Growing explanations

Historical perspectives on recent science

M. Norton Wise, Editor

Duke University Press Durham and London 2004

10 The word for world is computer: simulating second natures in artificial life

Stefan Helmreich

In a video promoting the Santa Fe Institute, biologist Thomas Ray introduces us to his computer simulation of evolution, Tierra. Situated in the midst of a *Star Trek*–like set, he narrates us into the world shimmering beyond his computer screen. Our gaze, guided by the camera's eye, passes through the cathode ray looking glass and is catapulted into a dreamlike fantasy flight over the rich "ecosystems" of an "artificial world," where "populations" of "digital organisms" vie to "self-replicate." Ray provides a voice-over in the style of a nature show host:

> Now we're going into the computer which is where the creatures actually live, and we can see the environment that they inhabit. This is the central processing unit that provides their energy, the CPU, like the sun. And now we're going to fly over the memory which provides the space that the creatures inhabit. . . . . In the real world, plants cover the surface of the land. In the digital world, digital organisms fill the memory space.[1]

For Ray and many others working in the field of Artificial Life, computer programs that self-replicate can be seen as new forms of life, forms that can be sparked into existence by scientists who view the computer as an alternative universe. As Ray tells us in his video narration, "Tierra is Spanish for Earth. I called it that because I thought of it as a different world that I could inoculate with life. It's not the same world we live in. It's not the world of the chemistry of carbon and hydrogen. It's a different universe. It's the chemistry of bits and bytes."[2]

How have computers become different universes? How have practitioners of Artificial Life, and of the sciences of complexity more generally, managed to transubstantiate computer simulations into epistemological and ontological spaces capable of harboring "life"? There are many answers. Some come from historians and philosophers of science, who have alerted us to how theory and experiment fold into one another in the era of computer modeling, positioning simulations as halfway houses between the real and the imaginary.[3] Others come from simulation scientists themselves, who maintain that the universe is a mammoth computer, a conviction that underwrites the idea that computers are kinds of universes.[4] In an age when the essence of vitality is often compressed into "genes" figured as equivalent to "programs,"[5] it is not surprising that computational universes can support "life."

But these historical, philosophical, and internalist accounts of simulation science must be supplemented by attention to the cultural contexts within which scientists have worked. Drawing on anthropological fieldwork I conducted among Artificial Life scientists at the Santa Fe Institute for the Sciences of Complexity in Santa Fe, New Mexico, from 1993 to 1994, I maintain that simulations "come to life" when elements from complex systems theory and computer science combine with elements from Judeo-Christian cosmology, science fiction, an American frontier imagination, a calculative rationality that is often coded masculine, and a visual common sense committed to one-to-one mappings between representation and reality. Welded together, these elements persuade Artificial Life scientists that computers can be considered their own worlds, a belief that may foreshadow new ways of thinking about nature in the age of simulation. Downloading nature into computers may offer a new court of appeal for those who would point to nature as a source of lessons about what is inevitable, given, and even rationally designed.[6] On the other hand, bitmapping nature *in silico* may make obvious the role of human interpretation in constructing any nature.

The title of this essay puns on science fiction author Ursula Le Guin's *The Word for World Is Forest*, a tale about a forest-dwelling people who use their dreams as resources for guidance in the waking world.[7] The Le Guin story is a romantic one that imagines a people existing outside the stream of history, so it may seem odd to tweak its title to speak of late-twentieth-century scientists who exist largely within a post–Judeo Christian, European-American cultural context. There is, however, a romantic incandescence to the project of Artificial Life, to practitioners' claims that they can mime nature technologically, that leads me to discern similarities between Artificial Life researchers and Le Guin's mythical Athsheans. Artificial Life workers, like Athsheans, resource a set of culturally specific dreams—of transcendence, discovery, creation, colonization—to manufacture the worlds, the second natures, they interpret. I take the concept of "second nature" from a lineage that begins with Hegel, who "taught us to see a difference between 'first nature'—the given, pristine, edenic nature of physical and biotic processes, laws, and forms—and 'second nature.' Second

nature comprises the rule-driven social world of society and the market, culture and the city, in which social change is driven by a parallel set of socially imposed laws."[8] Computer worlds are second natures in the sense that they are human constructions but also in that they are modeled after first nature. The artificial worlds of Artificial Life are "second natures" in still another sense: they not only ape first nature but seek to replace it, to succeed it as a resource for scientific knowledge. Before traveling into these second natures, background on Artificial Life will be helpful, as will a soirée into Thomas Ray's Tierra, a popular artificial life world.

Artificial life and Tierra

Artificial Life is dedicated to the computer simulation—or, more grandly, synthesis—of biological systems. It emerged in the late 1980s, growing out of conversations among computer scientists, biologists, and physicists. Artificial Life researchers envision their project as a reinvigorated theoretical biology and as an initially more modest but eventually more ambitious enterprise than Artificial Intelligence. Where Artificial Intelligence attempted to model the mind, Artificial Life hopes to capture on computers the formal properties of organisms, populations, and ecosystems—the life processes that support the evolution of such things as minds. The intellectual charter for this practice is summarized in Artificial Life scientist Christopher Langton's declaration that life "is a property of the *organization* of matter, rather than a property of matter itself."[9] Some have found this claim so compelling that they believe real artificial life-forms can exist in computers, and they hope the creation of computer life-forms will expand biology's purview to include not just life-as-we-know-it, but also life-as-it-could-be.[10] Though Artificial Life research is carried out at many places, it has been most popularly associated with the Santa Fe Institute (SFI), a gathering ground for an international community of scientists interested in computer modeling of nonlinear dynamics in physical, biological, and social systems.

Ray's Tierra exemplifies the approach of the sciences of complexity, setting computational entities into interactions which result in nonlinear, emergent dynamics. It also offers up the most ambitious claim of Artificial Life, namely that propagating information structures can count as real life in a virtual world. Tierra is a computer program that serves as an environment within which short assembly language programs "resident" in random-access memory (RAM) can replicate based on how efficiently they make use of central processing unit (CPU) time and memory space. When the program is set in motion, an array of "digital organisms" emerge, descending in a cascade from an ancestral self-replicating program inoculated into the system by the programmer at the beginning. Only the "fittest"—those which replicate most quickly, those which pirate the replicative subroutines of other programs—survive. According to Ray, Tierra is not just a *model* of evolution. It is "an *instantiation* of evolution by natural selection in the computational medium."[11] Ray's definition of evolution allows him to enfranchise Tierran organisms into the dominion of life: "I would consider a system to be living if it is self-replicating, and capable of open-ended evolution."[12] Indeed, for Ray, the parallels are many between organic and computer life:

> Organic life is viewed as utilizing energy, mostly derived from the sun, to organize matter. By analogy, digital life can be viewed as using CPU (central processing unit) time, to organize memory. Organic life evolves through natural selection as individuals compete for resources (light, food, space, etc.) such that genotypes which leave the most descendants increase in frequency. Digital life evolves through the same process, as replicating algorithms compete for CPU time and memory space, and organisms evolve strategies to exploit one another.[13]

The digital life in Tierra consists of assembler language programs. The code of each creature occupies some block of memory and reproduces by copying its code into another block. Tierran creatures are nothing more than short programs that code for self-replication.

Ray has claimed that in his observations of Tierra, he has seen the emergence of evolutionary dynamics, including the rise of digital organisms that parasitize others. Ray argues that getting to know the alternative biology in Tierra can help biologists expand their theories about what is necessary and what contingent in biological systems. There is of course a paradox here, one Ray recognizes but finesses.[14] This is that the system must be engineered with basic evolutionary ideas in mind (scarcity of resources, the idea that organisms can only be one place at one time, etc.), but must *also* be general enough to allow new, alternative evolutionary phenomena to emerge. One researcher I interviewed said that deciding which lifelike notions to include as basic was "where the 'art' in Artificial Life comes in." The programmer-experimenter must mix intuitions about where science is already correct with programming decisions general enough to allow new phenomena to grow. Ray describes the process this way: "We must derive inspiration from observations of organic life, but we must never lose sight of the fact that the new instantiation is not organic and may differ in many fundamental ways."[15] Ray sees a new nature inside the computer but has in fact already engineered this nature to have features with which he is familiar. It is these features that render the

program legible as a simulation of evolution at all. As N. Katherine Hayles writes of Tierra, "The interpretation of the program through biological analogies is so deeply bound up with its logic and structure that it would be virtually impossible to understand the program without them. These analogies are not like icing on a cake, which you can scrape off and still have the cake. . . . . The biological analogies do not embellish the story; in an important sense, they constitute it."[16] I have explored these biological analogies in depth elsewhere.[17] Here, I focus on scientists' foundational belief that computers count as alternative worlds or universes.

Computers as worlds or universes

For many people I interviewed, a *world* or *universe* could be understood as a self-consistent, complete, and closed system governed by low-level laws that supported higher-level phenomena which, while dependent on these elementary laws, could not be simply derived from them (here *low* refers to physics and *high* to chemical, biological, and social phenomena). Put into the language of the sciences of complexity, a world or universe is a dynamical system capable of generating surprising emergent properties. If we accept this definition, computational systems reasonably count as worlds or universes. This is the view taken by scientist David Hiebeler in an article titled "Implications of Creation," where he writes, "Computers provide the novel idea of simple, self-contained 'artificial universes,' where we can create systems containing a large number of simple, interacting components. Each system has its own dynamics or 'laws of physics'; after specifying those laws, we set the system into motion and observe its behavior."[18] One researcher drew the similarity between worlds and universes and computer simulations for me rather tightly: "Worlds and universes are complex processes, based on fixed, low-level principles. Computer simulations are complex processes, based on fixed, low-level principles." Computer simulations, he concluded, can therefore be worlds or universes. How have pronouncements like these become possible? A glance at the history of computer modeling offers preliminary answers.

Computers have been used for quite a while to simulate aspects of the world we inhabit. Los Alamos scientists used them early on to simulate nuclear reactions, and the American military has also used them to model nuclear war scenarios. Simplified computer models of the world became a component in Artificial Intelligence research in the early 1970s, as scientists attempted to provide programs with representations of the world about which the programs were to make reasoned decisions.[19] These representations of aspects of the world came to be called microworlds. Paul Edwards has argued that computer microworlds were also "closed worlds," and were manufactured as such by the military, which favored computer simulations of conflict that simplified international relations into formal game scenarios. Edwards has argued that the military origins of computer modeling set the stage for understanding computers as surrogate worlds, and has written that the image of computer as world has served as a powerful attraction for rationalist epistemologies:

> Every microworld has a unique ontological and epistemological structure, simpler than those of the world it represents. Computer programs are thus intellectually useful and emotionally appealing for the same reason: they create worlds without irrelevant or unwanted complexity. . . . The programmer is omnipotent but not necessarily omniscient, since highly complex programs can generate totally unanticipated results. . . . This makes the microworld exceptionally interesting as an imaginative domain, a make-believe world with powers of its own.[20]

Edwards captures the textures of computing that have attracted many people to fields like Artificial Life. He maintains that the microworlds of computers have been appealing particularly to many men, to whom "power is an icon of identity and an index of success. . . . With a 'hard' formalized system of known rules, operating within the separate reality of a microworld, one can have complexity and security at once: the score can always be calculated; sudden changes of emotional origin do not occur. Things make sense in a way human intersubjectivity cannot."[21] Following Edwards, I suggest that rational, calculative masculinity has been one resource that has helped transform computers into worlds for many Artificial Life scientists. In the late seventies and early eighties, many of those men who came to be involved in Artificial Life purchased PCs as personal rites of passage, rites they narrated to me as accounts of mastery and self-actualization through the taming of machinery (some 90 percent of scientists in Artificial Life are men). Several told me their wives would complain when they stayed up all night programming, "lost in their own worlds." One said of his spouse, "I think she is jealous of the computer." Another self-consciously reflected that he built simulations because he wanted to get away from a world that felt difficult to control. He told me, "I didn't like chemistry because it involved measuring the real world, and I've never been a big fan of the real world. I'd much rather make my own world on the computer and then measure that." Of course, to boil down to masculinity people's perceptions of computers as worlds is overly simple. Masculinity is by no means monolithic, and gender is a structure of dispositions that, while often bundled together in people referred to as men or women, are

not all or ever the exclusive property of such persons. One woman researcher I spoke with well expressed what some might see as a typically masculine motivation for using computers: "Having the world at your control is something that has a lot of appeal. You can figure the whole thing, with the parameters you want. It gives you this sense that everything's fine and under control."

Of course, in many Artificial Life worlds, everything is not under control. Many researchers hope that their worlds will surprise them. In Sherry Turkle's terms, an aesthetic of "hard mastery," in which programmers seek to comprehend and structure programs, is giving way to one of "soft mastery," in which people encounter and appreciate computers as dynamically changing systems only partially available to complete understanding.[22] The masculinist imperatives of standard AI—rationality, objectivity, disinterestedness, and control—have yielded to what are commonly characterized as more "ecological" programming techniques. Turkle argues that new modes of computing may be more appealing to women, who have stereotypically been trained to value negotiation, relationship, and attachment. But this is only part of the story. Many men in Artificial Life see themselves refiguring their masculinity as they work with modes of computation that mimic nature. In a conversation with two younger heterosexual men about how their gendered subjectivity might be implicated in their science, they told me Artificial Life allowed them to express and work with a side of themselves that was more intuitive, perhaps more stereotypically "feminine," even "Gaian." This way of putting things shores up the category of gender even as it purports to erode it, keeping "femininity" stable as a resource that men might mine to broaden their intellectual work. As Judith Genova notes, "Perhaps it is no accident that men become intuitive and holistic just at the time when computers can successfully simulate logical, analytic thought."[23] The ways gender is recoded in Artificial Life scientists' subjectivities troubles any simple attachment of Artificial Life aesthetics to masculinity, old or new, but it is nonetheless important to keep masculinity in view, especially when male researchers speak of themselves, as I will discuss later, as masculine gods "inoculating" computational matrices (often, "soups") with self-replicating "seed" programs.

The notion of microworld has largely been superseded by the "artificial world," signaling a shift from understanding computer worlds as toy worlds to seeing them as realities in their own right. How do people articulate this belief that computers contain real worlds? Examining what I will tag "scientific warrants" provides a view of how many Artificial Life researchers I interviewed reflected on this question.

Scientific warrants for construing computers as worlds

I want to back up a bit more into history to revisit high speed computing and simulation as they developed at Los Alamos during and after World War II. Los Alamos is important for the Artificial Life tale because senior fellows at the lab created SFI, and much common sense about computers comes directly from this institution.

Peter Galison has discussed how computer simulations were employed by nuclear weapons researchers at Los Alamos and elsewhere for problems too complex to solve analytically and impossible to investigate experimentally. Computer simulations of microphysical events like nuclear reactions came to occupy a liminal place between theory and experiment. On the one hand, they resembled theory because they set into motion processes of symbolic manipulation. On the other hand, they resembled experiments because they exhibited stable results, replicability, and amenability to error-analysis procedures. "Data" generated by simulations could be given the same epistemic status as data from "real" experiments.[24] On a deeper level, the simulations in question—those using pseudorandom numbers as starting points for the emulation of physical processes—were seen to share a "fundamental affinity" with "the statistical underpinnings of the world itself."[25] As Galison notes, "The computer began as a 'tool'—an object for the manipulation of machines, objects, and equations. But bit by bit (byte by byte), computer designers deconstructed the notion of a tool itself as the computer came to stand not for a tool, but for nature itself."[26] Galison claims that Monte Carlo simulations, as these were called, were assimilated to experiment in part because the stochasticity embedded in them was seen as directly analogous to the stochastic processes that characterized microphysical nature. Theories could be tested with reference to an artificial reality that was just as good as the real thing, that was in fact itself a sort of alternative, artificial reality. Simulations could be stand-ins for experiment, but more boldly they could be seen as understudies for nature itself.

Computers as nonlinear and complex systems

Researchers in Artificial Life inherited this tradition of simulation. In my interviews, people gave me a more current take on the ontological similarities between worlds and computers: both worlds and computers are nonlinear dynamical systems. More, they imagined computer and natural systems as transforming information. Many complexity scientists hold that the universe is just a computer transforming information, and that computers, which do this so well, should on this definition be considered

universes or worlds. This belief allows Thomas Ray to write, "The computational medium of the digital computer is an informational universe of boolean logic, not a material one."[27] But matter need not be factored out entirely. Steen Rasmussen and others have insisted that matter is self-programmable, that the world we inhabit is really a computation instantiated in the pattern of matter that composes our universe.[28]

Cellular automata

Many in Artificial Life have been enamored of a mathematical formalism known as the cellular automaton (CA), which allows a programmer to specify rules for local interaction between "cells" on a lattice-like grid, specifications which then produce a variety of emergent patterns. States of cells change according to the states of their neighbors, and using CAs, a variety of simple systems can be simulated, including self-reproducing automata.[29] Because of the CA formulation's generality, virtually any process that can be algorithmically specified can be modeled. CAs thus support a sort of alternative universe capable of sustaining alternative realities. Langton writes that "the transition function for the automata constitutes a *local physics* for a simple, discrete space/time universe. The universe is updated by applying the local physics to each 'cell' of its structure over and over again."[30] Artificial Life researcher Andrew Wuensche writes that a CA may "be viewed as a logical universe with its own local physics, with [emergent structures] as artificial molecules, from which more complex [emergent structures] with the capacity for self-reproduction and other essential functions of biomolecules might emerge, leading to the possibility of life-like behaviour."[31] Some people I interviewed claimed that our universe might be thought of as a giant cellular automaton.[32] While I was at SFI, I overheard many jokes and serious comments about how this could be so. In 1994 one researcher wrote me in an e-mail: "Many years before the term 'Artificial Life' was coined by Langton I learned about cellular automata and von Neumann's research. . . . From that point on I tended to think of the physics of our universe as a 3-D cellular automaton (even though I know such models tend not to have gravity, other fields, distortions of space, quantum effects, etc.). I view myself as a pattern in a CA world—one in which motion is just an illusion."[33]

Many people studying Artificial Life at Santa Fe began experiments at home with CAs, and some were fascinated by the most popular of CA formulations, Conway's "Game of Life," in which the switching off and on of cells results in patterns that can look like shapes growing or traveling across the screen. One researcher told me in an e-mail interview, "By chance, my work in computers got me exposed, in a peripheral way, to

Cellular Automata (CA). What I like about CA is the very thing that makes them so unusual in the clockwork world of computers: they harbor the unexpected; emergent behavior that's not designed into them." CAs are compelling metaphors for thinking about complex emergent phenomena in part because they are visually surprising, and the consequences of low level rules are quite unpredictable.

The physical Church-Turing thesis

Because SFI is so focused on computation, many SFI scientists subscribe to versions of the physical Church-Turing thesis: the notion that any physical process can be thought of as a computation, and that therefore any physical process can be recreated in a computational medium. In the 1930s, mathematician Alan Turing proposed that any human cognitive process that could be described algorithmically could be translated into a sequence of zeroes and ones and could therefore be implemented on a computer. After it was shown that the lambda calculus (a recursive mathematical system that allows functions to act as objects of other functions) of logician Alonzo Church was equivalent in power to the Turing machine (itself equivalent to CAs), the Church-Turing thesis was formulated, stating that all reasonable computational processes are equivalent to discrete, digital models of computation. The physical Church-Turing thesis figures the universe as such a computational process, as a physical system that converts inputs, or initial conditions, into outputs, the system's final state.

All of these elements—ideas about computers as stochastic and nonlinear systems, formulas drawn from cellular automata theory, and the physical Church-Turing thesis—are scientific resources that Artificial Life researchers use to think of computers as ontologically like nature and hence capable of being worlds. The idea that the physical world is a computation is so prevalent that it affects the ways some people construct their intuitions about the physical world. As one Artificial Life researcher told me, "The universe is a computation of which I am a part. . . . It's the information patterns of things that make them important rather than anything else. . . . I'm perfectly comfortable . . . with the notion that we're running on some big simulator out there. It seems to me as good as anything."

Philosophical positions

While there are many scientific warrants for construing computers as worlds, the equation remains controversial. Some philosophers of computing have argued that computers are tools for manipulating symbols; the

fact that they can be systematically interpreted as worlds does not make them worlds. Langton told me of a conversation he had with philosopher Stevan Harnad on this topic. Harnad said he could imagine an artificial system that produced signs systematically interpretable as a world. As Harnad reconstructs his position in the journal *Artificial Life*,

> The virtual system could not capture the critical (indeed the essential) difference between real and virtual life, which is that the virtual system is and always will be just a dynamical implementation of an implementation-independent symbol system that is systematically interpretable as if it were alive. Like a highly realistic, indeed oracular book, but a book nonetheless, it consists only of symbols that are systematically construable (by us) as meaning a lot of true and accurate things, but without those meanings actually being in the symbol system.[34]

Harnad argues that virtual worlds and virtual life can no more be real worlds and life than simulated fires can make things burn.

Computationally inclined Artificial Life researchers have a response: things *can* be alive or on fire *with respect to* computer worlds. One researcher told me: " 'Life' can only be defined WITH RESPECT TO A PARTICULAR PHYSICS. A computer virus is almost as 'alive' as a real virus (not yet, but close) but only within the physics of the computer memory." This notion that computers can contain separate, closed worlds came up again and again, and was one of the rhetorical moves people used to grant simulations an ontology usually reserved for universes. One person told me that, with computer simulations, "we have something totally self-contained in the computer." Another argued for the distinctness of computational realities by saying that self-reproducing programs were "alive in there," but only "a model out here." He continued, "They're alive with respect to their own universe, their own rules. Wimpy, pitiful little life, but I can't rule it out."

But researchers in computational Artificial Life are not content simply claiming that computers contain symbolic or informational worlds. Some have been adamant about asserting the physicality or materiality of computers and have used this as a lever to claim that real artificial worlds and life can exist in the computer. Bruce MacLennan makes an argument that many Artificial Life workers have found compelling:

> I want to suggest that we think of computers as programmable mass-energy manipulators. The point is that the state of the computer is embodied in the distribution of real matter and energy, and that this matter and energy is redistributed under the control of the program.

> In effect, the program defines the laws of nature that hold within the computer. Suppose a program defines laws that permit (real!) mass-energy structures to form, stabilize, reproduce, and evolve in the computer. If these structures satisfy the formal conditions of life, then they are real life, not simulated life, since they are composed of real matter and energy. Thus the computer may be a real niche for real artificial life—not carbon based, but electron-based.[35]

This interpretation has pleased people fussy about the distinction between worlds and universes; here computers are figured as worlds that exist in the same universe as the familiar organic world we know. A computer simulation manipulates structures and patterns of real voltages and so is not purely "symbolic," though its symbolic character is important for how those real events take place.

But the fact of materiality does not solve the question of symbols. When MacLennan writes, "If these structures satisfy the formal conditions of life, then they are real life, not simulated life, since they are composed of real matter and energy," he not only retreats from the materiality he is trying to assert (by stating that what matters is form), but also ignores the fact that whatever the "formal conditions of life" are, they will be defined in language. Brian Cantwell Smith has argued that computers' very physical existence is completely enmeshed in our social and linguistic world, that the way disc drives, windows programs, file systems, and RAM caches work results from many scientific, cultural, and economic decisions.[36] To treat computers as entities that come to us straight from nature ignores the decisions that have produced them, that allow us to contemplate them as worlds. Material practices—of which language is one—have made and will make or unmake computers as worlds or as niches for artificial life. Langton's argument that computer programs that cannot be linguistically distinguished from known life-forms should be considered life—the position he took against philosopher Stevan Harnad—recognizes that language is an essential technology for materializing vitality. I would side with Langton against Harnad, though argue that Langton does not adequately recognize the specificity of his own use of a language that names *life* as a process that haunts both organic and electronic entities. As Richard Doyle points out in *On Beyond Living*, there is nothing about computers in themselves (their speed, capacity to set math in motion, informatic logic) that forces us to see them as homes for artificial life. Rather, Doyle notes, our ways of seeing and working with them are structured by a kind of "rhetorical software" that allows us to enliven them with narratives fished from the reservoirs of our culture. In the next sections, I write about the extrascientific or "cultural" resources researchers employ to animate artificial worlds, resources I

rhetorically separate from "science" because they are not called upon in official discourse about why computers are artificial worlds.

Cultural resources for constructing computers as worlds

Many Artificial Life researchers use *world* or *universe* as synonymous with *nature*, and Western science usually constructs *nature* as a system ordered by physical and chemical laws. Thomas Ray says that Tierra can be considered an artificial world because it has its own physics and chemistry whose rules produce a nature in the computer.[37] Ray writes that we must "understand and respect the *natural* form of the digital computer, to facilitate the process of evolution in generating forms that are adapted to the computational medium, and to let evolution find forms and processes that *naturally* exploit the possibilities inherent in the medium."[38] Following the logic of Tierra as alternative nature, a supporter of Ray said at one workshop, "I would argue that your work is empirical, not theoretical. You've built a new world and are doing empirical work in it." The creation of laws in the universe of the computer, Artificial Life researchers believe, is an important step toward evolving real virtual life. For Ray, the future for artificial life looks bright once we recognize that computers can be full-blown worlds:

> Until recently, life has been known as a state of matter, particularly combinations of the elements carbon, hydrogen, oxygen, nitrogen, and smaller quantities of many others. However, recent work in the field of AL has shown that the natural evolutionary process can proceed with great efficacy in other media, such as the informational medium of the digital computer. These new natural evolutions in artificial media are beginning to explore the possibilities inherent in the "physics and chemistry" of those media. They are organizing themselves and constructing self-generating complex systems. While these new living systems are still so young that they remain in their primordial state, it appears that they have embarked on the same kind of journey taken by life on earth and presumably have the potential to evolve levels of complexity that could lead to sentient and eventually intelligent beings.[39]

I've been following Paul Edwards in understanding computers as closed worlds, ordered and technically created as bounded conceptual spaces. Edwards writes that the alternative to the closed world has been not the open world, but the "green world": "The green world is an unbounded natural setting, such as a forest, meadow, or a glade. . . . . Green world drama thematizes the restoration of community and cosmic order through the transcendence of rationality, authority, convention, and technology."[40]

In the imagination and practice of Artificial Life scientists, the closed world comes together with the green world; computers are cultivated to contain worlds open with possibility, resistant to total rational explanation, and full of surprising (but law-governed) potential. Claus Emmeche's book *The Garden in the Machine* diagnoses this fusion of closed and green worlds in Artificial Life, this hoped-for coming together of the planned and the possible in the sphere of simulation.

Western creation stories

Definitions of the universe, worlds, or nature as law-governed resonate with conceptions specific to Western Judeo-Christian cosmology as it has been shaped in the wake of the scientific revolution; these definitions summon up images of a law-giving Creator, and recall pictures of the universe as a giant clockwork or as a book in need of careful reading and deciphering. Many of the people I interviewed were raised as Jews or Christians, but virtually all now count themselves as atheists, a belief system that did not prevent them, when speaking of artificial worlds, from relying on a host of Creationist mythologies, sometimes directly, sometimes channeled through the medium of science fiction. In one conversation, a researcher explicitly asked me "to think theologically for a moment" when trying to understand artificial worlds. He told me that there is a moment of creation when the programmer writes the formal rules that will govern the system. To buttress his arguments about why simulations might be considered worlds, one man appealed to the possibility that our universe might be just a cosmic simulation. He said, "If God up there turned off the simulator and then turned it back on again, we wouldn't know. So, that puts us in some kind of epistemologically inferior position, a lesser degree of reality than Him, since we can't do the reverse. And that would be true of the guys inside [the computer]."

Describing programmers as a genus of god was a frequent strategy among people with whom I spoke, and this was not just a playful way of speaking, but a move that granted programmers the epistemological authority to erase their own presence as the beings who gave their simulations meanings as worlds. This permitted programmers to have the same relation to their simulations as the god of monotheism has to His creation (most vividly in his Deist incarnation as a divine watchmaker). Both occupy a transcendent position, the position of the "unmoved mover." When I asked one researcher how he felt when he built simulations, he replied bluntly, "I feel like God. In fact, I am God to the universes I create. I am outside of the time/space in which those entities are embedded. I sustain their physics [through the use of the computer]." MacLennan's discussion

of the experimental use of artificial worlds relies on images of a god who creates and then dispassionately observes the world: "Because synthetic ethology creates the worlds it studies, every variable is under the control of the investigator. Further, the speed of the computer allows evolution to be observed across thousands of generations; we may create worlds, observe their evolution, and destroy them at will."[41] The use of this kind of God imagery allows Artificial Life researchers to disappear themselves from the scene and give their simulations what Hayles has called "ontological closure."[42] This desire to push to one side the human activity involved in making artificial worlds was in evidence at one Artificial Life conference, when Langton contended that some simulations have less human agency embedded in them than others. Many allow the programmer to be the agent of natural selection, but it is Ray's Tierra that Langton describes as "the system that went all the way," the system in which "we've removed the hand of God."[43] The God imagery allows programmers to alternately shape and observe their worlds, to minimize the importance of their own post-creation interventions, and to draw the boundaries between creation and tinkering strategically. God imagery also secures a sort of ultimate objectivity. As Ray puts it in one interview, "Even if my world gets as complex as the real world, I'm god. I'm omniscient."[44]

God imagery is ubiquitous in popular treatments of Artificial Life. An advertisement for SimEarth™, computer software that simulates global ecological dynamics, reads: "More than just a home computer game, SimEarth™ was developed with Professor James Lovelock, originator of the Gaia hypothesis, to give us all an opportunity to play god—from the safety and security of our own homes." Ad copy for SimLife™, a computer toy for experimenting with evolution of artificial organisms, reads: "Build your very own ecosystem from the ground up, and give life to creatures that defy the wildest of imaginations." The theological elements that make SimLife™ thinkable are apparent in a review of the product written by Chris Langton: "The role of the user in these games is not so much participant in the action, as is the case with most computer games, but rather as the reigning 'God' who designs the universe from the bottom up. . . . In SimLife, Maxis has essentially created a flight simulator that gives one a taste of what it would be like to be in the pilot's seat occupied by God."[45] Note the identification of God with a pilot in a flight simulator; this reminds us that the god we are supposed to have in mind is a god in heaven. This is a god who uses the tools of extraterrestrial technology to examine and create the world, and the satellitelike map given to the user of SimLife™ is a perfect tool for this floating panoptic entity.

The god after which Artificial Life researchers are imagined is a biblical god. And more, a masculine god. Ray names himself a god who "inoculates" the "soup" of Tierra with a single self-replicating "seed" "ancestor" program. Carol Delaney has argued that in cultures influenced by Judeo-Christian narratives of creation and procreation, to use the word "seed" to speak of the impetus of creation summons forth gendered images. In the creation tales of these traditions, God, imagined as masculine, sparks the formless matter of earth to life with a word, a kind of divine seed, the *logos spermatikos*.[46] Creation and procreation in these narratives is monogenetic, generated from one source, symbolically masculine. "Man" and "God" take after one another. The creation in Tierra—and note that *Tierra* means *soil* as well as *Earth* in Spanish—symbolically mimics the biblical story of creation. We might see in Tierra images of a symbolically "male programmer mating with a female program to create progeny whose biomorphic diversity surpasses the father's imagination."[47] The programmer in Artificial Life becomes God the Father, not surprising given the gendered character of the Judeo-Christian deity after which researchers model themselves.

Science fiction

Science fiction was a rich resource for my informants' imaginings of computers as worlds. Several referred me to stories in which artificial worlds were created by entities who imagined themselves gods. Stanislaw Lem was mentioned frequently, particularly a story in his book, *The Cyberiad*.[48] I reproduce a fragment of the story here because for Artificial Life it has become almost scripture. The discussion between the two characters anticipates almost exactly the conversation between Langton and Harnad reported earlier—and anticipates it so exactly that one might conclude that science fiction informs science as much as the reverse. Trurl the constructor has just returned home to explain to his friend Klapaucius that he has fashioned a model of a kingdom for a despotic king. He feels he has given this king a toy that will keep him from oppressing real creatures.

> "Have I understood you correctly?" [Klapaucius] said at last. "You gave that brutal despot, that born slave master, that slavering sadist of a painmonger, you gave him a whole civilization to rule and have dominion over forever? . . . Trurl how could you have done such a thing?!"
>
> "You must be joking!" Trurl exclaimed. "Really, the whole kingdom fits into a box three feet by two by two and a half . . . it's only a model . . ."
>
> "A model of what?"
>
> "What do you mean of what? Of a civilization, obviously, except that it's a hundred million times smaller."

> "And how do you know there aren't civilizations a hundred million times larger than our own? And if there were, would ours then be a model? And what importance do dimensions have anyway? In that box kingdom, doesn't a journey from the capital to one of the corners take months—for those inhabitants? And don't they suffer, don't they know the burden of labor, don't they die?"
>
> "Now wait just a minute, you know yourself that all these processes take place only because I programmed them, and so they aren't genuine. . . ."
>
> "Aren't genuine? You mean to say the box is empty, and the parades, tortures and beheadings are merely an illusion?"
>
> "Not an illusion, no, since they have reality, though purely as certain microscopic phenomena, which I produced by manipulating atoms," said Trurl. "The point is, these births, loves, acts of heroism and denunciations are nothing but the minuscule capering of electrons in space, precisely arranged by the skill of my nonlinear craft, which—"
>
> "Enough of your boasting, not another word!" Klapaucius snapped. "Are these processes self-organizing or not?"
>
> "Of course they are!"
>
> "And they occur among infinitesimal clouds of electrical charge?"
>
> "You know they do."
>
> "And the phenomenological events of dawns, sunsets and bloody battles are generated by the concatenation of real variables?"
>
> "Certainly."
>
> "And are we not as well, if you examine us physically, mechanistically, statistically and meticulously, nothing but the minuscule capering of electron clouds? Positive and negative charges arranged in space? And is our existence not the result of subatomic collisions and the interplay of particles, though we ourselves perceive those molecular cartwheels as fear, longing, or meditation? And when you daydream, what transpires within your brain but the binary algebra of connecting and disconnecting circuits, the continual meandering of electrons?"[49]

Trurl is being accused of playing a god fully outside creation. In this story, we reread a familiar theology, translated into cybernetic jargon.

Science fictional common sense encodes a number of cultural themes aside from those around creation. The most salient is of exploring and colonizing the universe. Several researchers told me that creating artificial worlds in computers is necessary for a universal biology since, at the moment, we are unable to do natural history on other planets. Since we don't have *Star Trek*'s USS *Enterprise* at our disposal, we must construct the worlds we would explore. This imagining of exploring the universe is warranted in the Artificial Life's official ideology. As Langton puts it in a promotional video, "It's very difficult to build general theories about what life would be like anywhere in the universe and whatever it was made out of, when all we have to study is the unique example of life that exists here on Earth. So, what we have to do—perhaps—is the next best thing, which is to create far simpler systems in our computers."[50] Doyle has commented that the idea that theoretical biology is hamstrung by its imprisonment on earth derives from a desire to occupy a transcendent position from which to scan the universe. It is this position which Artificial Life scientists strive to create for themselves by manufacturing their own galaxies of artificial worlds.

There is also another figure at work here: the future. Like people who have their bodies or heads put in cryonic suspension, Artificial Life researchers are impatient for "the future" to arrive, impatient enough to want to reel it into the present. One person said in conversation with me that he was frustrated by his finitude and mortality. He wished he could live long enough to see "all the cool things that would happen in the future." He wished he could be around when and if humans eventually contacted life on other planets, and his desire to create life in computers had to do with this curiosity. In this vision, cyberspace is figured as the new outer space.

Perhaps the impulse to think of computers as worlds results in part from a desire to author a reality, just as a science fiction writer does. One person told me that he thought of himself as a storyteller, and programming, like the Dungeons and Dragons designing he used to do, was one way of telling stories. Ursula Le Guin's essay "Do-It-Yourself Cosmology" provides a useful account of how science fiction writers and scientists create speculative alternative worlds:

> Scientist and science-fictioneer invent worlds in order to reflect and so to clarify, perhaps to glorify, the "real world," the objective Creation. The more closely their work resembles and so illuminates the solidity, complexity, amazingness and coherence of the original, the happier they are."[51]

This is clear in Langton's review of SimLife™:

> SimLife allows the construction and study of simple, artificial ecologies, and the surprising complexity and richness of behavior that emerges in even these extremely simple "artificial natures" has already given me a greater appreciation of the real thing—Nature in all her real glory—writ with a capital "N." That glory shines all the more brightly even from the meagre illumination that this simple "Software Toy" is able to shed upon Her.[52]

Science fiction–fueled simulation has become a new tool for thinking natural theology, a new tool for revealing and reproducing the plans of an omnipotent creator.

Cyberspace as a new creation and colonial space

The idea that computational processes can be thought of as existing in a kind of territory is supported by discourse about computer networks as "cyberspace." David Noble summarizes the often millenarian, Christian language surrounding cyberspace:

> The religious rapture of cyberspace was perhaps best conveyed by Michael Benedikt. . . . Editor of an influential anthology on cyberspace, Benedikt argued that cyberspace is the electronic equivalent of the imagined spiritual realms of religion. The "almost irrational enthusiasm" for virtual reality, he observed, fulfills the need "to dwell empowered or enlightened on other, mythic, planes." Religions are fueled by the "resentment we feel for our bodies' cloddishness, limitations, and final treachery, their mortality. Reality is death. If only we could, we would wander the earth and never leave home; we would enjoy triumphs without risks and eat of the Tree and not be punished, consort daily with angels, enter heaven now and not die." Cyberspace, wrote Benedikt, is the dimension where "floats the image of the Heavenly City, the New Jerusalem of the Book of Revelation. Like a bejeweled, weightless palace it comes out of heaven itself . . . a place where we might re-enter God's graces . . . laid out like a beautiful equation."[53]

Computers are figured as a place to begin again. Artificial Life participates in this imaginary, maintaining that simulated worlds might be places to see possible ways life could have evolved. At one conference, I saw a simulation called Aleph, a nice pun on Alife, but also a name that summoned up, with its Hebrew letter name, the beginning of things. The subtitle of Steven Levy's popular book, *Artificial Life: The Quest for a New Creation*, captures the imagination at work here.

This image of computers as new worlds dovetails with another image: the electronic frontier. As Robert N. Bellah has argued, notions of the new holy land and of the frontier are often mutually constitutive.[54] People imagine new frontiers as allowing them to start anew from an Edenic state: early English colonists saw in America a land of milk and honey, pilgrim John

Winthrop saw in America a "City upon a Hill" (a reference to a new Jerusalem), and Mormons saw in Utah a new Zion. The Americas, in their guise as "the New World" were often understood as a place for (European) humanity to begin again. In the frontier territories of Artificial Life, we find that Man will be as God again, having regained a creative capacity modeled after God. He will create creatures and give them their rightful names, just as Adam did, and just as Linnaeus, the eighteenth-century taxonomist who called himself a "second Adam," did at the moment modern biology was born. The image of a Garden of Eden in cyberspace fuses nicely with the spatialized metaphor of the electronic frontier and allows Artificial Life researchers to think of themselves as creating, populating, and exploring new lands.

This notion of colonization and taming underwrites Thomas Ray's plan to have a global version of his Tierra system. Ray hopes that Tierran organisms can "run wild" in an Internet reserve, traveling around the globe in search of spare CPU cycles, terraforming cyberspace in the process. To hear Ray speak of global Tierra is to hear him speak of an empty world he plans to colonize with his digital organisms. Cyberspace becomes a new frontier, a second nature ready for colonization by the first-world imagination.[55]

In a paper titled "Visible Characteristics of Living Systems: Esthetics and Artificial Life," a company of philosophers and artists articulate—apparently without irony—the idea that Artificial Life researchers should think of themselves as colonizing new spaces:

> Artificial Life researchers habitually give names to their creations, build up complicated typologies for them and come up with bold new syntactic designations for areas that are still terra incognita. They are the true successors of the Conquistadors of the 15th and 16th centuries, of the explorers of the 18th and 19th. . . . Having created his creature in real or virtual space, the researcher or artist-researcher tries to capture it with language and to master its imaginative dimension in such a way as to turn it into a usable object, one that can be proposed for comparison, criticism, and reconstruction.[56]

The rhetorics of exploration, colonization, and conquest in Artificial Life are intensely masculine. Imagining programmers as gods, as single-handed creators of life, as objective, transcendent observers, and as intrepid explorers of the final frontiers of cyberspace all invoke masculine imagery and not just this, but imagery of a kind of white masculinity, of a white man who hunts, explores, and goes on adventures in undiscovered lands, and feels at ease and assured in his power in naming and conquering. The fact that the majority of Artificial Life practitioners are white men who grew up reading cowboy science fiction is not trivial. The masculine imagery of exploration

also reinforces a gendering of the "lands" of cyberspace as feminine, waiting to be penetrated or unveiled, continuing a Western tradition of seeing Nature as a woman (recall Langton's pronouncements about "Nature in all her real glory," coupled with his images of a masculine god using SimLife™ to create the world). Nature, a living—sometimes nurturing, sometimes wild—being in seventeenth-century European cosmology was devivified and mechanized in the eighteenth and nineteenth centuries and has now been resuscitated as an enormous computer.[57]

Technologies of vision

The data researchers garner from their simulations are usually presented visually, and in Artificial Life simulations, visuals almost always afford a god's eye view, allowing experimenters to survey an entire world at once. In many systems, we are provided with a panoptic picture of a world, over which we can witness the careenings of computational creatures. In Tierra, we are presented with graphs that summarize evolutionary activity and chart the rise and fall of program lineages. The visual access we are granted to artificial worlds positions us as "objective" observers, located everywhere and nowhere at once. Artificial Life programs instantiate the dream of objectivist science. Donna Haraway has written that in Western thought, "the eyes have been used to signify a perverse capacity—honed to perfection in the history of science tied to militarism, capitalism, colonialism, and male supremacy—to distance the knowing subject from everybody and everything in the interests of unfettered power. . . . [The] view of infinite vision is an illusion, a god-trick."[58] This illusion is manufactured as reality in computational Artificial Life.

Vision is a sense researchers invoke to speak about unmediated pictures of the empirical world. They speak of "seeing" phenomena emerge in their simulations, and when speaking this way they take themselves to be reporting—rather than, say, hallucinating—real results. At many conferences I attended, people referred to the "real world" or "nature" by pointing out the window, while they indicated artificial worlds by pointing at images on computer screens. At an SFI workshop on artificial worlds, one researcher compared the technology of computer simulation to telescopes and microscopes, saying that these technologies allow us to peer into whole new worlds.

The idea that life only evolved once on Earth, and that it would be interesting to see what else might have happened, is one to which Artificial Life scientists frequently refer. The world is often compared to a videotape, one that we might rewind, fiddle with, and watch for different story lines. Langton writes, "Although studying computer models of evolution is not the same as studying the 'real thing,' the ability to freely manipulate computer experiments, to 'rewind the tape,' perturb the initial conditions, and so forth, can more than make up for their 'lack' of reality."[59]

This image of the world as videotape fast-forwards me to a description of a compelling video I saw at one Artificial Life conference. Accompanying a talk entitled "Artificial Fishes with Autonomous Locomotion, Perception, Behavior, and Learning in a Simulated World," the video showed simulations of swimming fish.[60] The audience was enraptured as simulated fishes acted out their artificially evolved capacities to swim and hunt. The presentation ended with simulations strung together in an extended parody of a Jacques Cousteau documentary. As the audience laughed at the video and at the movements of the fishes on the screen, it became clear that the lifelike quality of these simulations produced an unease and sense of the wonder that was itself precisely the cultural resource that made these creatures seem lifelike. The laughter bespoke a set of intuitions and untheorized thoughts about autonomy and agency. This reference to Cousteau invokes another ocular technology: the aquarium, which also interposes a glass barrier between an observer and a bundle of phenomena. A few Artificial Life researchers call upon people's familiarity with aquariums or terrariums to rhetorically structure their simulations as closed worlds. Some systems show us fishes or birds moving around as though in an enclosed space.

Artificial Life worlds, visualized on computer screens, depend on a complex of viewing habits developed in such diverse activities as watching documentary video, looking out windows, and gazing into aquariums. What all of these practices have in common is a commitment to the notion that representation *represents*, that visual accounts of the world can be isomorphic with the world itself.[61]

Exit

At an SFI workshop on artificial worlds, linguist George Lakoff argued that seeing computers as worlds is enabled by metaphors that allow scientists to import everyday language into the space of simulation. But while SFI and practitioners of Artificial Life may come up with a stable practice for interpreting computer simulations as model worlds, or even as real, independent worlds, this does not mean that they become such things for people who do not share the enabling metaphors. Lakoff maintained that what models do is "create an expert priesthood, and what SFI is doing is setting up a new kind of priesthood."[62] Following this pronouncement, Lars Risan has suggested that just as the authority of Catholic priests empowers them to convince people that wine can literally, not just metaphorically, be turned into blood, so it might be that the expert priesthood of Artificial Life, through skilled interpretation of computer simulation, can convince people that computer simulations can literally be turned into worlds and life. Artificial Life techniques have already made their way into everyday common sense through such programs as SimLife™, extending the network of priestly training in a kind of Protestant dispersal of Artificial Life.[63]

The transubstantiation work of Artificial Life researchers signals new ways of understanding nature. For these scientists, worlds generated in simulation are congealing into new epistemological and ontological territories. As I've argued here, this is the result of a complex commerce of language and sensibility between silicon second natures and the second natures represented by the cultural worlds of Artificial Life researchers. As Evelyn Fox Keller and Elisabeth Lloyd write about scientific meanings of words, "By virtue of their dependence on ordinary language counterparts, technical terms carry, along with their ties to the natural world of inanimate and animate objects, indissoluble ties to the social world of ordinary language speakers. . . . [They] have insidious ways of traversing the boundaries of particular theories, of historical periods, and of disciplines. . . . They serve as conduits for unacknowledged, unbidden, and often unwelcome traffic between worlds."[64] This semiotic traffic is not only at high density between social and simulated worlds, but has become knotty enough to produce simulations *as* worlds, as new kinds of spaces, as Gardens of Eden where explanations grown in silicon can supplement or supplant the very natures they seek to illuminate. But simulations can only crystallize as worlds in complex webs of hardware, software, and human wetware. In this essay, I have fixed attention on semiotic traffics that many Artificial Life practitioners would disavow, but I maintain that it is precisely at the intersections of domains coded as *science* and *culture* that Artificial Life worlds come to life for the people who craft them. It is at these junctures that scientists of the artificial solidify simulations as sites for growing explanations.

Notes

1 Thomas Ray on Tierra, in Santa Fe Institute, *Simple Rules . . . Complex Behavior* (Santa Fe Institute video, 1993).

2 Santa Fe Institute, *Simple Rules*.

3 Claus Emmeche, *The Garden in the Machine: The Emerging Science of Artificial Life*, trans. Steven Sampson (Princeton, N.J.: Princeton University Press, 1994); also Peter Galison, "Computer Simulations and the Trading Zone," in Galison and D. J. Stump (eds.), *The Disunity of Science: Boundaries, Contexts, and Power* (Stanford, Calif.: Stanford University Press, 1996), 118–157.

4 Steen Rasmussen, Rasmus Feldberg, and Carsten Knudsen, "Self-Programming of Mat-

ter and the Evolution of Proto-Biological Organizations" (SFI preprint 92–07–035, 1992).

5 Evelyn Fox Keller, *Refiguring Life: Changing Metaphors of Twentieth Century Biology* (New York: Columbia University Press, 1995); also Richard Doyle, *On Beyond Living: Rhetorical Transformations of the Life Sciences* (Stanford, Calif.: Stanford University Press, 1997).

6 Sylvia Yanagisako and Carol Delaney, "Naturalizing Power," in Yanagisako and Delaney (eds.), *Naturalizing Power: Essays in Feminist Cultural Analysis* (New York: Routledge, 1995), 1–22.

7 Ursula K. Le Guin, *The Word for World Is Forest* (New York: Berkeley, 1976); and Le Guin, "Do-It-Yourself Cosmology," in *The Language of the Night: Essays on Fantasy and Science Fiction* (New York: HarperCollins, 1989), 118–122.

8 Neil Smith, "The Production of Nature," in G. Robertson, M. Mash, L. Tucker, J. Bird, B. Curtis, and T. Putnam (eds.), *Future Natural: Nature, Science, Culture* (London: Routledge, 1996), 35–54.

9 Christopher G Langton, "Toward Artificial Life," *Whole Earth Review* 58 (1988): 74.

10 Christopher G. Langton, "Artificial Life," in Langton (ed.), *Artificial Life* (Redwood City, Calif.: Addison-Wesley, 1989), 1.

11 Thomas Ray, "An Evolutionary Approach to Synthetic Biology: Zen and the Art of Creating Life," *Artificial Life* 1 (1994): 183.

12 Thomas Ray, "An Approach to the Synthesis of Life," in C. Langton, C. Taylor, D. Farmer, and S. Rasmussen (eds.), *Artificial Life II* (Redwood City, Calif. Addison-Wesley, 1992), 372.

13 Ibid., 373–374.

14 Ray, "Evolutionary Approach," 183.

15 Ibid.

16 N. Katherine Hayles, "Simulated Nature and Natural Simulations: Rethinking the Relation between the Beholder and the World," in W. Cronin (ed.), *Uncommon Ground: Toward the Reinvention of Nature* (New York: W. W. Norton, 1995), 421.

17 Stefan Helmreich, *Silicon Second Nature: Culturing Artificial Life in a Digital World* (Berkeley: University of California Press, 1998).

18 David Hiebeler, "Implications of Creation" (SFI preprint 93–05–025, 1992), 2.

19 Terry Winograd, *Understanding Natural Language* (New York: Academic Press, 1972); also Hubert L. Dreyfus, *What Computers Can't Do: A Critique of Artificial Reason*, 2d ed. (New York: Harper and Row, 1979); Paul Edwards, *The Closed World: Computers and the Politics of Discourse in Cold War America* (Cambridge: MIT Press, 1996).

20 Edwards, *Closed World*, 171–172.

21 Ibid., 172.

22 Sherry Turkle, *Life on the Screen: Identity in the Age of the Internet* (New York: Simon and Schuster, 1995).

23 Judith Genova, "Women and the Mismeasure of Thought," in N. Tuana (ed.), *Feminism and Science* (Bloomington: Indiana University Press, 1989), 212.

24 Galison, "Computer Simulations," 142–143.

25 Ibid., 144.

26 Ibid., 156–157.

27 Ray, "Evolutionary Approach," 184

28 See Rasmussen, Feldberg, and Knudson, "Self-Programming of Matter."

29 Christopher G. Langton, "Self-Reproduction in Cellular Automata," *Physica D* 10 (1984): 135–144.

30 Langton, "Artificial Life," 28.

31 Andrew Wuensche, "Complexity in One-D Cellular Automata: Gliders, Basins of Attraction, and the Z Parameter" (SFI preprint 94–04–025, 1994), 193.

32 Since I wrote this essay in 1997, this position has been newly championed by Stephen Wolfram, *A New Kind of Science* (Champaign, Ill.: Wolfram Media, 2002).

33 Here and elsewhere in this essay, at their request, I omit specific information on people interviewed.

34 Stevan Harnad, "Levels of Functional Equivalence in Reverse Bioengineering," *Artificial Life* 1(3) (1994): 297–298.

35 Bruce MacLennan, "Synthetic Ethology: An Approach to the Study of Communication," in Langton et al., *Artificial Life II*, 638.

36 Brian Cantwell Smith, *On the Origin of Objects* (Cambridge: MIT Press, 1996).

37 Ray, "Evolutionary Approach," 184.

38 Ibid., 183.

39 Ibid., 182–183.

40 Edwards, *Closed World*, 13.

41 MacLennan, "Synthetic Ethology," 637.

42 N. Katherine Hayles, "The Closure of Artificial Worlds: How Nature Became Virtual," paper presented at "Vital Signs: Cultural Perspectives on Coding Life and Vitalizing Code," Stanford University, 2–4 June 1994, 4.

43 Langton, lecture at "Artificial Life IV," Massachusetts Institute of Technology, 6 July 1994.

44 Ray quoted in Kevin Kelly, *Out of Control: The Rise of Neo-Biological Civilization* (Redwood City, Calif.: Addison-Wesley, 1994), 297.

45 Christopher G. Langton, "SimLife from Maxis: Playing with Virtual Nature," *Bulletin of the Santa Fe Institute* 7 (1991): 4.

46 Carol Delaney, "The Meaning of Paternity and the Virgin Birth Debate," *Man* 21 (1996): 494–513.

47 N. Katherine Hayles, "Narratives of Evolution and the Evolution of Narratives," in J. L. Casti and A. Karlqvist (eds.), *Cooperation and Conflict in General Evolutionary Processes* (New York: John Wiley and Sons, 1994), 125.

48 Stanislaw Lem, *The Cyberiad*, trans. Michael Kandel (1967; San Diego: Harcourt Brace Jovanovich, 1985).

49 Ibid., 167.

50 Santa Fe Institute, *Simple Rules*.

51 Le Guin, "Do-It-Yourself Cosmology," 120.

52 Langton, "SimLife from Maxis," 6.

53 David Noble, *The Religion of Technology: The Divinity of Man and the Spirit of Invention* (New York: Knopf, 1997), 159–160.

54 Robert N. Bellah, *The Broken Covenant: American Civil Religion in Time of Trial*, 2d ed. (Chicago: University of Chicago Press, 1992).

55 Ziauddin Sardar, "alt.civilizations.faq: Cyberspace as the Darker Side of the West," in Sardar and J. R. Ravetz (eds.), *Cyberfutures: Culture and Politics on the Information Superhighway* (New York: New York University Press, 1996), 14–41.

56 D. Lestel, L. Bec, and J.-L. Lemoigne, "Visible Characteristics of Living Systems: Esthetics and Artificial Life," in J. L. Deneubourg, S. Goss, G. Nicolis, H. Bersini, and R. Dagonnier (eds.), *ECAL 93: Self Organisation and Life: From Simple Rules to Global Complexity* (photocopied proceedings from the Second European Conference on Artificial Life, Santa Fe Institute, 11–13 November 1993), 598.

57 Carolyn Merchant, *The Death of Nature: Women, Ecology, and the Scientific Revolution* (New York: Harper and Row, 1980).

58 Donna Haraway, "Situated Knowledges: The Science Question in Feminism and the Privilege of Partial Perspective," in Haraway, *Simians, Cyborgs, and Women: The Reinvention of Nature* (New York: Routledge, 1991), 188–189.

59 Christopher G. Langton, introduction to Langton et al., *Artificial Life II*, 7–8; also Walter Fontana and Leo Buss, "What Would be Conserved if 'The Tape Were Played Twice'?" in G. Cowan, D. Pines, and D. Meltzer (eds.), *Complexity: Metaphors, Models, and Reality* (Redwood City, Calif.: Addison-Wesley, 1994), 223–244. The notion of evolution as a "tape" is discussed in Stephen Jay Gould, *Wonderful Life: The Burgess Shale and the Nature of History* (New York: W. W. Norton, 1989). Artificial Life scientists hope to make Gould's metaphor do literal work, but do not demonstrate how "rewinding" simulated evolutionary history can "make up" in any straightforward way for the " 'lack' of reality" in computer models.

60 Demetri Terzopoulos, Xiaoyuan Tu, and Radek Grzeszczuk, "Artificial Fishes with Autonomous Locomotion, Perception, Behavior, and Learning in a Simulated Physical World," in R. Brooks and P. Maes (eds.), *Artificial Life IV* (Cambridge: MIT Press, 1994), 17–27.

61 Timothy Mitchell, *Colonising Egypt* (Berkeley: University of California Press, 1988).

62 George Lakoff, "Artificial Worlds" workshop, Sante Fe Institute, 13 November 1993.

63 Lars Risan, personal communication, July 1994; see also Risan, *Artificial Life: A Technoscience Leaving Modernity? An Anthropology of Subjects and Objects* (Ph.D. diss., University of Oslo, 1996).

64 Evelyn Fox Keller and Elisabeth A. Lloyd, introduction to Keller and Lloyd (eds.), *Keywords in Evolutionary Biology* (Cambridge: Harvard University Press, 1992), 1–2.

11 Constructing and explaining emergence in artificial life: on paradigms, ontodefinitions, and general knowledge in biology

Claus Emmeche

There is nothing wrong with a good illusion as long as one does not claim it is reality.—H. H. Pattee, "Simulations, Realizations, and Theories of Life"

An explanation is always a reproduction.—H. R. Maturana and F. J. Varela, *Autopoiesis and Cognition*

By explaining things, we change them. They do not remain the same in our conceptions. Explanations should satisfy our quest for understanding. There are, of course, forms of understanding that do better without explanation, like jokes. In general, explanations are a good thing to pursue in science; they are called upon in courtrooms, and they are often required in the upbringing of children and in everyday life; we should, however, be careful about their use and about the idea that all explanations of any kind share a unique conjunctive set of properties.

Explaining life in biology

I will consider here the role of explanations in the quest to understand life as a coherent phenomenon, as pursued in traditional biology and within one of the "sciences of complexity": the interdisciplinary field of Artificial Life (Alife). Though the approach is conceptual, not historical or sociological, the motivation for this study is a set of very general assumptions about scientific activity, which should be subject to closer scrutiny within the history, sociology, and philosophy of science. These assumptions include the following. (1) From science, the assumption that modified forms of reductionism are called for when a science is faced with the problem of complexity. Thus it is often assumed that "growing explanations" or constructing emergent patterns as the outcome of computer simulations—presumably representing (even in a very abstract sense) patterns of biological processes—is a case of extending the traditional reductionist ex-