disciplines, then "fitness" is also placed under pressure and defined recursively, according to the qualities MIT synthetic biologists define as fit. Synthetic biologists, by their own definition, are both part of the environment to which the phage must adapt and also outside or beyond it, demiurges dictating which organisms will succeed and which will fail.[47]

If a fit organism thrives in its environment, then the environment for which T7.1 is designed is an MIT laboratory in the Koch Biology Building. MIT synthetic biologists thereby insert themselves into evolution, making themselves the arbiters of which organisms are most "fit." As he flashed the slide of the photographed plaques on the overhead projector, Endy told the assembled faculty and graduate students that he will "ignore everything associated with the natural living world, and define an artificial living world that I completely *control* in the lab. . . . And this is it." Comprehensibility is an adaptive trait for phage in synthetic biology labs.

Five months later, I had dinner with Endy and Austin Che (a graduate student working with both Endy and Knight) in a Cambridge restaurant

in MIT's neighboring Technology Square. Che is a quiet yet sharp-eyed man with a brutally sardonic wit. He arrived at MIT after completing an undergraduate degree in computer science at Stanford, and he retrained with Tom Knight toward a master's thesis that incorporated biology into his computer science training. The night of the dinner, he was two years into his PhD research. Conversation again turned to the viral plaques languishing in Endy's laboratory. Between appetizers and the main course, Endy posed the problem to me as a question: "Is there an environment that would naturally give rise to T7.1?" The question felt like a test. It tangled with definitions of natural and artificial, evolution and design: the use of the verb "give rise" effectively erased the years of graduate student labor that went into synthesizing and rebuilding the viral genome. Che smirked; he clearly had heard Endy pose this question before.

After a beat, in which I thought back to his lecture the previous November, I answered, "Yes, it's called a synthetic biology lab," and Endy laughed approvingly: "That's exactly what I say when people pose the same question to me." As he put it in his lecture when a grad student interrupted him to ask the same question, "So in nature, right, this [wild-type] one probably is going to rock. . . . In my lab, this [chimeric] one's going to survive, and this [other] one isn't." Inserting themselves into evolutionary narratives, synthetic biologists here serve as both agents and participants in a grand evolutionary narrative, one that artificially selects on the basis not of adaptability but of comprehensibility.[48]

The "Other" Intelligent Design

A year after Endy's lecture, at 5 p.m. on a Wednesday I sat in my usual spot in the back of the reading room on the fifth floor of the old Koch building at MIT, sandwiched between two bookshelves overfilled with back issues of *Science*, *Nature*, and *Cell*. I was by then acclimated to the mood of Endy lab meetings, which did not stand on ceremony. Grad students streamed into the reading room in pairs from the open adjacent laboratory door, midconversation, toting laptops and snacks. The room had a relaxed and convivial air, more so than other biology and biological engineering labs I had observed at MIT. Each week, a different student chaired the meeting. Today, Jason Kelly had donned the hat and held the scepter that marked him as presiding over the next two hours of research reports. Each week a different student was also tasked with providing snacks; Ilya Sytchev, a

computer programmer developing a semantic web ontology for standardized biological parts, arrived a little after 5 p.m. laden with home-cooked foods prepared by his mother—salmon pirok, apple tarts, and fried dough shaped like roosters. Graduate students and undergraduate researchers appreciatively filled their paper plates while the lab technician made brief announcements. She lured students to upcoming safety training by telling gruesome stories of centrifuge rotors failing.

Endy arrived fifteen minutes late. He was giddy with news about a lecture he had just attended, in which he described seeing "kickass pictures" of magnetotactic bacteria.[49] He dubbed the research to the assembled graduate and undergraduate students as "just *soooo* fucking cool" and brainstormed how magnetotaxis could be implemented to serve functional ends in engineered organisms. Students next discussed whether after the lab meeting they should adjourn to watch a movie in the lounge down the hall, where a broken centrifuge was well stocked with beer. Chalk it up to disciplinary dispositions—feeling themselves to be at the forefront of a new approach to biological engineering, members of the Synthetic Biology Working Group cast themselves as firebrands and subversives, and one of the first things they did was dispose of many of the formalities and hierarchies of academic biological research. Over the next hour, as students reported on their week's work, they cracked jokes and interrupted one another. They believed they were on the cusp of something important, and their enthusiasm was infectious.

Imagine my surprise, then, when the atmosphere suddenly turned formal, even icy. Halfway through the meeting, a first-year graduate student in Computational and Systems Biology anxiously delivered his first presentation to the lab. Despite clearly having carefully prepared his slides and talking points, he stumbled over his words and was red-faced and uncomfortable at the front of the room. He made the unfortunate mistake of beginning a sentence: "What Drew did after he created this [bacteriophage T7.1] . . ." The room, which moments earlier had been abuzz with questions and side conversations, fell abruptly silent. Seconds passed. Endy spoke first, in measured tones. "We don't *create* biology; we *construct* it." The student blushed deeply from his shirt collar to his hairline, stammering after Endy, "Umm, right, right, *constructed.*"

In the ensuing silence, I sympathized with the grad student, having earlier stumbled into a similar semantic snafu in an e-mail exchange with Reshma Shetty, a graduate student figuring out how to use DNA promoters and terminators as biological equivalents of logic gates in electronic

circuitry. Shetty was a grounded and serious grad student who arrived at MIT to study with Knight after she finished a degree from the University of Utah. We met a few weeks after I began studying in the lab, as she had been traveling that summer introducing synthetic biology to undergraduate students in South Asia. After observing an undergraduate bioengineering teaching lab in which she served as teaching assistant, I had e-mailed her to double-check my understanding of the science behind the lab protocol. In my e-mail, I wrote, "The enzymatic activity of beta-galactosidase creates the pigment in those cells not exposed to light." In her response, Shetty redressed my language: "We like to avoid using the word 'create' in synthetic biology because of its god-like connotations and because it is not scientifically accurate. I would say that beta-galactosidase *generates* the pigment from a substrate instead of *creates*."[50] Clearly the callow graduate student and I had hit the same nerve, but why, I wondered, was it so important to synthetic biologists to describe their work as "constructing" rather than "creating"? The trouble, I realized, had by then been brewing for over a year.

While natural philosophers, Darwinians, and evo-devo (evolutionary developmental) biologists regularly invoked the divine in biological design, they were certainly not the only ones to do so. Religious proponents of creationism and intelligent design and supporters of evolutionary theory waged contests in American courtrooms, school boards, and congressional committees throughout the twentieth century. The Scopes trial upheld Tennessee's Butler Act in 1925, declaring it illegal for state-funded schools to teach evolutionary theory. Dozens of court cases have made similar rulings in other states and school districts. While creation science (a term coined in 1970 to rebrand "flood geology") holds that Earth is six thousand years old and that God created Earth and all life on it in six days, intelligent design (ID) proponents widely believe that while Earth is ancient, the complexity of life establishes the presence of a divine agent and planner.

Though the US Supreme Court ruled in 1987's *Edwards v. Aguillard* that teaching creationism was unconstitutional, it left open the possibility of teaching alternative scientific theories, and so intelligent design advocates repackaged intelligent design as a scientific theory. Republican politicians in the 1980s and 1990s, including Ronald Reagan in his presidential run, promoted teaching creationism and ID. A 1993 Gallup poll reported that 58 percent of Americans supported teaching creationism in public schools, while only 11 percent of Americans believed in evolutionary theory.[51] This fraught history suffused the way MIT synthetic biologists talked about creating and designing life.

In 2005 and 2006 ID had begun to inflect and infect synthetic biologists' thinking about their own design projects. MIT graduate students described synthetic biology as "the other intelligent design." Shetty proposed in all seriousness at a time when synthetic biology lacked a dedicated peer-reviewed journal that such a journal be titled the *Journal of Intelligent Design*. Thinking about synthetic biology as "the other intelligent design" put synthetic biologists in the awkward, if to them sometimes flattering, position of having to think of themselves as life's Mechanics and Watchmakers.

In December 2005 the US District Court for the Middle District of Pennsylvania ruled in *Kitzmiller v. Dover Area School District* that teaching ID in US public schools violates the First Amendment of the Constitution. A volley of e-mails lit up the synthetic biology LISTSERV that afternoon and the next day. Tom Knight forwarded the 139-page court opinion to the entire list, and Endy praised the language of the judge's decision. Che responded more circumspectly, asking whether a defeat for ID was indeed a victory for synthetic biologists: "Aren't we trying to show that it is possible to intelligently design the biological world? Will we ever see synthetic biology be used as evidence for intelligent design?" He ended his e-mail by suggesting that if synthetic biologists were successful in their project, they might unwittingly lend credence to creationists.[52]

Che, noticing that my anthropological interest was piqued whenever synthetic biologists brought up design, had started forwarding articles to me. He found one that had appeared on a pro-creationism blog in November 2005, the same month that synthetic biology landed on the cover of *Nature* with the provocative line "life is what we make it." In the blog post, an ID advocate drew analogies between synthetic biology and Paley's "old Divine Watchmaker."[53]

The author cited an article published by David Sprinzak and Michael Elowitz, synthetic biologists at Caltech who built a series of genetic "switches" in bacteria. These "switches," when combined to form a "circuit," caused protein expression in the bacteria to oscillate cyclically, so that the bacteria fluoresce either yellow or green. Sprinzak and Elowitz describe their engineered system as a "synthetic genetic clock" and conclude their article poetically: "perhaps at this stage one can learn more by putting together a simple, if inaccurate pendulum clock than one can by disassembling the finest Swiss timepiece."[54] Again, life, for these authors, is best understood not by its deconstruction and decomposition but by its assembly.

The ID blogger quoted this particular paper at length, taking this passage as one of many examples of a "design theme" that is "ubiquitous [in

the *Nature* special issue], while references to evolution were merely assumed and seemed forced." What the blogger did not realize was that Endy and his students took design to be a better approach to organizing living systems than evolution, which they parsed as *unintelligently* designed—hardly evidence of the Godhead. Remember, for example, Endy's comparison of evolution to a "tyrant." He used similar language in an interview with the *Bulletin of Atomic Scientists*, in which he grumbled, "Intelligent design, from an engineer's perspective, would have documentation, and we don't see that."[55] By this he meant that an "intelligent" approach, from the standpoint of an engineer, would require that every artifact come with its own user's manual explaining how it works, which is notably absent from living organisms—T7 did not evolve toward human comprehensibility. ID proponents, on the other hand, read synthetic biologists' use of "design" altogether differently—they take it not as a rejection of evolution as aesthetically and practically insufficient but rather as a refutation of evolution as a mechanism of biological change in the first place.[56]

Bruno Latour notes the ubiquity of "design" in contemporary life, as it "has been extended from the details of daily objects to cities, landscapes, nations, cultures, bodies, genes, and . . . to nature itself—which is in great need of being re-designed."[57] Asking what design now means, Latour claims that "designing" holds a middle ground between revolutionizing and modernizing. Designing is never creating, nor is it re-creating—it is not "construction, creation or . . . fabrication"[58]—because design always entails *redesign*. As such, "To design is never to create *ex nihilo*. It is amusing that creationists in America use the word 'intelligent design' as a rough substitute for 'God the Creator.' They don't seem to realize the tremendous abyss that exists between creating and designing."[59]

In line with Latour's insight about the gulf between design and creation, synthetic biologists sometimes use "design" to denote engineering work operating halfway between revolution and modernization—that is, improvement through redesign. Yet at other times, they use it precisely *because* of the creative semantic ambiguity in "intelligent design." It allows them to slip between thinking of themselves as designers and as creators, despite the distance between design and creation.

"We Shall Be as Gods"

At its origins, members of the Synthetic Biology Working Group compared themselves to God. In a 2002 seminar at MIT's Computer Science

and Artificial Intelligence Laboratory (CSAIL), Che posed the question, "Did God create us so we could become God ourselves?" Yet by 2006, synthetic biology had started coming under fire—from the popular press, citizen action groups, and other scientists—who accused synthetic biologists of wanting to "play God." No wonder everyone in the working group had begun shying away from using the word "create." A 2007 *Nature* editorial quoted a representative of ETC Group, a Canadian civil action organization that publicly critiques synthetic biology, as saying, "For the first time, God has competition." The *Nature* author even described the quotation as "justif[ied]."[60] The verb "create" had turned inflammatory, even as it added to the field's hype by suggesting that synthetic biology was indeed powerful enough to give God a run for his money.[61]

Further, MIT synthetic biologists leveraged the create/construct distinction to distance what they were doing from the "synthetic genomics" of Craig Venter, the *enfant terrible* of the HGP, who had lately begun work in the J. Craig Venter Institute (JCVI) to build an entirely synthetic organism (i.e., a cell whose genome was manufactured using DNA synthesis).[62] In response to a question posted on the synthetic biology LISTSERV about the semantic difference between synthetic biology and synthetic genomics, Endy replied: "synthetic biology = let's make biology easy to engineer + understand how the natural living world works along the way // synthetic genomics = let's construct genomes + talk about playing god." When an article appeared in *Newsweek* (June 3, 2007) about Venter's efforts to engineer a "synthetic" cell, the cover portrayed Venter looking presciently into the distance, his face illuminated in an ethereal glow. The headline announced: "Playing God: How Scientists Are Creating Life Forms or 'Biodevices' That Could Change the World." By all appearances, God, it turned out, was indeed a powerful white man with a beard. Tom Knight brushed off the press as merely "Venter playing god again." The comparisons of Venter to a latter-day in vitro God would only multiply when in 2010 he announced he had engineered an "entirely synthetic" bacterium. A *Time* article reporting on this feat waxed biblical: "In the beginning, Craig Venter 'created life' in a lab."[63]

The watchdog groups and protests against synthetic biology also focused on life's manufacture as edging dangerously close to God's territory. Journalists often ask Venter and his colleagues at the JCVI whether building synthetic organisms is tantamount to "playing god," to which research scientist Hamilton "Ham" Smith regularly responds, "We don't play."[64] In 2007 ETC Group issued a press release that nicknamed one of Venter's synthetic organisms the "Original Syn." One of the ETC Group's

self-published reports on synthetic biology, which they distributed at a bioengineering conference I attended, bore a cover depicting a modified version of Michelangelo's *Creation of Adam*, in which Adam's hand is holding a Lego, which he is placing atop an assembled Lego model of the double helix (fig. 1.1). An article in the *Berkeley Science Review* reported on the work of Jay Keasling and the Synthetic Biology Department of the Lawrence Berkeley National Laboratory (titled "Intelligent Design: Playing with the Building Blocks of Biology"). It was similarly illustrated with color reproductions of Michelangelo's frescoes from the Sistine Chapel, including *Fall of Man* and *Expulsion from the Garden of Eden*. Half a page was devoted to another modified version of *Creation of Adam*, this time depicting God stretching out his hand to bestow a pipette on Adam (fig. 1.2).[65]

Such iconography functions on several levels. It renders ambiguous which figure represents the synthetic biologist: is it the Godhead or the human? And if the human, then are synthetic biologists beneficiaries of godlike powers, symbolized by pipettes and Lego double helices, or are they about to pay the price of their overreach? In these images, stories about creation and knowledge are entangled with warnings about hubris, impulse, and human recklessness. Origin stories are always also morality tales.[66]

While Endy made light of such controversies by pinning to the wall of his office an illustration of Adam and Eve standing nude before the Tree of Knowledge, others were more eager to distance the Synthetic Biology Working Group from any allusions to "playing God," whether leveled by fellow researchers, protesters, or journalists. Toward that end, the working group commissioned Laurie Zoloth, a bioethicist from Northwestern University, to comment upon and analyze the ethical issues raised by synthetic biology. In preparation for the second annual meeting on synthetic biology, she forwarded a list of questions to researchers at MIT who had convened a working group to hash out such issues. Presenting her thoughts to the "Synthetic Society" assembled in an MIT conference room in 2006, she offered one bullet point for our further discussion, titled "We will be as gods." The quotation references the book of Genesis, in which the serpent cajoles Eve to eat the fruit of the Tree of Knowledge: "on the day ye eat thereof, then your eyes shall be opened, and ye shall be as gods, knowing good and evil."[67] If synthetic biologists were worrying over the theological implications of their work, they were doing so from squarely within a Judeo-Christian tradition (although many of the graduate students at MIT

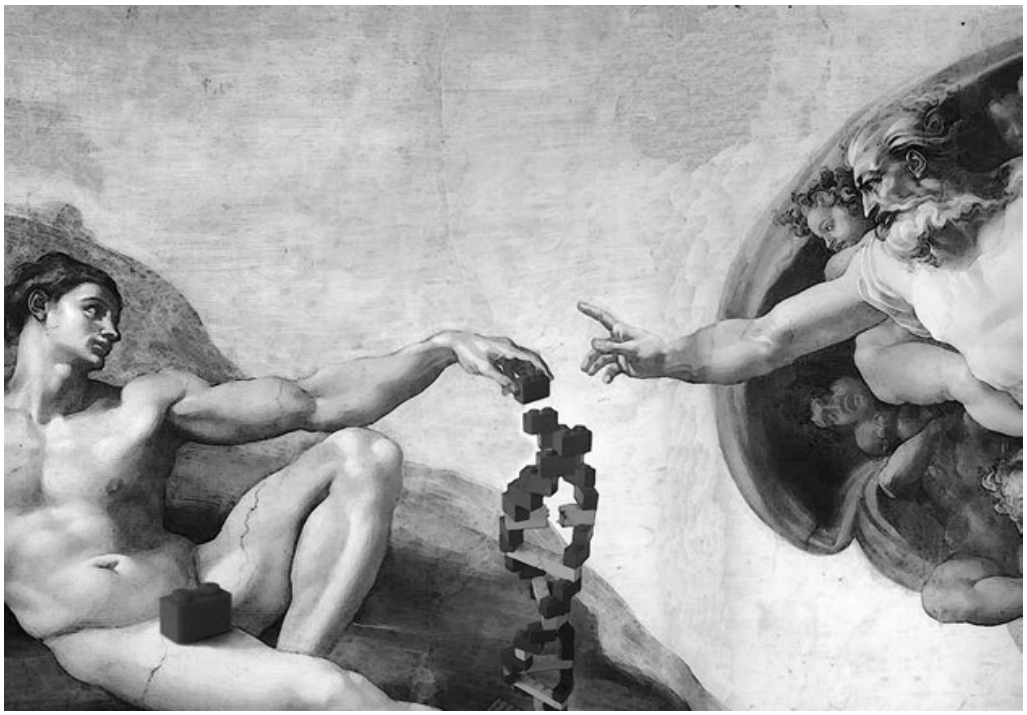

FIGURE 1.1. Cover image of ETC Group, "Extreme Genetic Engineering: An Introduction to Synthetic Biology," January 2007. Courtesy of ETC Group and Reymond Pagé.

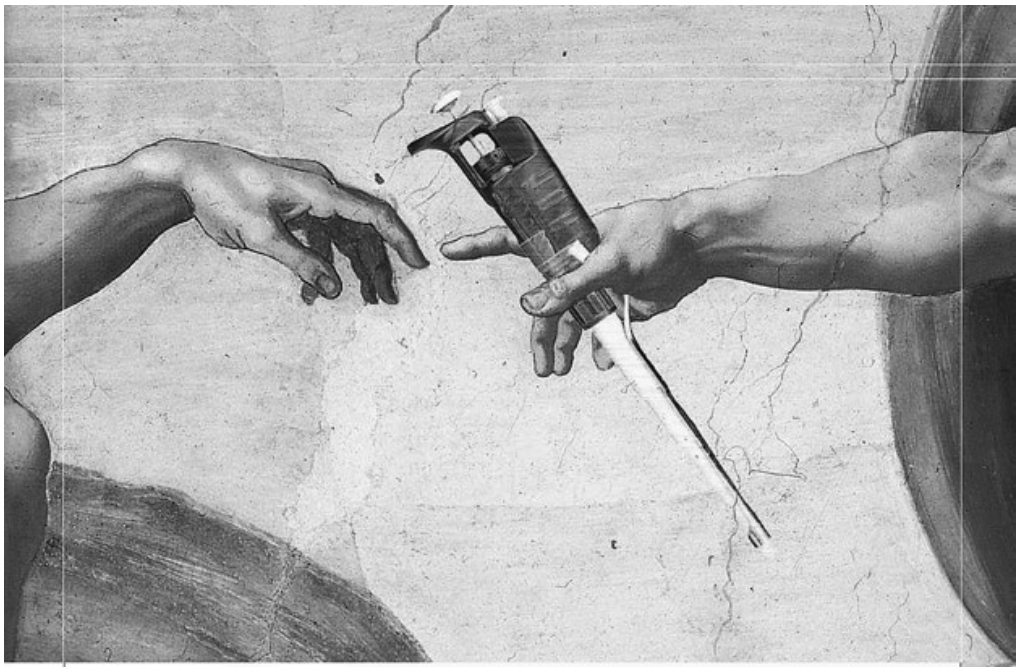

FIGURE 1.2. Michelangelo's *Creation of Adam*, modified for synthetic biology. Image from Alan Moses, "Intelligent Design: Playing with the Building Blocks of Biology," *Berkeley Science Review* 5, no. 1 (2005). Courtesy of Tracy Powell / *Berkeley Science Review*.

were not raised in Jewish or Christian households, and many identified as unreligious, secular, or atheist). Such ethical concerns would have been articulated and illustrated differently if they had been rooted in, for example, Hindu or Buddhist cosmologies.[68]

In his ethnography of Artificial Life, Stefan Helmreich argues: "In their story of how evolution has hijacked humans' working energies to engineer the next stage of evolution, Artificial Life researchers only occasionally notice that this narrative positions them as a new elite. When they speak of humanity, they are speaking of a small fraction of humanity, and they are explicitly locating themselves as the vanguard force of evolution."[69] Joining acts of creation to partaking of forbidden knowledge—making life to understanding life—Judeo-Christian imagery casts synthetic biologists as acting outside the "natural order," even as it also allows them to imagine themselves simultaneously as either a "vanguard force of evolution" or explicitly invested with godlike powers (think of Endy's declaration that his laboratory is the "artificial living world that [he] completely control[s]," in which T7.1 is allowed to flourish).

Other synthetic biologists were more than willing to accept the mantle of "intelligent designer," with all its theological connotations. Harvard synthetic biologist George Church described his thinking on the matter, "We're acting as engineers, possibly as intelligent designers. The religiously inclined would not put humans in the same league with the 'Intelligent Designer,' or God. . . . We, as intelligent designers, are not in the same league as the 'Intelligent Design' forces that started the whole shebang. . . . We're not even designing the basic idea of life; we're just manipulating it."[70] Yet in the same lecture, he pushed the ID metaphor further, leveraging it to reflect on the work of synthetic biologists as a continuation of natural selection, viewing his fellow scientists as objects and agents of natural selection: "We seem to be 'designed' by nature to be good designers. In that sense we're part of some huge recursive design, but we're not doing something we're not designed (and microevolved) to do. Engineering is one of the main things that humans do well. . . . It's just what we do and it's *natural*."[71]

Church's comments, which equate evolution with design and nature with artifice, elicited this response from popular historian and essayist George Dyson, who asked laconically, "are we learning to manipulate life or is life learning to manipulate us?" He speculated that perhaps synthetic biologists have been parasitized by "code-consuming and code-spewing microprocessors" that allow them to "help" life self-replicate into more evolved forms.[72]

Science studies scholar Richard Doyle has argued that human capacities, such as rhetoric, consciousness, and technology, sculpt biological evolution, just as humans are themselves imbricated in an ecological "involution" in which other species also exert forces, impulses, and desires that torque evolution and constitute living form.[73] Church and Dyson's staging of synthetic biologists as the unwitting vectors of biological evolution unseats synthetic biologists as creators, engineers, or designers. They suggest instead that T7 had designs on Endy and his students, rather than the other way around.

Natural, Unnatural, Supernatural

The various evolutionary tales MIT synthetic biologists tell themselves about themselves accomplish a neat rhetorical sleight of hand: synthetic biologists appear as (1) self-directed engineers who manipulate and "design" life without creating it; (2) biological beings who are fulfilling their evolutionary destiny by doing what they were "designed" by nature to do anyway, which is make "better" versions of life; and (3) "intelligent designers" with godlike powers to shape and modify life itself. Or perhaps the phage had infected them, and they were hosts in its next self-directed iteration of its own genome. Squint and tilt your head just so, and the story changes—it's all a matter of perspective.

Tracking the convergence of biological making and biological knowing as it was pursued by synthetic biologists at MIT in 2005 and 2006, especially around the T7.1 project, reveals that "better" is an ambiguous term. It refers to both biology that *functions* better (that does the things MIT synthetic biologists want it to do) and biology that is more *comprehensible* to them (systems that are easier to understand). For these synthetic biologists, a "well-designed" living thing is one that is optimized for human understanding, and most evolved organisms do not pass the biologists' comprehensibility test. The rationale for such thinking is the circularity that inheres in the convergence of knowing and making. Composition, for synthetic biologists, furthers biological understanding, but sometimes composition is also guided by understanding as *itself* a design principle.

Turning the equation life = information inside out, life in the early twenty-first century became *information's opposite*, and T7.1 was demonstrative of that fact: more noise than signal, more complexity than simplicity, more randomness than design. The computer virus is already imagined, in computer science circles, to be bad or "junk" code. The sorts of viruses

made of genetic material and protein capsids are now imagined to also be bits of bad code.[74] They need to be recoded, refactored, and salvaged—to rescue life from its own proliferating misinformation. When making new biological things becomes the path by which biology is best understood, then understandable biological things get preferentially made. Exegesis becomes a selective evolutionary force.