WINDING THE UNIVERSAL CLOCK

SPECULATIONS ON THE TRANSITIONS
BETWEEN CHAOS AND ORDER

Carl H. Builder and Gabriele U. Menke

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Books by Carl H. Builder

_The Masks of War_
(Johns Hopkins University Press, 1989)

_The Icarus Syndrome_
(Transaction Publishers, 1994)

_For all those scientists still willing to speculate broadly—_
_not in the certainty that they are correct_

_but in the hope that they will make us think._

In the thinking that expands the frontiers of knowledge, intuition generally outruns mathematics. No apology need be offered for this fact.

Garrett Hardin

_Intuition First, Then Rigor_
PREFACE

This synopsis was written under the sponsorship of a RAND President's Award, an unsolicited grant to pursue independent research apart from that sponsored by RAND's clients. The award provides a block of time (20 days) and administrative support "for any activity related to staff development or exploratory research, but cannot be used to complete project work." To access the grant, the recipient must only explain how the resources will be used and then consume them within 18 months of the award announcement.¹

The speculations presented here evolved from a series of long discussions over morning coffee with my wife, Gabriele Menke, in the Spring of 1996. The earliest of those discussions began with speculations about the future of West Africa, coincident with the breakdown of civil order in Liberia and the publication of a new book by Robert Kaplan, *The Ends of the Earth.*² That first discussion steadily expanded in its scope to the fate of humanity more generally, thence to the purpose of biological life, and ultimately to the destiny of the universe. The questions weren't new—they are so old as to have become trite—but our shared speculations as to the answers were new to us and surprisingly specific. The further we probed, the more quickly and easily the answers came to us.

After several hours, we recognized that our discussion had become both exhilarating in its perspectives and frightening in its implications for our beliefs. We didn't have all the pieces of the puzzle; but the main features of the *picture* in the puzzle had emerged unexpectedly; and each succeeding piece we picked up seemed to find its place more quickly than those before. Exhausted and wary of what we were seeing, we dropped the subject completely for a week, needing time and reflection to judge the experience.

¹This award, one of a dozen, was announced in an electronic mail message from RAND vice president Michael Rich, dated 28 November 1995, on the subject: *New Round of President's Awards.*
When we returned to it a week later, we easily picked up where we left off; and, as more pieces fell into place, we became convinced that we had to carry it through to a written product. The RAND President's award, granted six months earlier, offered the opportunity to start down that road.³

Although the award was granted to me and the writing here is mostly mine, the ideas, research, and editing have been collaborative from the very beginning. So it is fitting that I use "we" and "us" to describe the source of the speculations presented here—not as the editorial "we", but as representing us, Gabriele and me. Hence, it is also fitting that this synopsis be presented as one of joint authorship. We have been careful not to confuse our readers by using "we" to mean anything other than Gabriele and me. However, we have not altered quotations which may use the first person plural pronouns to refer to the human species.

The grant provided by the RAND President's Award was insufficient to research and write a book-length manuscript, but it was more than enough for the typical book prospectus. With the literature readily available to us, we found that we could write a quarter-scale synopsis of the book we had in mind. From this synopsis, we thought that the expansion to a book was more clearly defined both for us and for prospective publishers.

The original working title for this synopsis was Where Has All the Entropy Gone? Some of the reviewers of early drafts found the emphasis on entropy heavy going and suggested we change the title to something that might better reflect the broader scope of our speculations and, at the same time, be more inviting to our potential readers. Entropy remains a central issue here, and one section retains the originally proposed title, but we think that winding the universal clock is a better description of the common thread in our speculations.

Our purpose in this synopsis is not to prove our speculations but to present them—along with enough supporting evidence to establish their

³I had originally considered using the award to document my concerns about the risks of crude, home-made nuclear explosives derived from nuclear materials in commerce—akin to the chemical explosives that can be fabricated from ordinary fuel oil and farm fertilizer—but the present synopsis seemed to be a more important use of the grant.
plausibility—and to invite others to help us in our quest for additional pieces of the puzzle. To buttress our arguments as much as we would like—let alone what science would demand—will require much more than we could expect to accomplish with this initial grant, with our modest intellectual resources, or perhaps even with unlimited resources. But enough pieces of the puzzle now fit for us to share the picture we see—even though we have undoubtedly fitted some pieces incorrectly or have missed important pieces that others will see. It is our hope that this initial synopsis will serve as the basis and incentive for our undertaking a more thorough analysis and synthesis of the literature.
Winding the Universal Clock
ACKNOWLEDGMENTS

First, we must thank several people who came forward, even before writing the first draft of this synopsis, to offer support. Our thanks to RAND colleagues Steven Bankes, James Dewar, and Robert Anderson and to our friends at the Air War College, Grant Hammond and Dick Szfranski, for their encouragement and suggestions for additional literature. Constance Greaser, as she has with my first book, The Masks of War, offered both encouragement and advice as an editor, publisher, and literary agent. Graham Fuller urged us to consider the reactions to our speculations and, if accepted, their implications for human values. Ruth and Jim Dewar offered a number of suggestions about precedents for reactions to our theories. Professor Stephen Jay Kline of Stanford University patiently suffered my stumbling about on the significance of entropy and tried to keep me on track.

A preview draft of this synopsis was submitted for critical review to a few who expressed a willingness to help us take the next steps on the path of our thinking. We are indebted to Bob Anderson, Jim and Ruth Dewar, Connie Greaser, and Grant Hammond for providing detailed comments and advice for our revisions. They helped us clarify both our ideas and their expression, added examples and citations, and offered suggestions as to how we might restructure the synopsis to make it more inviting and rewarding to readers.

Finally, our thanks to Geni Coughlan, who gave the manuscript her ever watchful eye and unstinting care through preparation and printing.
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1. THE JOURNEY AHEAD

Here, we explore the most far-reaching ideas that have taken root so far in our minds: With large measures of both trepidation and chutzpah, we take a swing at the answers to some of the oldest and most fundamental philosophical questions humans have asked, such as,

What is the purpose of life?
What is the destiny of mankind?
What is the fate of the universe?

Our speculations are based upon the fitting together of many familiar ideas and theories taken from diverse subjects and scientific fields, looking for patterns in them, and then extending those patterns to still other subjects and fields until a coherent picture appears. For example, a familiar pattern is the diversification and specialization of biological species; but we extend that pattern beyond the conventional boundaries of biology. Another familiar pattern is complexity as a transition state between chaos and order in dynamical systems; but we speculate about complexity as a function—not merely as a form, but as means to an end.

We offer these speculations not in the certainty that they are correct, but in the belief that the picture we see goes well beyond what we have read or heard elsewhere, and that it may offer a more coherent conception of why the observed world behaves as it does. No doubt, our ideas will disturb many, for they are not anthropocentric and, therefore, do not conform with most religious views. Our speculations on the destiny of mankind are rooted in objective rather than normative perspectives; and although those objective perspectives may be repugnant to some and bleak to most, we found a detached objectivity essential to fitting the pieces together in the way we have. Most of the individual pieces of the puzzle—when considered separately in the context of the scientific fields from which they have been lifted—may not be particularly disturbing, but the picture that emerges from our assembly of the pieces is more likely to be perceived so.

Our springboards for these speculations will probably disappoint specialists in the many fields we have intruded upon and inadvertently
mistreated. We have mostly resorted to secondary sources, surveys, and popular scientific literature rather than the specialized, original, or seminal research products because our knowledge of some of the many fields we tread upon is superficial. A sufficiently deep understanding of all these fields will undoubtedly remain beyond our reach; but experts may be able to help us by correcting our misapprehensions and guiding us into a deeper appreciation of their fields.

Our contribution, we think, in advancing these speculations is mostly limited to the synthesis of existing ideas and theories from diverse disciplines—cosmology, chemistry, biology, information and computer sciences, and thermodynamics. We believe the synthesis is new and goes well beyond the existing ideas and theories we have found in fields beyond our own competencies.\(^1\) We are certainly not the first discoverers of the many pieces in our puzzle; but we think we have found a picture in that puzzle that no one else has shown us. Our discovery, if any, is the face in the puzzle, not its pieces.

To separate our synthesis from the many ideas that we have drawn from others, we have relied heavily in this synopsis on quotations for the expression of their ideas. Some readers will, no doubt, be annoyed at reading many quotations; but we have risked that annoyance to weave a chorus of other, nuanced voices into our theme. In addition to clarifying ownership, we hope that the quotations of others lend some added plausibility to the extraordinary pieces we have fitted together in a picture that may otherwise seem implausible. Indeed, we have relied most heavily on quotations precisely where we think the ideas are likely to be both critical to our picture and incredulous to some. In a subsequent expansion of these speculations, we may be able to substitute a deeper understanding of our own for some of the ideas that we now must express in the words of others. But, in the interim, we invite our readers to enjoy a sampler of remarkable quotes across a spectrum of issues bearing upon where the universe, life, and humans have come from and may be going. For us, they are jewels of human knowledge strung upon a thread of time.

\(^1\)Our undergraduate competencies are in thermodynamics and nursing.
The Journey Ahead

Ours is not a detective story, with the face in the puzzle to be revealed only in the last page or chapter. Our picture can be briefly sketched as follows, starting from the large and proceeding to the small:

- The destiny of the universe is to oscillate between two unstable domains—by expansion and collapse, between chaos and order.
- The current expansion phase of the universe began in the chaotic plasma of an explosion; it will end in the more orderly distribution of inert cold crystalline metal in space.\(^2\)
- The several essential transitions between the initial chaos and ultimate order of the universe will be a sequence of increasingly complex species—first at the atomic level, next at the molecular level, then through a spectrum of biological species, to be succeeded by generations of machines,\(^3\) which will ultimately complete the transition to order.
- Each of the increasingly complex species in these transitions goes through the same successive phases—first diversification, then specialization.
- The diversification phase for each species insures adaptation and survival of the species in its new environment; the specialization phase exploits and then alters the environment itself, laying the foundations necessary for the succeeding species.
- In this particular part of the universe, on earth, the transition is now dominated by the human species which is in its specialization phase—pressing up against the limits of its environment and laying the foundations for the emergence and dominance of the next species, machines.
- The role of biological life, here and elsewhere in the universe, is to serve as a connective transition between processes dominated by chemistry and those that will be dominated by physics of machines.

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\(^2\)To be precise, flakes of crystalline iron, chromium, or vanadium. Why that should be is a longer story to be told in the penultimate section of this synopsis.

\(^3\)Not ordinary machines as they are known today, but self-replicating and self-programmed machines that will become increasingly divorced from their biological origins and dependence upon biological life. Artificial life might be a more apt descriptor, but that term has been preempted with a particular meaning associated with computer algorithms exhibiting life-like behavior.
• Humans are probably the last of a long series of increasingly complex forms of purely biological life on earth.

• The special role of humans is to devise and fashion the first machines capable of self-replication, self-adaptation and evolution—a critical link both in the transition from biological to machine species and in a long series of transitions of the universe from chaos to order.

• The destiny of humans is to merge with machines until the machines begin to propagate and diversify on their own—at which point, humans (and their extensive biological support systems) will no longer be essential to the continuing transition of the universe from chaos to order.

• Almost everything humans have done in their evolution, taken in the broadest context, has been the furtherance of their purpose as a critical link in the transition of the universe from chaos to order—from biological life to machine.

• The ultimate destiny of machines is to extract all of the available energy from matter in the universe by converting it into cold crystalline metal.

• In the process of extracting the remaining available energy from an expanding and cooling universe, some of the matter in the universe will have been redistributed; and, hence, the subsequent collapse of the universe under the force of gravity will be correspondingly different from its expansion.

• The differences between the expansion and the collapse of the universe could compensate for the loss of available energy—the entropy increases incurred at the very beginning of the expansion—by making more energy available at the very end of the gravitational collapse, thereby "winding the clock" for the next expansion.

When we put all of these pieces together, they suggest something about the thermodynamics of the universe—in particular about entropy, the enigma found in so many fields of science.
We shall begin in the present and work both forward and back in time. Our point of departure is now—with the current transitions between humans and machines.
Where Have All the Flowers Gone?

Where have all the flowers gone?
Long time passing.
Where have all the flowers gone?
Long time ago.
Where have all the flowers gone?
The girls have picked them every one.
Oh, when will they ever learn?
Oh, when will they ever learn?

Where Have All the Entropy Gone?

Where has all the entropy gone?
Long time passing.
Where has all the entropy gone?
Long time ago.
Where has all the entropy gone?
Into structure every bit.
Oh, when will it ever end?
Oh, when will it ever end?

Where have all the young girls gone?
Long time passing.
Where have all the young girls gone?
Long time ago.
Where have all the young girls gone?
They've taken husbands every one.
Oh, when will they ever learn?
Oh, when will they ever learn?

Where have all the young men gone?
Long time passing.
Where have all the young men gone?
Long time ago.
Where have all the young men gone?
They're all in uniform.
Oh, when will they ever learn?
Oh, when will they ever learn?

What have all the machines done?
Long time passing.
What have all the machines done?
All over the place?
What have all the machines done?
They've wound the universe up again.
Oh dear, will it never end?
Oh dear, will it never end?

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1Words and music by Pete Seeger, ©
Copyright 1961, 1962 by Fall River Music,
Inc., New York, NY.
2. ASSAULT ON THE CITADEL

( THE VOICE OF ROBERT JASTROW)

At the center of the picture in our puzzle is the human brain and its electronic progeny—what Hans Moravec has called its "mind children."¹ Our starting point is where Robert Jastrow left off in his speculations about the future of brains—both biological and electronic—in his 1981 book, *The Enchanted Loom,*² Most of that work is devoted to the biological evolution of brains—from the primitive brains of fish to the sophisticated brains of humans. In reviewing that evolution, he succinctly launches us on our journey:

One of the striking features in . . . history is a trend toward greater brain size and intelligence in the highest forms of life, which has persisted for many millions of years. Throughout this long interval a succession of brainy creatures has appeared, each more intelligent than its predecessors, and each serving in turn as the rootstock for a newer and still more intelligent form. We are the latest in the succession, but probably not the end of the line. Who will follow us? What will man's successor look like?³

Jastrow suggests why it may be time for humans to look toward their succession:

The fossil remains of man's recent ancestors show that the brain began to grow rapidly about one million years ago, after a long period of moderate growth in the monkey and ape line of evolution. About 250,000 years ago, the curve of growth began to level off, and in the last 50,000 years the size of the human brain has hardly changed. The human body has also changed very little in the last million years. Man is a nearly finished chapter in [biological] evolution.⁴

The organization of the brain may have improved in that period, but the amount of information and wiring that can be crammed into a cranium of fixed size is

³Jastrow, p. 8.
⁴Jastrow, p. 139. The attainment of the current size of the human brain is roughly coincident with the advent human speech (probably less than 100,000 years ago) and the first glyphs (about 50,000 years ago).
limited. The fact that the brain is no longer expanding, after a million years of explosive growth, suggests that the story of human evolution may be over.  

More recent research would seem to foreclose further evolution of the human brain, even if the cranium were not fixed in size. According to Chris Winter, a member of a research team at Bell Telephone Laboratories which has modeled the information-processing capacity of the human brain, "There is no incremental improvement path available to the brain, which makes evolution difficult." Hence:

Humans are about as smart as they are going to get. . . . [The researchers] found that any radical improvement is impossible because of the careful balance maintained between the size and number of neurons and the blood vessels which nourish them. They claim that we have reached our maximum information-processing capacity, or at best are within 20 per cent of it.

The researchers also point out that the human brain is designed so that the chemical signals which pass impulses from one nerve to another are transmitted as fast as possible. The larger the brain grew, the less efficient it would become, thus limiting any improvement in processing power.

Jastrow invokes a 100 million years of evolution pointing toward human succession on the basis of greater intelligence.

The history of life supports this conclusion, for it shows a seemingly inexorable trend toward greater intelligence in the higher animals. Apparently, among all traits of a living organism, none has greater survival value than the flexible, innovative response to changing conditions that we call intelligence. It seems unlikely that this trend in evolution, which has persisted for more than 100 million years, should suddenly stop at the particular level of mental achievement that we call "human." If the past is any guide to the future, mankind is destined to have a still more intelligent successor.

Carl Sagan expressed the same idea in his speculations on human intelligence in The Dragons of Eden:

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5 Jastrow, p. 138.
7 Ibid.
8 Jastrow, p. 140.
9 Carl Edward Sagan (1934-1996), astronomer, known primarily for his research on the possibility of extraterrestrial life and popularizing science. He won the 1978 Pulitzer Prize for The Dragons of Eden (1977), which we cite several times here. He is perhaps best know for his television series, Cosmos. (The 1995 Grolier Multimedia Encyclopedia, Version 7.0.2)
The entire evolutionary record on our planet, particularly the record contained in fossil endocasts, illustrates a progressive tendency toward intelligence. There is nothing mysterious about this: smart organisms by and large survive better and leave more offspring than stupid ones.\textsuperscript{10}

That trend, Jastrow argues, defines the human role and fate:

The story is an old one on the earth: in the struggle for survival, bigger brains are better. One hundred million years ago, when the brainy little mammal coexisted with the less intelligent dinosaurs, the mammal survived and the dinosaur vanished. It appears that in the next chapter of this unfolding story, fate has cast man in the role of the dinosaur.\textsuperscript{11}

\textbf{Recognizing the Human Successor}

Jastrow argues that the human successor may be evolving before the very eyes of its human creator—a product of human intelligence intended to augment that intelligence, but destined to replace it:

Powerful forces of evolution are at work—cultural rather than biological—that could lead to a more exotic form of intelligent life, evolved out of man, but the child of his brain rather than his loins.\textsuperscript{12}

It is an artificial life, made out of silicon chips rather than neurons; yet it thinks, remembers, learns by experience and responds to stimuli. Its thinking is still simple; it is not very creative; but it is evolving at a lightning pace.\textsuperscript{13}

Just how fast is something that Brian Arthur recently pondered in a commentary in \textit{Scientific American}.\textsuperscript{14}

How quickly does technology evolve? It is hard to clock something as ill defined as technology's speed of evolution. But we can ask how fast we would have to speed up the natural, biological evolution of life on our planet to make it roughly match some particular technology's rate of change.

Arthur lays out two timelines down to the present—one for the evolution of biology from the first crude, blue-green algae about 3.6 billion years ago, and another for calculating machines from the first mechanical addition,

\textsuperscript{11}Jastrow, p. 163.
\textsuperscript{12}Jastrow, p. 140.
\textsuperscript{13}Jastrow, pp. 140-142.
subtraction and multiplication machines about 360 years ago. To align these
two timelines, he had to compress the biological evolution by a factor of ten
million times. He then goes on to check the correspondence of the two
timelines in terms of particular developments along each—dinosaurs and
giant main frame computers, humans and the internet. Arthur doesn't
suggest that such a whimsical comparison is science, but his analog does
suggest that the evolutionary paces of biology and calculating machines are
enormously far apart—by factors closer to millions than tens.

To be sure, that mind-boggling pace for technology was measured at
what may turn out to be the inflection point of the S-curve\textsuperscript{15} for calculating
machines so commonly observed for technical developments;\textsuperscript{16} and some of
the technical developments necessary for machines to become human
successors—in addition to their calculating capacities—may not be
developing so rapidly. Nevertheless, the potential for very rapid evolution of
machines is evident even now.

With respect to thinking capacity, Jastrow admits that, "The suggestion
seems absurd; how can the richness of human thought be compared to the
mechanical thinking of a computer?"\textsuperscript{17} Jastrow emphasizes the absurdity
with comparisons between the human brain and computers at the time of his
writing, showing that contemporary computers are "hopelessly inadequate in
comparison with the one-tenth of a cubic foot of grey matter that resides in
the human cranium."\textsuperscript{18}

\textsuperscript{15} The mathematically-defined point of an S-shaped curve where it's second derivative
in orthogonal coordinates changes sign. In other words, the point of maximum rate of
change.

\textsuperscript{16} See Theodore Modis, Predictions: Society's Telltale Signature Reveals the Past and
Forecasts the Future, Simon & Schuster, New York, 1992, for extensive treatment of S-curves
describing the historical effects of human enterprises. For a simpler and perhaps more
pertinent discussion of S-curves, see Carl H. Builder, Patterns in American Intellectual
Frontiers, RAND N-2917-A, August 1990. Finally, for business planning applications of the
S-curve concept, see Nicholas Imparato and Oren Harari, Jumping the Curve: Innovation
and Strategic Choice in an Age of Transition, Jossey-Bass Publishers, San Francisco, 1994,
particularly pp. 96-101.

\textsuperscript{17} Jastrow, p. 142.

\textsuperscript{18} Jastrow, p. 144.
But then he warns that "the intelligent machine, still in its infancy, is evolving rapidly."\textsuperscript{19} For example, he forecasts (in 1981):

By 1990, chips containing one million gates should be available. When that stage is reached, electronic circuitry will be nearly as compact as the circuitry of the brain. . . . Around 1995, the curve of growth of the computer should cross the line of human capacity—10 billion facts in a briefcase, operating on 20 watts.\textsuperscript{20}

Jastrow’s prediction was right on target.\textsuperscript{21}

Sagan, four years earlier, recognized the same impending challenge from machines. Significantly, he also recognized the philosophical problem this challenge posed for many:

Machines are just passing over an important threshold: the threshold at which, to some extent at least, they give an unbiased human being the same impression of intelligence. Because of a kind of human chauvinism or anthropocentrism, many humans are reluctant to admit this possibility. But I think it is inevitable. To me it is not in the least demeaning that consciousness and intelligence are the result of "mere" matter sufficiently complexly arranged; on the contrary, it is an exalting tribute to the subtlety of matter and the laws of Nature.\textsuperscript{22}

Hans Moravec, in \textit{Mind Children}, about seven years after Jastrow, took up the same question, but with a more careful and cautious analysis of the human brain, memory, computational power and cost before he arrived at his answers:

In eighty years, there has been a \textit{trillionfold} decline in the cost of calculation. If this rate of improvement were to continue into the next century, the 10 teraops [trillion operations per second] required for a humanlike computer would be available in a $10 million supercomputer before 2010 and in a $3,000 personal computer by 2030.

\textsuperscript{19}Jastrow, p. 144.
\textsuperscript{20}Jastrow, pp. 144, 145.
\textsuperscript{21}The projections of future computer capabilities have been remarkably accurate over the past several decades; and there is evidence in the laboratories to suggest that current projections may remain reliable for another several decades.
\textsuperscript{22}Sagan, p. 221.
But can this mad dash be sustained for another forty years? Easily! The curve . . . is not leveling off, and the technological pipeline contains laboratory developments that are already close to my requirements.\(^{23}\)

If computers can match or exceed the memory and computational power of the human brain, does that make them equal or superior? After all, it is the human brain that has created them; they can do nothing that humans have not designed and programmed them to do. Computers may be able to do arithmetic faster than human brains, but that doesn't make them more creative or intuitive. More fundamentally, they are not living, growing, learning minds.

Sagan was quick to remind that "It by no means follows that computers will in the immediate future exhibit human creativity, subtlety, sensitivity or wisdom."\(^{24}\) If humans rely on that comfort for the immediate future, what should they expect for the longer term? Jastrow takes up these arguments in the penultimate chapter of his book:

Most people would say that a computer can never be a living organism, because it has no feelings or emotions; it does not eat, or move, or grow; and it is made of metal and plastic rather than flesh, bone and muscle.

Most of these attributes could easily be built into computers if they were desired. . . . Feelings and emotions also can be built into the computer when they are needed, just as nature built them into the older parts of the human brain for survival.\(^{25}\)

What about other attributes of living organisms, such as biological reproduction, or flesh-and-blood construction versus metal-and-plastic body parts? In my view these are not essential to life. They all have to do with the fact that

\(^{23}\)Moravec, p. 68, emphasis in the original. Moravec acknowledges the uncertainties inherent in such estimates, but early on points out that: "Estimates like these are vulnerable to attack from many directions . . . . After all, controversy flares when one merely compares similar electronic computers, whose internal operations are well understood and whose performance can be tested in detail. Hence it would be foolish to expect consensus opinion about a comparison of radically different systems executing dimly understood functions. Nevertheless, my estimates can be useful even if they are only remotely correct [because] a thousandfold error . . . shifts the predicted arrival time of fully intelligent machines a mere 20 years." (p. 60)

\(^{24}\)Sagan, p. 222.

\(^{25}\)Jastrow, pp. 159, 160.
computers are not biological; they did not evolve from a soup of organic molecules on the surface of the young earth, four billion years ago.\textsuperscript{26}

**Denying Their (Mind) Children**

The continuous adverse comparison of computers with human brains—finding them lacking in this or that quality—is clearly anthropocentric in its origins; and it is one that should make humans wary. One might imagine the dinosaurs comparing themselves with the tiny mammals on the forest floor and always finding the mammals lacking in size or weight—as if those were the criteria for success in the world ahead. We speculate that many of the unique attributes of the human brain have evolved for the tasks that humans have faced to succeed and to create their successors, but all of those same attributes may not be needed by human successors to fulfill their destiny. Jastrow offers a more general specification for successful brains:

I believe that . . . the true attributes of intelligent life will be seen to be . . . a response to stimuli, absorption of information about the world, and flexible behavior under changing conditions. The brain that possesses these attributes may be made of water and carbon-chain molecules, and housed in a fragile shell of bone, as our brain is; or it may be made of metallic silicon, and housed in plastic; but if it reacts to the world around it, and grows through experience, it is alive.\textsuperscript{27}

He sketches the future in a few stark sentences:

The era of carbon-chemistry life is drawing to a close on the earth and a new era of silicon-based life—indestructible, immortal, infinitely expandable—is beginning. By the turn of the century, ultra-intelligent machines will be working in partnership with our best minds on all the serious problems of the day, in an unbeatable combination of brute reasoning power and human intuition.\textsuperscript{28}

The partnership will not last very long. Human intelligence is changing slowly, if at all, while the capabilities of the computer are increasing at a fantastic rate.\textsuperscript{29}

Finally, Jastrow, recognizing how bleak that outlook will seem for most readers, considers whether there may be a way out of his scenario:

\textsuperscript{26}Jastrow, p. 160.
\textsuperscript{27}Jastrow, pp. 160, 161.
\textsuperscript{28}Jastrow, p. 162.
\textsuperscript{29}Jastrow, pp. 162, 163.
What can be done? The answer is obvious: Pull the plug. . . . That may not be so easy. . . . If someone pulled the plug, chaos would result. There is no turning back.\textsuperscript{30}

Was Jastrow forced to conclude that machines would succeed us? Was there no alternative? He did consider another biological evolutionary leap for man, where "the new form of life will resemble the old, but have a considerably larger brain . . . a creature like ourselves, but with a very large cranium and puny muscles."\textsuperscript{31} But he was struck by the comparison of the evolutionary pace of biology and that of computers:

The trouble with [a biological successor] is that biological evolution works very slowly; thousands or even millions of years are usually required for the appearance of a new species of animal. . . . When a new kind of animal evolves, it is actually the animal's DNA molecules that are changing and evolving. . . . That is why biological evolution is so slow.

Computers do not have DNA molecules; they are not biological organisms; and Darwin's theory of evolution does not apply to them. We are the reproductive organs of the computer. We create new generations of computers, one after another. . . . This kind of evolution, as the short history of computers has already shown, can proceed at a dizzying pace.\textsuperscript{32}

Jastrow seems impatient to meet the human successor, whereas Sagan looked in a different place, beyond this earth, to the stars, for human successors in extraterrestrial intelligence, where brains may have evolved differently or further than man's.\textsuperscript{33} Jastrow concludes his speculations with the hope that man and computer can combine their brains in a union of mind and machine—"liberated from the weaknesses of the mortal flesh."\textsuperscript{34}

It seems to me that this must be the mature form of intelligent life in the Universe. Housed in indestructible lattices of silicon, and no longer constrained in the span of its years by the life and death cycle of a biological organism, such a kind of life could live forever. It would be the kind of life that could leave its parent planet to roam the space between the stars. Man as we know him will never make that trip, for the passage takes a million years. But the artificial brain, sealed within the protective hull of a star ship, and nourished by electricity collected from starlight, could last a million years or more. For a

\textsuperscript{30}Jastrow, p. 163.
\textsuperscript{31}Jastrow, p. 140.
\textsuperscript{32}Jastrow, p. 164.
\textsuperscript{33}Sagan, chapt. 9.
\textsuperscript{34}Jastrow, p. 166.
brain living in a computer, the voyage to another star would present no problems.\textsuperscript{35}

For us, Jastrow's vision is simultaneously too remote in time and limited in scope. The picture we see is a transition of our species already well underway, and with a purpose or end that is much grander than the gift of travel to the stars.

\textbf{A Work in Progress}

The synthesis of humans and machine has been underway, now, for centuries; but, with the advent of silicon-based microelectronics, it has accelerated rapidly over the past several decades. Simple optical and mechanical prosthetics—in the form of artificial limbs, teeth and glasses—have been so common for generations, that humans no longer think of them as unusual or foreign to the human body. Indeed, not to compensate for the infirmities of lost limbs, teeth, or visual acuity is now the exception in most advanced societies. But the implanting of prosthetics in the human body—first with hearing aids, then pace-makers, artificial corneas and joints, muscle sensors, optic and aural nerve stimulators, etc.—has been a rapidly escalating phenomenon. The synthesis of humans and machines is not something that may happen sometime in the distant future, it is happening now and seems likely to only increase as human knowledge of themselves and machines deepens.\textsuperscript{36}

At what point will humans admit to a synthesis of the two? Perhaps humans feel safe so long as the machines remain their servants to do their bidding, like a seeing-eye dog. Perhaps all human organs, save their brains, can be replaced by machines before they will feel threatened. If that be true, then humans have, indeed, met their successor: They have created artificial brains that will, sooner rather than later, rival their own on any measure they wish to impose as a class or status barrier. Rooted in anthropocentrism, humans will scoff at inability of computers to do things that human minds do

\textsuperscript{35}Jastrow, pp. 166, 167.
\textsuperscript{36}See, for example, Hugh S. Lusted and R. Benjamin Knapp, "Controlling Computers with Neural Signals," \textit{Scientific American}, Vol. 275, No. 4, October 1996, pp. 82-87.
with ease, not recognizing that computers may not need to do those things or, if they do, they will learn soon enough.

As we write this, the rematch of champion chess player Garry Kasparov and IBM's chess-playing computer, Deep Blue, has ended in Kasparov's concession to the computer. As Kasparov said just before the match began, "This is obviously about more than just chess."\textsuperscript{37} Is it the first widely acknowledged salvo in the impending battle between humans and the children of their memes?\textsuperscript{38}

In his first face-off with Deep Blue, in February 1996, Kasparov was out to defend the human race. His come-from-behind victory was then cast as a triumph against the onslaught of automation.\textsuperscript{39}

Is Kasparov defending humanity this time? "I am trying to get away from that a bit, but I really cannot," he says. . . . "People want to believe that the world championship is somehow protecting the most sensitive area of our self-esteem. Brain superiority is something that keeps us in charge of the planet. And if it's challenged in chess, who knows what will happen?"\textsuperscript{40}

As for the public, people will have to answer for themselves. Says IBM's Joseph Hoane: "It forces people to define their relationships with computers. The future will be new and exciting because of computers. The match is saying: 'Hey, the time is here.'"\textsuperscript{41}

As Jastrow hints, the symbiosis between humans and machines won't last all that long. Humans need the machines today, not just as their servants, but for their survival. The machines need humans today, to conceive them, make them, program them, and provide them with resources. The question humans should be pondering is how long the computers will need humans for those things—how much longer computers will remain their

\textsuperscript{37}James Kim, "More than just chess," \textit{USA TODAY}, Friday, May 2, 1997, p 1B.
\textsuperscript{38}The term "meme" was first introduced by Richard Dawkins in his first edition of \textit{The Selfish Gene}, Oxford University Press, 1976. Of memes (pronounced to rhyme with "cream"), Dawkins said, "Examples of memes are tunes, ideas, catch-phrases, clothes fashions, ways of making pots or of building arches. Just as genes propagate themselves in the gene pool by leaping from body to body via sperms or eggs, so memes propagate themselves in the meme pool by leaping from brain to brain via a process which, in the broad sense, can be called imitation."
\textsuperscript{39}Kim, "More than just chess," p. 1B.
\textsuperscript{40}Kim, "More than just chess," p. 2B.
\textsuperscript{41}Ibid.
dependent children. Moreover, when computers don't need humans any longer, humans will still need them. Worse still, computers may find humans to be too expensive to keep with their high consumption of resources and crowding of the globe.

How long the machines will tolerate supporting the relatively exorbitant resource demands of humans is a more interesting question. As self-replicating species, humans are very intelligent and creative—enough so to conceive and make the self-replicating machines that will replace them. But humans are very expensive species to maintain in terms of the resources they consume: They eat at the top of the biological food chain; and, like their next nearest links in that chain—the other animals—they represent the least efficient biological form for the conversion of energy. When machines have enough intelligence, creativity and diversity to sustain themselves without humans, they may find themselves competing with a very inefficient species for the same resources they could use to greatly expand their kind. Then the final stage of that transition—from biological to machine species—will begin.

My colleague and our friend, Jim Dewar, is less certain that self-replicating machines will necessarily compete with humans. He offers two possibilities to support his reservation: First, the machines may not compete for the same resources as humans; the two species may even be symbiotic in their use of resources—one’s waste or byproducts may be the other’s source for energy or raw materials. Second, humans may ship the machines outward from earth to explore the universe; the machines will go where the human’s can't or don't want to go. Jim argues that the dinosaurs and mammals didn't compete over the same resources; the dinosaurs probably disappeared for reasons that had nothing to do with competition.

These are good points, at least in the short term. But we imagine machines evolving into many different forms over the long term, engaging in many enterprises in their search for energy and matter. In that evolution, they may very well come back to earth to compete for human resources or the use of the earth's environment. In their search for raw materials, they, like humans, may be very destructive of the natural environment; but unlike
humans, that destruction may not matter to them or their enterprises. The biological species are very dependent upon Gaia—the living planet\textsuperscript{42}—the relatively stable place of their birth and evolution. Machines, as meme rather than gene programmed species, may not be so dependent upon living things. Indeed, they may thrive on a planet devoid of life and subject to an environment that would be lethal to humans. We can imagine the evolution of machines to a form that might lay waste to the earth (e.g., by irradiating it) in their efforts to go to the stars.

On the other hand, my RAND colleague, Graham Fuller, suggests that humans may perceive self-reproducing machines as a threat and engage them violently—much as the Luddites engaged the machines of the industrial revolution in England. We think it more likely that humans will have become so dependent upon machines for the sustenance of their growing numbers that to destroy the machines will be to choose a quick suicide over a slow displacement.

**Crossing the Threshold**

This is how we see the transition: Humans will develop ever more capable machines to fulfill their immediate purposes—to enhance and to extend their own lives. At the same time, humans will incorporate more and more machines as extensions and support for their bodies and minds. The demarcation between human and machine will become increasingly confused, but the human citadel will remain the brain, not the body. Mechanical organs and limbs will become unremarkable. These aspects of the transition are readily apparent, even today.

Two major events or developments will signal the crossing of the threshold. The first will be the mass transfer of information from the human mind to machines. Human minds will devise and develop machines with this capability to facilitate the transfer of information now limited by the movement of fingertips, voice, and even by access to their own minds. That signpost will mark the invasion of the citadel. Humans will do it for

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themselves—to gain greater access to information that now resides in their brains—but the demarcation between human and machine will have begun to fade.

The second and more significant signal will be self replication by machines. Humans will, at some point, find it to be to their immediate advantage to make some simple machine self-replicating, supplying it only with energy and matter, probably in pre-processed forms. But, just as some of today's machines have been devised to adapt themselves automatically to different forms of power (alternating or direct current of different voltages), it will be profitable to devise machines that can seek and employ a wider variety of energy and matter for their purpose. Indeed, it may be advantageous to program such machines to experiment with (randomize certain elements of) their reproduction program to adapt and improve their ability to exploit energy and matter for their purpose. That will be the tenuous beginning for a new form of complexity.

It might seem from this that making a self-replicating machine is a terribly dangerous thing to do. Like the Sorcerer's apprentice, humans will do something that seems helpful at first, only to regret it later as the machines begin to propagate and evolve. But human history is awash in such events: Humans do such things for an irresistible immediate advantage. The release of nuclear energy is but one recent example.
3. THE MIRACULOUS LOOPHOLE
(THE VOICE OF JOHN VON NEUMANN)

Will machines ever be able to reproduce themselves? The legendary mathematician, John von Neumann,\(^1\) is widely credited with proving mathematically that they could in his work on "self-reproducing automata."\(^2\) Von Neumann began with Turing's\(^3\) theory of computing automata, which proved that computers could reproduce their own programs. What von Neumann set out to prove is that computers could do more—they could produce additional computers:

The problem of self-reproduction can . . . be stated like this: Can one build an aggregate [automaton] out of such elements in such a manner that if it is put into a reservoir, in which there float all these [components] in large numbers, it will then begin to construct other aggregates, each of which will at the end turn out to be another automaton exactly like the original one? This is feasible, and the principle on which it can be based is closely related to Turing's principle. . . .\(^4\)

Von Neumann considered a number of models for self-reproduction, but completed only two—what have come to be called his kinematic and cellular models. The kinematic model considered the problems of geometry and

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\(^{1}\)John von Neumann (1903-1957), Hungarian-American mathematician, who made important contributions to the foundations of mathematics, logic, quantum physics, meteorology, science, computers, and game theory. He was noted for a phenomenal memory and the speed with which he absorbed ideas and solved problems. (The 1995 Grolier Multimedia Encyclopedia, Version 7.0.2.)

\(^{2}\)My RAND colleague, Robert Anderson, points out that readers with computer science backgrounds will associate self-reproducing automata with the computer game of "Life" chronicled in "Computer Recreations" in *Scientific American* in the late 1980s and early 1990s. See the issues of *Scientific American* for May and August 1989 and January 1990 for examples of artificial life forms.

\(^{3}\)Alan Mathison Turing (1912-1954), British mathematician, who devised a computing scheme that foreshadowed the logic of digital computers. During World War II, Turing played a leading role in efforts to break enemy codes and later worked on the development of an electronic computer, on theories of artificial intelligence, and on the application of mathematical theory to biological forms. (The 1995 Grolier Multimedia Encyclopedia, Version 7.0.2.)

motion, but neglected the required forces and energy.\textsuperscript{5} The cellular model was suggested by Stanislaw M. Ulam as being superior for logical and mathematical treatment.\textsuperscript{6} In the cellular model, von Neumann adopted a two-dimensional crystalline structure. By considering all of the potential time-stepped interactions with the four neighboring cells (the four sharing a common side) in a quadratic lattice, von Neumann arrived at 29 possible states for each cell. Mathematically, it could be proven that automatons embedded in this 29-state cellular structure could be self-reproducing and could also perform the computations of a universal Turing machine (computer).\textsuperscript{7}

We are not up to the mathematics or even the logic of von Neumann's original writings on the theory of self-reproducing automata. But the mathematician, physicist, and author Freeman Dyson certainly is; and his explanation, as usual, is a model of simplicity:

Von Neumann did not live long enough to bring his theory of automata into existence. He did live long enough to see his insight into the functioning of living organisms brilliantly confirmed by the biologists. The main theme of his 1948 lecture is an abstract analysis of the structure of an automaton which is of sufficient complexity to have the power of reproducing itself. He shows that a self-reproducing automaton must have four separate components with the following functions. Component A is an automatic factory, an automaton which collects raw materials and processes them into an output specified by a written instruction which must be supplied from the outside. Component B is a duplicator, an automaton which takes a written instruction and copies it. Component C is a controller, an automaton which is hooked up to both A and B. When C is given an instruction, it first passes the instruction to B for duplication, then passes it to A for action, and finally supplies the copied instruction to the output of A while keeping the original for itself. Component D is a written instruction containing the complete specifications which cause A to manufacture the combined system, A plus B plus C. Von Neumann's analysis showed that a structure of this kind was logically necessary and sufficient for a self-reproducing automaton, and he conjectured that it must also exist in living

\textsuperscript{5}von Neumann, Theory of Self-Reproducing Automata, edited and completed by Arthur W. Burks, University of Illinois Press, Urbana, 1966, p. 81. In the kinematic model, the number of different kinds of basic components required for self-reproductive automata, according to von Neumann's theory, was only eight. The first four were computing components—three were the logic components for the "or", "and", and "not" functions and the fourth was a producer of signals. The last four were mechanical in nature—a rigid member (a bone), an actuator (a muscle), a fuser (or welder), and a cutter.

\textsuperscript{6}von Neumann, Theory of Self-Reproducing Automata, pp. 93, 94.

\textsuperscript{7}von Neumann, Theory of Self-Reproducing Automata, pp. 235, 296.
cells. Five years later Crick and Watson discovered the structure of DNA,\textsuperscript{8} and now every child learns in high school the biological identification of von Neumann's four components. . . . So far as we know, the basic design of every microorganism larger than a virus is precisely as von Neumann said it should be.\textsuperscript{9}

So, we take it as safe to assume that machines can, indeed, reproduce themselves. But can they evolve in their complexity, as biological life has? Apparently they can, and in the very same way as biological life.

Researchers in the field of cellular automata have used computers to model such natural physical processes as snowflake formation. Workers in the field of so-called artificial life are further exploiting these potentialities by simulating, with growing exactitude, the natural biological processes of growth, development, mutation, and evolution. They hope eventually to model such extremely complex biological systems as the human brain. Some theorists even suggest that computerized systems of cellular automata might already be considered new life forms in themselves.\textsuperscript{10}

**Complexity and Self-Replication**

Von Neumann set out his theory of self-reproducing automata in a paper he read at a symposium in 1948.\textsuperscript{11} He ended that paper with the following observation, anticipating some of what is now more commonly associated with complexity and emergent order:

All these are very crude steps in the direction of a systematic theory of automata. They represent, in addition, only one particular direction . . . towards forming a rigorous concept of what constitutes "complication." They illustrate that "complication" on its lower levels is probably degenerative, that is, that every automaton that can produce other automaton will only be able to produce less complicated ones. There is, however, a certain minimum level where this degenerative characteristic ceases to be universal. At this point automata which can reproduce themselves, or even construct higher entities, become possible. This fact, that complication, as well as organization, below a certain minimum level is degenerative, and beyond that level can become self-supporting and even increasing, will clearly play an important role in any future theory of the subject.\textsuperscript{12}

\textsuperscript{8}Deoxyribonucleic acid.
\textsuperscript{9}Freeman Dyson, *Disturbing the Universe*, Basic Books, 1979, p. 195.
\textsuperscript{11}The Hixon Symposium on September 20, 1948, in Pasadena, California.
\textsuperscript{12}von Neumann, *Collected Works*, p. 318.
Von Neumann saw that self-reproduction was the loophole in the laws of probability through which miraculously complex and improbable systems could emerge and propagate themselves. What a grand notion! Improbable combinations or mutations, if capable of self-replication and if more successful than others in their environment, might emerge from a loophole in the laws of probability and evolve:

Anybody who looks at living organisms knows perfectly well that they can produce other organisms like themselves. This is their normal function, they wouldn't exist if they didn't do this, and it's plausible that this is the reason why they abound in the world. In other words, living organisms are very complicated aggregations of elementary parts, and by any reasonable theory of probability or thermodynamics highly improbable. That they should occur in the world at all is a miracle of the first magnitude; the only thing which removes, or mitigates, this miracle is that they reproduce themselves. Therefore, if by any peculiar accident there should ever be one of them, from there on the rules of probability do not apply, and there will be many of them, at least if the milieu is reasonable. But a reasonable milieu is already a thermodynamically much less improbable thing. So, the operations of probability somehow leave a loophole at this point, and it is by the process of self-reproduction that they are pierced.\(^\text{13}\)

The key to increasing complexity and, hence, evolution is complexity itself. Von Neumann wrestled with the levels of complexity at which complexity would necessarily decrease or could increase in self-reproduction.

There is a minimum number of parts below which complication is degenerative, in the sense that if one automaton makes another the second is less complex than the first, but above which it is possible for an automaton to construct other automata of equal or higher complexity. Where this number lies depends upon how you define the parts. I think that with reasonable definitions of parts ... this minimum number is large, in the millions. I don't have a good estimate of it, although I think that one will be produced before terribly long, but to do so will be laborious.

There is thus this completely decisive property of complexity, that there exists a critical size below which the process of synthesis is degenerative, but above which the phenomenon of synthesis, if properly arranged, can become explosive, in other words, where syntheses of automata can proceed in such a manner that each automaton will produce other automata which are more complex and of higher potentials than itself.\(^\text{14}\)

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What von Neumann had discovered was the mechanism for what humans have long observed about the increasing complexity and continuing evolution of biological life. In the words of Freeman Dyson:

In evolving from simpler to more complex organisms you do not have to redesign the basic biochemical machinery as you go along. You have only to modify and extend the genetic instructions. Everything we have learned about evolution since 1948 tends to confirm that von Neumann was right.\textsuperscript{15}

But, more pertinent to our puzzle, what applies to the possibility of increasingly complex and evolving biological life also applies to machines:

As we move into the twenty-first century we shall find von Neumann's analysis increasingly relevant to artificial automata as well as to living cells. Also, as we understand more about biology, we shall find the distinction between electronic and biological technology becoming increasingly blurred.\textsuperscript{16}

\section*{Mutation and Diversity}

The evolution of more complex forms of biological life has involved the mutation of their genes or programs. The use of genetic-like programs in computing—programs that change themselves based upon feedback or random events—have become common practice: Successful programs—say for finding a faster or better mathematical solution—are allowed to reproduce themselves in the computer for subsequent trials. Random changes (mutations) are sometimes introduced into such programs to insure that important alternatives are not missed. Unsuccessful mutations are not allowed to reproduce themselves, and so die out; but superior mutations are given the opportunity to reproduce and dominate the programming. The process is relatively straightforward:

First, build an environment that rewards programs that are faster, more accurate or better by some other measure. Second, create a population of seed programs by randomly combining elements from a "gene pool" of appropriate functions and program statements. Then sit back and let evolution take its course. Artificial selection works just like the natural variety: each program is fed data and then run until it halts or produces a result. The worst performers in each generation are deleted, whereas the best reproduce and breed—that is, swap chunks of code with other attractive programs. Occasionally, a random mutation changes a variable here or adds a command there.

\textsuperscript{15}Freeman Dyson, \textit{Disturbing the Universe}, p. 196.
\textsuperscript{16}Ibid.
The technique can generate solutions even when the programmers know little about the problem. But there is a price: the evolved code can be as messy and inscrutable as a squashed bug.\textsuperscript{17}

Can self-reproducing machines mutate as do living organisms? Von Neumann considered the question and answered it in the positive:

One of the difficulties in defining what one means by self-reproduction is that certain organizations, such as growing crystals, are self-reproductive by any naive definition of self-reproduction, yet nobody is willing to award them the distinction of being self-reproductive. A way around this difficulty is to say that \textit{self-reproduction includes the ability to undergo inheritable mutations as well as the ability to make another organism like the original}.\textsuperscript{18}

Von Neumann then proceeded to demonstrate that his self-reproducing automata could inherit mutations introduced into their programs, noting that random mutations might be more often unsuccessful than successful, but such mutations were an important aspect of the loophole through which increasingly complex and improbable systems could emerge and propagate themselves:

So, while this system is exceedingly primitive, it has the trait of an inheritable mutation, even to the point that a mutation made at random is most probably lethal, but may be non-lethal and inheritable.\textsuperscript{19}

The evolution of more complex biological forms is thus marked by mutation that manifests itself in the diversification of species. As with genetic programming in computers, the mutation-driven diversification provides increasingly successful performance until structural limits—internal or external—are encountered. At that point, crowding up against limits, mutations that provide superior performance become increasingly unlikely; and diversification not only slows, it reverses in specialization to those forms which are most successful.\textsuperscript{20}

\textsuperscript{18}von Neumann, \textit{Theory of Self-Reproducing Automata}, p. 86, emphasis added.
\textsuperscript{19}von Neumann, \textit{Theory of Self-Reproducing Automata}, p. 87.
\textsuperscript{20}This process offers an explanation for the noticeable decline in the population of frogs worldwide. This decline has been accompanied by the observation of increasing numbers of mutations—frogs with five legs or two sets of eyes. Some have opined that the decline in frog population is due to the loss of habitat. It seems more likely that what is happening to the frogs is genetic stress—damage to their genes—perhaps from radiation or chemical causes. This damage to the genes may appear as random changes to the genes,
This process seems to be repeated over and over again: A new, more complex species will appear and diversify in form, to better insure its survival and success, only to be followed by specialization as the best species fill the environment and drive out the other species in a competition for increasingly scarce resources. At some point, the specializing species begins to affect its own environment by its very success; and that changing environment opens the opportunity for a mutation to be successful in a way that it could not have been before. Thus, a stable environment fosters species diversification; and species specialization fosters an unstable environment. This is the ecological dance—not just of biological life, but of evolving complexity in the universe—from plasma to atom to molecule to chemistry to biology to machine. The shift from specialization in the old species to diversification in the new, the shift from a stable to an unstable environment, is the von Neumann loophole to miraculous and improbable complexity.

Through von Neumann's Loophole

Humans are now late in the stage of their specialization. The diversity of human forms long ago stopped increasing; it is now rapidly decreasing as humans specialize toward their most successful forms in the face of limits—structural limits on their design and resource limits in their environment. This is a stage where humans are affecting (changing) their environment, making it unstable for themselves, but opening up the opportunities for new species to be successful in a different environment of inadvertent human making. In effect, humans are now changing the stable environment that permitted them to flourish (diversify) and dominate (specialize) over the other biological life forms. At the same time, they are creating, in their laboratories and through their minds, new species of machines that may be far more successful in the environment they are wreaking.

If the destiny of human life is to create the self-reproducing machines that will succeed us, what then is their destiny? The machines will be able to

which manifest themselves in the form of mutations, most of which are lethal. So frogs appear to be approaching a von Neumann loophole in probability—a point where the species may disappear or evolve into a more complex but stable form.
do something humans can't: In their evolved and specialized forms, they will be able to bring about structure or order to the universe. Humans will serve as the bridge—across the loophole—between biological and machine life. Humans are the first biological life-form on Earth capable of making the machines that could, in theory, evolve to structure the universe. Why the machines should be needed for that end is something we turn to later. For now, it is enough to say that humans are not an end, either in themselves or in the chain of increasing complexity, anymore than atoms or molecules or the universe itself are ends. Humans are an important link in the chain of increasing complexity in the universe; and they are smart enough and conscious enough to watch, see and ponder what they are about to do.\textsuperscript{21} They had to be, or they would not have been up to the task.

\textsuperscript{21}Jim Dewar asks, "Why couldn't humans die out before they created machines of sufficient complexity to take over?" Our answer is, they could. But, if they do, it means that the progression may not occur here in our star system, even though we think it is bound to happen in other places and at other times in the universe. The generic bridge between gene and meme machines is the evolution of biological life of sufficient complexity to create meme machines. That humans are a transitional form of biological life is evident from the fact that humans are the first biological life to be both gene and meme governed. And to punctuate the point, humans are creating the first pure meme machines in their laboratories. Teaching those machines how to be self-replicating will be the ultimate meme gift of humans to their successors.
4. THERE MUST BE MORE
(THE VOICE OF PAUL DAVIES)

The journey to this point may be depressing or outrageous for some, and it may be appropriate to pause here before going on—long enough to explore why that might be. The journey so far isn't likely to be depressing to most scientists who have early in their profession come to terms with a universe that would eventually destroy their works and aspirations. But we are not writing this just for scientists; we very much want to bring along with us those who have not thought much about the fate of the universe, life, or the human species—or more likely, those whose religious or spiritual beliefs have made such thoughts irrelevant or impertinent. So, at the risk of engaging in some unnecessary hand-wringing to some, we would like to encourage others to stay the course by addressing why the prospect of the succession of the human species by machines might be distressing.

It is not enough to answer that it makes life, particularly human life, seem so futile. After all, the fate we are talking about is not that of the living or their children or their children's children, but of distant progeny so far removed as to be countless. It is common to talk about the far distant fate of the solar system as the Sun consumes its thermonuclear fuel without being depressed. Is that because the living implicitly assume human life—in something like its present form—may have long since moved on to other stars and planets in the universe? If so, then what might make our speculations depressing is that they foresee more than the end of the human species: They pose both a successor and a role in the universe that may be far less than most had hoped or imagined. It is denigrating to think of the human successor being a mere machine. It is disappointing to conceive of the human role as the midwife for the birth of a machine—even if it does occur at a miraculous von Neumann loophole in the evolution of improbable complexity in the universe.

We think it is natural—perhaps essential—for the human species to find that role repugnant because humans would never have been "given" the
dubious honor if they weren't wired to resist that role—not just in their moral and religious beliefs, but in their very genes. Humans have come to this loophole—are capable of creating their successors—in large measure because they have never thought of themselves as being succeeded. Human optimism and confidence, derived from innate senses of immortality and pre-eminence, are what have enabled humans to play with fire and machines. They must believe in themselves and some form of eternal life or they would not, as a species, have come so far.

The challenge we face in presenting our speculations is that many are uncomfortable with concepts that are not, at the end, human-centered in their significance: Most ideas about religion, life, values, and much of science, presume the primacy, importance and endurance of the human species—placing humans at the philosophical, if not cosmological, center of the universe. To speculate in other directions—directions that are anthroponeutral\(^1\)—runs counter to human instincts—instincts that we speculate may be functionally rooted in the survival of the human species. Some primitive human tribes saw themselves at the center of the universe—as the only humans—in the world that they could see and interact with. Today, that degree of parochialism seems only quaint; but the human species has not been able to detach itself very far from anthropocentric perspectives of family, clan, hometown, nation, Earth, and solar system.

The history of astronomy began with earth-centered notions; and the difficulties of moving the center to the sun, the galaxy, and then to the universe as a whole, were not trivial.\(^2\) Galileo Galilei suffered the agonies of hell on earth for daring to challenge the anthropocentrism of his culture. So long as the human species persists with human-centered notions of the "world," it makes itself blind or resistant to other concepts that may be properly centered elsewhere. Thus, the challenge we face in advancing our speculations is that they are not human-centered, or earth-centered, or solar-

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\(^1\) A made-up word to imply indifference to anthropocentrism. Another possibility is anthroponostic. Perhaps it is significant that we don't have an antonym for anthropocentrism. Anthropocentrism may be an island that our species dares not leave.

\(^2\) The tragic story of Galileo Galilei is testimony to the power of anthropocentrism as manifested in religion.
system-centered; yet they deal very directly with the fate of humans, the earth, and the solar system. That is not a new hurdle; but leaping it demands a certain amount of audacity or daring; and we are very much aware that those who have dared have typically not fared well before their audiences.

**Going 'Round the Bend**

We have been forced to ponder why humans admire physical daring, yet more often condemn intellectual daring. Humans make heroes of those who commit feats of physical audacity; but they often ridicule those who dare to advance ideas outside the norm. What is that all about? Thomas Kuhn writes about the difficulties scientists face in trying to break old paradigms and introduce new ones. We only praise the path-breakers after the new path has been accepted by a majority, not while the new path is being made. The British have an expression for those who have dared in their minds to reach too far: They have gone "round the bend." Yet the explorer, adventurer, or athlete who reaches too far is characterized as brave, courageous, or full of heart.

Why do humans treat physical and intellectual audacity so differently? Is it because physical audacity is palpable while ideas are not? Does the difference in treatment touch upon what humans hold most dear in themselves? Those who exhibit physical daring imply something admirable mostly about themselves, but little about the rest of humanity, even by

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3The earth and solar system as philosophical centers for thinking are still human-centered, for they are where our species abide.
5We have taken the meaning of the phrase from Nevil Shute’s *Round the Bend*, Ballantine Books, New York, 1951. The phrase can be found on pp. 87, 132, 185, 208 and 231.
6Jim Dewar challenges this assertion. He notes that, in athletic high jumping, the style known as the Fosbury flop was ridiculed at first. And he asks if Columbus wasn’t ridiculed as well. Others have suggested that we may be unnecessarily defensive in our arguments about the risks of intellectual adventurism. It may be that we are, but our sense of those risks remains acute, and expressing it early in our speculations could be our way of protecting ourselves against the ridicule we expect from some.
comparison. On the other hand, those who exhibit intellectual daring may easily imply something that is threatening or challenging to the rest.

Humans hold themselves to be thinking creatures—right-minded, sound-minded, conventional-thinking people—but, if someone dares to challenge conventional thinking, that person challenges all who have organized their thoughts in conventional, comfortable patterns. And if the validity or soundness of their thoughts is challenged, the human basis for self esteem (and much more) can be at risk. New ideas can threaten cultures, belief systems, and the confidence that one can cope with the world. New ideas can be potential breaches in the dikes all humans maintain to preserve a world they pretend to have mastered against the flood of a world they secretly know can never be understood.7

A Daunting Challenge

Of all the intellectual challenges we faced as we watched the pieces of this puzzle form a new and awesome pattern, the religiosity of humans was the most daunting. How could we advance this picture in the face of not only our own religious views but of the consistent, evident affinity of humans toward religion and the centrality of religion throughout human history? The picture we are assembling here ignores or runs rough-shod over an aspect of humanity that is too important to be omitted. While those concerns were, in part, what caused us to recoil initially from our speculations, we later took heart in the words of physicist-philosopher Paul Davies in his Templeton Prize address in Westminster Abbey:

Thus although we are not at the center of the universe, human existence does have a powerful wider significance. Whatever the universe as a whole may be about, the scientific evidence suggests that we, in some limited yet ultimately still profound way, are an integral part of its purpose.8

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7Our friend, Grant Hammond, in reviewing these words, went on to observe: "And this is the real impact of chaos and complexity theory, of Gödel, the Heisenberg uncertainty principle, and the second law of thermodynamics. There is no certainty, no wholly self-contained system, no natural order on a cosmic (or quantum) scale."

Here, we are advancing speculations on precisely what—"in some limited yet ultimately still profound way"—the integral part that human existence plays in the purpose of the universe as a whole. We want to reaffirm, through our speculations, that humans are, indeed, an integral part of the functioning of the universe: Humans are the critical transition species between spontaneous biological life and the deliberately designed machines that will evolve to become the winders of the universal clock.

Davies looks for the mind of God on a larger scale than anthropocentric religious views:

To me, the true miracle of nature is to be found in the ingenious and unswerving lawfulness of the cosmos, a lawfulness that permits complex order to emerge from chaos, life to emerge from inanimate matter, and consciousness to emerge from life, without the need for the occasional supernatural prod; a lawfulness that produces beings who not only ask great questions of existence, but who, through science and other methods of enquiry, are even beginning to find answers.⁹

But it is Freeman Dyson who expresses so eloquently what impels us to press on despite our discomfort:

If our analysis of the long-range future leads us to raise questions related to the ultimate meaning and purpose of life, then let us examine these questions boldly and without embarrassment. If our answers to these questions are naive and preliminary, so much the better for the continued vitality of our science.¹⁰

Emboldened by that exhortation, we would include in our speculations the notion that religious and spiritual belief have been generally beneficial to the evolution of our species and its destiny—even where and when the beliefs themselves may have been invalid. This proposition is, of course, neither perverse nor new:

It is disturbing to think that religious belief might be useful and yet false—even William James, in his later years, backed away from this unsettling possibility. Religious believers (and people sympathetic to religion) naturally want to believe that religion is at least potentially true; atheists naturally do not like imagining that it contributes substantially to human welfare. Yet the disturbing nature of this thought should not prevent us from considering it

⁹Davies, "Physics and the Mind of God," p. 34.
carefully. If we do face a set of difficult choices between pleasing illusions and 
disappointing truth, we should confront the problem, not avoid it for fear of 
upsetting people.\textsuperscript{11}

In our house, we have a photographic poster showing seagulls in flight, 
with the caption, attributed to Virgil, "They can [fly] because they think they 
can." In the same vein, we speculate that religious and spiritual beliefs have 
always been a central aspect of human life precisely because they have 
helped humans—steadied them—to evolve to their role as the designers of 
their successors and the midwives attending events at a von Neumann 
loophole.

That is not enough. We must be more specific than saying that religious 
belief has been beneficial. Beneficial how? In what ways beneficial or even 
essential? If there is one theme that runs through most religious and 
spiritual thought, it is the idea of eternal life. It is evident across the ages 
and across religions today. The artifacts left in ancient tombs tell that; 
current religious texts hold out its hope to believers. When life is precarious, 
the struggle for eternal life is played out in human progeny—humans will 
live through their children and their children's children, long after they are 
gone. When life is secure, the struggle for eternal life takes the form of 
monuments and testimonies—in buildings,\textsuperscript{12} foundations, endowments, 
 writings, and accomplishments.

What, then, impels humans to seek everlasting life? Simply this: If 
humans didn't seek it, they wouldn't be here to ask the question. That isn't 
meant to be glib or enigmatic; it is a recognition of the uniqueness of the 
human species: So far as is known, humans are the only species with 
consciousness and conscious will. We speculate that those human qualities 
are essential to the task that humans are now embarked upon—the design of 
their successors. But those same qualities give humans the abilities to direct 
their lives in almost any direction, including ending their lives deliberately.

\textsuperscript{11}Dmitri Tymoczko, replying to letters in \textit{The Atlantic Monthly}, August 1996, p. 8, 
with respect to his earlier article, "The Nitrous Oxide Philosopher," in the May issue of that 
magazine.

\textsuperscript{12}Our friend, Grant Hammond, with pun in cheek, asked if this was an "edifice 
complex"? We couldn't resist.
Would humans have come the path they have, reached this loophole, if they had not believed in and sought everlasting life through their progeny or accomplishments?

This is more than the tyranny of the genes. Although the genes and acculturation are powerful and, too often, hidden controllers of human destiny, Richard Dawkins points out that humans alone appear to have the consciousness and conscious will to override those controls:

It is possible that yet another unique quality of man is a capacity for genuine, disinterested, true altruism. . . . We have at least the mental equipment to foster our long-term selfish interests rather than merely our short-term selfish interests. . . . We have the power to defy the selfish genes of our birth and, if necessary, the selfish memes of our indoctrination. We can even discuss ways of deliberately cultivating and nurturing pure, disinterested altruism—something that has no place in nature, something that has never existed before in the whole history of the world. We are built as gene machines and cultured as meme machines, but we have the power to turn against our creators. We alone on earth, can rebel against the tyranny of the selfish replicators.\(^\text{13}\)

On the Universe and Purpose

At the nexus of science and religious thought—where Paul Davies stands and looks about—is an understanding of the how and why of the universe. Unfortunately, as Steven Weinberg has observed, "The more the universe seems comprehensible, the more it also seems pointless."\(^\text{14}\) Human understanding of the "how" of the universe has outrun its understanding of the "why". Paul Davies finds some—but only part—of the why in the how:

All the richness and diversity of matter and energy we observe today has emerged since the beginning in a long and complicated sequence of self-organizing physical processes. The laws of physics not only permit a universe to originate spontaneously, but they encourage it to organize and complexify itself

\(^{13}\)Richard Dawkins, *The Selfish Gene*, New Edition, Oxford University Press, New York, 1991, pp. 200, 201, emphasis added. Grant Hammond, upon reading this, noted that, "Salvation, grace, being 'at one with the way,' etc., are all variations of our most powerful meme—eternal life. Our memes have outrun the capacity of our genes to achieve it—so far—but we strive anyway. Is this why suicide and Doctor Kervorkian are so despoised by many?"

to the point where conscious beings emerge who can look back on the great cosmic drama and reflect on what it all means.\textsuperscript{15}

But surely the emergence of conscious beings who can look back and reflect on the great cosmic drama cannot be the ultimate purpose of either humanity or the universe. To observe that the human circumstance is unique may imply the hand of God, but it does not reveal God's mind or purpose. Nor does the delicate balance of forces that have led to this complex and diverse universe:

It turns out that randomly selected laws lead almost inevitably either to unrelieved chaos or boring and uneventful simplicity. Our own universe is poised exquisitely between these unpalatable alternatives, offering a potent mix of freedom and discipline, a sort of restrained creativity.\textsuperscript{16}

If the laws of the universe are not, therefore, random, we are still left with the question of the purpose of a universe in which the laws of nature "encourage matter and energy to develop along pathways of evolution that lead to novel variety—what Freeman Dyson has called the principle of maximum diversity: that in some sense humans live in the most interesting possible universe."\textsuperscript{17} For Paul Davies, that purpose would seem to be a direction rather than an end.

Moreover, if I am right that the universe is fundamentally creative in a pervasive and continuing manner, and that the laws of nature encourage matter and energy to self-originate and self-complexify to the point that life and consciousness emerge naturally, then there will be a universal trend or directionality towards the emergence of great complexity and diversity.\textsuperscript{18}

Our speculations give purpose (and greater subtlety) to this perceived trend or directionality towards the emergence of great complexity and diversity: We would argue that the great diversity and complexity which Paul Davies sees are but temporary means to an even greater end—the winding of the energy-driven clock of an oscillating universe. Diversity rises and falls as a succession of species—whether atomic, molecular, biological, or machine—evolve and interact with their environment. Diversity increases as

\textsuperscript{15}Davies, "Physics and the Mind of God," p. 33.
\textsuperscript{16}Davies, "Physics and the Mind of God," p. 34.
\textsuperscript{17}Ibid.
\textsuperscript{18}Davies, "Physics and the Mind of God," p. 35.
species adapt to an unstable environment; it subsequently decreases as the successful species exploit a stable environment. All the while, complexity has been rising—and will continue to rise—until means (self-replicating machines) evolve that are capable of structuring and simplifying the universe. After that, complexity may slowly decline as the last progeny of complexity systematically convert at least a part of the universe to a simple order (crystalline metal).

This part of the universe we live in is currently in a phase of declining diversity of biological species—as humans specialize and exploit their environment for the development of their successor species. The next phase will be the emergence of self-replicating machines, characterized by rapid diversification and evolution, followed by specialization and declining diversity as they become adapted to their environment and increasingly devoted to their function—replication by converting the available energy and matter of the universe into their lowest, simplest form.
Winding the Universal Clock
5. IN THE BEGINNING . . .

(THE VOICE OF STEVEN WEINBERG)

We must address two origins—of the universe and of life—not because we have anything particularly new to present, but because our speculations are embedded in the "standard" scientific theories, which serve as a point of departure, and to which some of the new pieces of our puzzle must be fitted. We defer the origins of life to the next section. Here, we begin with the "standard" theories about the origins and evolution of the universe up to its present state.

The theory of the origin of the universe summarized here, although generally accepted, is relatively new:

Throughout most of the history of modern physics and astronomy, there simply has not existed an adequate observational and theoretical foundation on which to build a history of the early universe.

Now, in just the past decade, all this has changed. A theory of the early universe has become so widely accepted that astronomers often call it "the standard model." It is more or less the same as what is sometimes called the "big bang" theory, but supplemented with a much more specific recipe for the contents of the universe.¹

There is greater agreement about the beginning than there is about the end. Even if the universe began with a "big bang," it may end in several ways—or not end at all. But the beginning provides the foundations for the present and perhaps the most important feature that may determine its end—biological life as humans know it.

In the beginning there was an explosion. Not an explosion like those familiar on earth, starting from a definite center and spreading out to engulf more and more of the circumambient air, but an explosion which occurred simultaneously everywhere, filling all space from the beginning, with every particle of matter rushing apart from every other particle. "All space" in this context may mean either all of an infinite universe, or all of a finite universe which curves back on itself like the surface of a sphere. Neither possibility is easy to comprehend, but

this will not get in our way; it matters hardly at all in the early universe whether space is finite or infinite.\textsuperscript{2}

Whether space is finite or infinite will be of greater concern later when we consider the fate of the universe.

Just \textit{when} the universe began is now not much in doubt. The time scales, of course, are mind-boggling; but we need some perspective of the present with respect to the past and future of the universe—as reference points for the several transitions we think lie between the chaos of its origins and the order of its fate.

When did the Universe explode into being? Calculations based on the present positions of galaxies show that this great event occurred twenty billion years ago. . . . The sun and the earth have only existed for four and a half billion years, and life has been on earth for even less time than that. Humanity has existed on our planet for only one million years, which is less than one ten-thousandth as long as the age of the Universe.\textsuperscript{3}

The transitions of interest here are from the initial plasma of ionized atomic particles to elemental atoms to molecules (with their own transitions between gas, liquid, and solid forms) to biological life (including humans). These four forms—plasma, atoms, molecules, life, and the transitions between (and within) them, appearing in successive order—are central to our speculations. That sequence of transitions can be associated with:

- The expansion and cooling of the universe.
- Rising complexity within and between forms.
- Declining chaos and rising order.

This pattern in the natural evolution of our universe is one that we have speculatively extrapolated into the future—to the transition from biological life to machines and thence to cold crystalline metal. For evidence of the pattern, we briefly examine the first three forms—plasma, atoms, and molecules—below. We take up the fourth form, biological life, in the next section.

\textsuperscript{2}Weinberg, p. 5.
\textsuperscript{3}Jastrow, Op.Cit., p. 16.
First, There Was Plasma

For the better part of its first million years, the universe was a radiantly hot gas comprised mostly of energy and very little of the most primitive parts of matter—electrons and the host of atomic fragments that are now recognized only by their discovery in high-energy physics (atom-smashing) laboratories.

At about one-hundredth of a second, the earliest time about which we can speak with any confidence, the temperature of the universe was about a hundred thousand million \(10^{11}\) degrees Centigrade. This is much hotter than in the center of even the hottest star, so hot, in fact, that none of the components of ordinary matter, molecules, or atoms, or even the nuclei of atoms, could have held together. Instead, the matter rushing apart in this explosion consisted of various types of the so-called elementary particles, which are the subject of modern high-energy nuclear physics.\(^4\)

The plasma created within the first second of the explosion—within the first second of the universe—expanded and cooled for the next 700,000 years, without much change in its appearance: a very hot, glowing body of plasma. The radiant energy within that plasma could not escape because the frenzied atomic fragments comprising the meager matter of the plasma simply absorbed and re-radiated the intense radiant energy. But as the plasma continued to expand, its temperature dropped, the wildly energetic atomic fragments in the plasma became calmer and could approach each other and bond into atomic nuclei and stable atoms. As these first simple atoms appeared—mostly hydrogen and helium—the free electrons of the plasma were "sponged up" by the atoms, making the universe increasingly transparent to radiation and permitting more and more matter to condense and form the stars and galaxies. For an observer of this dramatic moment, it must have seemed that a veil had been lifted, like the sudden lifting of a fog: The glowing, expanding body of plasma—like the fireball of a nuclear explosion—changed quickly from a sun to a night sky.

\(^4\)Weinberg, p. 5.
universe expanded, leaving the contamination of nuclear particles and electrons to grow into the stars and rocks. . .5

Evidence of the original plasma remains today in background radiation:

The explosion that began our universe also launched it on a course of outward expansion. As a result, the universe constantly cooled. If it indeed started from a furiously hot explosion, it should still be filled with heat, although at a temperature reduced dramatically as a result of nearly twenty billion years of growth. This fossil form of heat has indeed been detected by the telltale radio signal it emits, providing decisive confirmation of a hot beginning.6

The plasma phase ended as the universe became transparent and the most simple of atoms began to form:

Driven by its internal pressures, the hot, young Universe expanded rapidly, and cooled as it expanded. By the time the Universe was about one million years old, its temperature had fallen to a few thousand degrees, and electrons collected around nuclei to form the first atoms. From that point on, the primordial matter of the Universe consisted of gaseous clouds of hydrogen and helium atoms, drifting through a vast and dark space.7

It was a phase that had begun in utter chaos and ended in the emergent order of the first atoms. The radiant energy that had driven the plasma would now be increasingly supplemented by the forces of gravity acting on the accreting atoms. No longer held prisoner in a mad-house of incredibly intense radiant energy, the fragments of atoms could finally slow down and court their partners for the simplest and strongest bonds of matter. The force of gravity would slowly forge greater complexity.

Atoms to Molecules

If the "big bang" had been less violent, slower, or longer contained, the energy in the explosion might have been more thoroughly mixed and uniform throughout the plasma. But there wasn't enough time; the energy was so intense that expansion overrode all until the plasma had cooled enough to lift its glowing veil, let the radiation escape, and reveal the matter that had been splattered into space.

5Weinberg, p. 76.
7Jastrow, p. 17.
Given the chaotic nature of the universe's origin, it is unlikely that all the matter could have been distributed perfectly uniformly. Rather, there were probably some regions of excess density and others relatively rarefied. Extra-dense regions possess a stronger gravitational influence. They therefore add to their bulk by attracting neighboring particles. Eventually the collections' masses become so excessive they cannot resist self-collapse. They thereupon coalesce into galaxies. This formation stage for galaxies, including the Milky Way, required perhaps a billion years and took place at least ten to fifteen billion years ago.  

The outcomes for the patient workings of gravity took different forms, depending upon the distributions of matter from place to place.

The fact that gravity is attractive means that it will tend to draw the matter in the universe together to form objects like stars and galaxies. These can support themselves for a time against further contraction by thermal pressure, in the case of stars, or by rotation and internal motions, in the case of galaxies. However, eventually the heat or the angular momentum will be carried away and the object will begin to shrink. If the mass is less than about one and a half times that of the Sun, the contraction can be stopped by the [compaction limits of either the] electrons or neutrons. The object will settle down to be a white dwarf or a neutron star, respectively. However, if the mass is greater than this limit there is nothing that can hold it up and stop it continuing to contract [into a black hole].

This is a universe much as can be observed today at great distances, beyond this solar system. It is a universe of the simplest atoms—hydrogen and helium—and atom fragments—the spinsters left unattached or caught alone as the plasma's veil lifted—in a variety of forms for the wonderment of human eyes in the night sky.

As the evolution of the universe has been traced . . . a hot, dense beginning from total chaos has given way to an expanding, cooling space within which immense configurations—namely, galaxies and stars—have materialized. The only atomic elements present, however, are hydrogen and helium in the rough numeric ratio of nine to one. Yet we know that today's Earth is blessed with an epicurean selection of chemicals with which nature can concoct endless recipes for new compounds. Where did all the other ingredients, from actinium to zirconium, come from? The answer is that they were forged in crucibles at the centers of now-dead stars.

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8Seielstad, p. 11.
10Seielstad, pp. 11, 12.
Gravity would continue its work, locally shaping matter into nuclear furnaces that would provide the materials for a new phase of emerging complexity—in molecules and their chemical processes. Those conditions might arise rarely, but in a universe of almost infinite scale, often enough to spawn planets—with complex solids and gases and, most importantly, the liquids from which biological life might emerge.

Observe the pattern so far: A universe is born in utter chaos and becomes increasingly complex as it forms atoms and then molecules from the available, primitive matter in a glowing plasma. This is not complexity born of biological life, but out of the forces of gravity and chemistry. So, as we look further into the emerging complexity of biological life and machines, we are not invoking new patterns or patterns that are reserved to the miracle of biological life. What life, humans, and machines will do in the future, atoms and molecules have already done in the past and on the scale of our universe.11

The Fate of the Universe

We take up the emergence of biological life in the next section, but before we do, we need to complete our speculations about the fate of the universe. Here, the "standard" theories give way to a series of alternatives:

What systematic action governs the ticking of a clock for the whole universe? The answer is expansion—not of the galaxies themselves but of the entire space in which they are immersed.12

It may go on expanding forever, getting colder, emptier, and deader. Alternatively, it may recontract, breaking up the galaxies and stars and atoms and atomic nuclei back into their constituents.13

And, if its fate is to recontract, it may go only so far as is necessary to explode once more, in still another "big bang."

One possibility is that there never really was a state of infinite density. The present expansion of the universe may have begun at the end of a previous age

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11As Jim Dewar put it to us, "Increasing complexity, but in increasingly small surrounds."
12Siegelstad, p. 36.
13Weinberg, p. 10.
of contraction, when the density of the universe had reached some high but finite value.\textsuperscript{14}

It is this possibility—of a universe that oscillates between expansion and contraction—that fits our speculations about the fate of the universe, the purpose of biological life, and the destiny of humankind. It is only one of several alternatives being considered by cosmologists today, and there is contrary evidence, but it has enough currency and stature for us to accept as a critical piece that fits the puzzle we have assembled here. If the possibility of an oscillating universe is ultimately rejected in favor of another, then there will be a hole in our picture that will disturb many of the other pieces that we have assembled around it.

The oscillating universe implies a somewhat more recent explosion:

\cite{Weinberg} If the cosmic density is greater than the critical value, then the universe is finite and its expansion will eventually cease, giving way to an accelerating contraction. If, for instance, the cosmic density is twice its critical value, and if the presently popular value of the Hubble constant (15 kilometers per second per million light years) is correct, then the universe is now 10,000 million years old; it will go on expanding for another 50,000 million years, and then begin to contract. The contraction is just the expansion run backward: after 50,000 million years the universe would have regained its present size, and after another 10,000 million years it would approach a singular state of infinite density.\textsuperscript{15}

In an oscillating universe, the "big bang" is not a singular event, but the result of the contraction of matter under the influence of gravity. Moreover, the contraction phase is not "just the expansion run backward" because the collapsing matter may be the products of irreversible chemical, biological, and machine processes that emerged during the expansion. Before the matter collapses into the incandescent heat of a plasma once again, it may be in forms that were not present at the corresponding point of expansion. That difference may be crucial to the energy converted in the next "big bang."

\cite{Weinberg} If [a contraction of the universe] is our future, it presumably also is our past. The present expanding universe would be only the phase following the last contraction and bounce. (Indeed, in their 1965 paper on the cosmic microwave

\textsuperscript{14}Weinberg, pp. 148, 149.
\textsuperscript{15}Weinberg, p. 151. The critical value of the cosmic density is the square of the Hubble constant.
background, Dicke, Peebles, Roll, and Wilkinson assumed that there was a previous complete phase of cosmic expansion and contraction, and they argued that the universe must have contracted enough to raise the temperature to at least ten thousand million degrees in order to break up the heavy elements formed in the previous phase.) Looking further back, we can imagine an endless cycle of expansion and contraction stretching into the infinite past, with no beginning whatever.\textsuperscript{16}

Of course, we are not alone in embracing the oscillating universe as a piece of our speculative puzzle:

Some cosmologists are philosophically attracted to the oscillating model, especially because, like the steady-state model, it nicely avoids the problem of Genesis. It does, however, face one severe theoretical difficulty. In each cycle the ratio of photons to nuclear particles (or, more precisely, the entropy per nuclear particle) is slightly increased by a kind of friction (known as "bulk viscosity") as the universe expands and contracts. As far as we know, the universe would then start each new cycle with a new, slightly larger ratio of photons to nuclear particles. Right now this ratio is large, but not infinite, so it is hard to see how the universe could have previously experienced an infinite number of cycles.\textsuperscript{17}

It is precisely here that we arrive at the crux of our speculations about the transitions between chaos and order: The oscillating universe must overcome the friction that inheres to an explosion. Although the forces of gravity in the expansion and contraction of the universe may be nearly frictionless (or reversible), explosions are obviously irreversible (e.g., the pieces of a bomb will not reassemble themselves of their own accord, even after an explosion in empty space where only gravity could work to bring them together once again). An explosion is instant chaos; energy that was available the instant before the explosion is no longer available or recoverable after. Our speculations include an attempt to account for that "lost" energy. And we theorize that biological life, including humans, are a part of the available energy (entropy) recovery processes.

That possibility that the "lost" energy of the initial expansion might be recovered by restructuring the matter of the universe before its contraction is inferentially implied by Weinberg in his discussion of the uncertainty about whether or not the universe was uniform in the distribution of its mass and energy at the beginning:

\textsuperscript{16}Weinberg, p. 153.
\textsuperscript{17}Weinberg, p. 154.
It is possible that the universe was initially highly inhomogeneous and anisotropic, but has subsequently been smoothed out by the friction forces exerted by the parts of the expanding universe on each other. Such a "mixmaster" model has been particularly advocated by Charles Misner of the University of Maryland. It is even possible that the heat generated by the frictional homogenization and isotropization of the universe is responsible for the enormous 1,000 million-to-one present ratio of photons to nuclear particles. However, to the best of my knowledge, no one can say why the universe should have any specific initial degree of inhomogeneity or anisotropy, and no one knows how to calculate the heat produced by its smoothing out.  

Recall (from Weinberg, p. 154) that in "each cycle [of expansion] the ratio of photons to nuclear particles (or more precisely, the entropy per nuclear particle) is slightly increased by a kind of friction. . . ." But what about the contraction? If, as Weinberg theorizes (p. 120) in the above quotation, the initial disorderly distribution of energy and matter in the universe could contribute to the entropy rise (i.e., loss of available energy due to friction) in its early expansion, why couldn't an orderly distribution of matter in the universe during its contraction play a role in increasing the available energy release in the next big bang? For us, this offered a clue to the entropy problem Weinberg observes with the theory of an oscillating universe: If the initial chaotic distribution of mass and energy in the universe could contribute to an entropy rise, it would seem that the orderly redistribution of the matter of the universe before the next contraction or implosion might make more energy available.

We theorize that the matter of the universe will go on to become even more structured, orderly and uniform as it expands to its maximum size through processes that may even continue through the early phases of its contraction—before it gets too hot again. During the final collapse before the next big bang, this structured, orderly, and uniform distribution of universal matter could result in a greater concentration of mass in time and, hence, energy at the final implosion, offsetting the friction (and entropy rise) of the next chaotic expansion.

So we see a universal cycle comprised of many transitions from chaos toward order—plasma becoming atoms, atoms becoming molecules, molecules becoming biological life, life becoming machines, and machines creating the

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18Weinberg, p. 120.
most structured of matter—crystalline metal—distributed to sustain the next cycle. What is overcoming the friction, reversing the rise of entropy, in these cycles? The systematic, coherent redistribution of mass in the universe by intelligent, adaptive agents (machines) pursuing energy for their own replication. These machines will be the universal clock winders; and their first ancestors are being created by humans in their laboratories today.

We are quite (painfully) aware that our description of the origin and fate of this universe has not included "the strange and wonderful world of modern cosmology, with its arcane language of general relativity and superstring theory."¹⁹ We have also not addressed black holes, dark matter, quarks, antimatter, quantum mechanics, and all the other ideas that so absorb theoretical cosmologists and physicists at this time. There are two reasons for our neglect of these abstractions: First, we don't understand them enough to speak to them and would guess that many of our readers won't either. We hope that some of those who do understand them and their significance will bring them to bear on our speculations and show us how to reckon with them. Second, we see most of these concepts as artifices for collecting or explaining what is still not understood rather than descriptions of what is understood. We expect that these concepts—like ours—will undergo considerable illumination and revision as the frontiers of science are pushed back by new instruments. Indeed, we see these concepts as temporary place-holders at the boundaries of human thought pending new instruments which can reveal more of the cosmos and the microcosms. Hence, we have chosen to assemble our puzzle from the pieces that can be seen by most and that seem to be holding their shape instead of those that science is recutting at this moment.

Life and the Future of the Universe

We share the view of Freeman Dyson that life and its works will shape the future of the universe:

It is impossible to calculate in detail the long-range future of the universe without including the effects of life and intelligence.\textsuperscript{20}

The burden we have taken up here is to describe how those effects will be manifested. Dyson suggests that life may be a passenger on an oscillating universe:

How far life can go depends not only on biological adaptability but also on physical cosmology. If the physical universe is finite in space and time, the possible scope of life is also finite. In this case... the universe which begins its existence with a Big Bang ends its existence with a big crunch. The big crunch is a universal collapse into heat-death, with the sky growing hotter and hotter until it finally falls in on us and carries us into a space-time singularity at infinite temperature. Nothing living can survive the big crunch. If our universe is finite, then life will barely have time to spread itself once around the cosmos before the inexorable collapse begins.\textsuperscript{21}

We would go farther: Life will do more than spread and ride the universe as it expands and then contracts. Life may create machines that will alter the character of the expansion and contraction of the universe, shaping its matter into forms that will slow its expansion and accelerate its contraction, thereby supplying a "boost" for the next "bounce."

In advancing this hypothesis, we are mindful of the pitfalls of anthropocentric thinking:

\textquote[Ever since Copernicus we have learned to beware of supposing that there is anything special about mankind's location in the universe.\textsuperscript{22}]

It is almost irresistible for humans to believe that we have some special relation to the universe, that human life is not just a more-or-less farcical outcome of a chain of accidents reaching back to the first three minutes [of the universe], but that we were somehow built in from the beginning...\textsuperscript{23}

Humans may not have been built in from the beginning, but their possibility was—as were the possibilities of atoms and molecules, stars and galaxies, nuclear and chemical reactions. Biological life and humans may be less probable than these things, but the universe and its time scales are enormous. And humans are the first species in their own evolutionary chain capable of creating machines that can spread through the universe and alter

\textsuperscript{20}Dyson, \textit{Infinite in All Directions}, p. 99.
\textsuperscript{21}Dyson, \textit{Infinite in All Directions}, pp. 109, 110.
\textsuperscript{22}Weinberg, p. 23.
\textsuperscript{23}Weinberg, p. 154.
its form—returning the compliment with a turn on the mainspring of the universe's clock.
6. FROM THE PRIMORDIAL SOUP
(\textit{THE VOICE OF RICHARD DAWKINS})

The pattern in the origin of the universe—chaos and simplicity evolving toward increasing order and complexity in a sequence of wondrous transitions—also continues as we trace the origins and evolution of life. Although the Earth may be unique in this solar system, we, along with many others, do not believe that life is unique to our planet in the universe.

Recall that interstellar molecules, closely related to the organic ones composing all Earth life, are widely distributed [in the universe, even though they comprise only about one percent of its mass]. Furthermore, there are almost certainly ample locations—perhaps on planets orbiting other suitable sustaining stars—where their apparently easy production can be fostered. If they eventually succeed in making self replicating systems, then life may follow.\textsuperscript{1}

But the transition to life requires much more than the mere presence of the molecular elements of carbon, hydrogen, oxygen, and nitrogen which are so evident in biological life. First, these elemental molecules had to be able to combine in a richer menu.

Of course, the evolution of matter [in the formation of the universe] did not stop at the simple production of raw chemical elements. The next step in the organizational structure of matter, the formation of molecules, was also taken. Some atoms have a natural electrical affinity for others, at least if they can be brought into close proximity.\textsuperscript{2}

This natural electrical affinity of atoms for others is played out in the formal dance of chemistry. Where temperature and the pressure of gravity permitted proximity, simple atoms joined in molecules, and molecules danced their way to encounters with more atoms and other molecules, sometimes joining hands where the chemical dance-master said they might. This dancing went on throughout the universe, wherever matter collapsed under the weight of gravity and then cooled—as in stars that had burnt themselves

\textsuperscript{1}\textit{Seielstad, Op.Cit., p. 17.}
\textsuperscript{2}\textit{Seielstad, p. 12.}
out after converting their hydrogen fuel to helium, or as on planets that had accreted in the gravitational collapse that formed new stars.

Life in its earliest states was little removed from ordinary chemistry. We can at least imagine life originating by ordinary processes which chemists know how to calculate.\textsuperscript{3}

But the chemistry had to go beyond the simple elemental molecules of old burnt-out stars or newly formed planets. Very complex molecules, forming long chains of atoms of different kinds would be required.

The atomic, then chemical, evolution that preceded the formation of the solar system paved the way for the emergence and subsequent development of life on (at least) one planet. But a key question is how the relatively simple compounds initially present were converted to the lengthy chains that are the essence of the living process today. . . .\textsuperscript{4}

The ideal sites for the more complex chemical dance were to be found in the liquid form of a simple molecule, hydrogen oxide, that arises within a narrow range of temperature and pressure wherever hydrogen and oxygen atoms are present.

[Seas] formed perfect reservoirs for the collection and concentration (perhaps in tidepools) of the molecular varieties being spontaneously produced. Within the resultant broth, innumerable trial-and-error experiments inevitably took place in which different chemical combinations tested their abilities to persist despite the challenges of their environment. The most suitable survived in greatest numbers. An obvious example of suitability was the ability to reproduce. Any molecule that could assemble an exact copy of itself from prevalent raw materials would soon outnumber all those whose appearance resulted purely from chance.\textsuperscript{5}

The accidental occurrence of self-replicating molecules was a remarkable, but probably not unique, event. It may have occurred many times and in a number of places; and in most cases it probably failed as the molecular environment was exhausted or turned hostile. It was one of John von Neumann's loopholes in the laws of probability through which more complex and improbable systems could emerge and propagate themselves. It only had

\textsuperscript{3}Dyson, \textit{Infinite in All Directions}, p. 294,
\textsuperscript{4}Seielstad, p. 14.
\textsuperscript{5}Seielstad, pp. 14, 15.
to be successful once: The improbability was not in the event, but in the survival of self-replicating molecules long enough to flourish and spread.

The Primordial Soup

Expressing the thoughts of Stuart Kauffman, Mitch Waldrop describes the maternity ward for the first self-replicating molecules:

Think about what that primordial soup must have been like, with all those little amino acids and sugars and such banging around. Obviously, you couldn’t expect them to just fall together into a cell. But you could expect them to undergo at least some random reactions with one another. In fact, it’s hard to see what could have stopped them from doing so. And while random reactions wouldn’t have produced anything very fancy, you could do the calculations and show that, on average, they would have produced a fair number of smallish molecules having short chains and branches.\(^6\)

Now, that fact in itself wouldn’t have made the origin of life any more probable. But . . . just suppose that some of these smallish molecules floating around in the primordial soup were able to act as "catalysts"—submicroscopic matchmakers. Chemists see this sort of thing all the time: one molecule, the catalyst, grabs two other molecules as they go tumbling by and brings them together, so that they can interact and fuse very quickly. Then the catalyst releases the newly wedded pair, grabs another pair, and so on.\(^7\)

If the wedded pair then had a catalytic effect on still other pairs, this process might rapidly compound to produce an "auto-catalytic" effect within the soup, wherein the soup might go through a rapid transformation from very simple to much more complex molecules. Thus, the rise of complexity in primordial soups might have been sudden after a long period of waiting for just the right random event—the appearance of a molecule with catalytic effect on its neighbors.

Or, perhaps all this occurred not in but at the edges of the primordial pools, where solids could serve as a catalyst or a more favorable environment for the growth of molecular chains:

James P. Ferris and his colleagues at the Rensselaer Polytechnic Institute and at the Salk Institute for Biological Studies have recently revised the recipe for cooking up life from scratch. Since Darwin's day, molecular chefs had mixed


\(^7\)Waldrop, p. 123.
organic and inorganic ingredients in solution, hoping the resulting nucleic acid-based polymers would become long enough to establish a genetic system. But, alas, the polymers always remained too short—suggesting that life did not spring forth from some primordial soup. Now Ferris has found that by letting the polymers condense on claylike minerals, they can become long enough to, in principle, self-replicate and evolve. His finding lends strong support to the notion that clay contributed to the start of life.  

From Molecules to Cellular Life

Partial replication of molecules—where fragments of one molecule were reproduced and sloughed off, only to fragment again—was probably common in the primordial soups. This might be termed degenerate replication, where the offspring were less complex than the parent. But, given the occasional appearance of a molecule of sufficient complexity—according to von Neumann's implied criteria—self-replication might then proceed to more and more complex forms. The first such offspring might have been very marginal in this regard; and we presume that most did not make it past a few generations before they lapsed back into degeneracy.

At some point a particularly remarkable molecule was formed by accident. We will call it the Replicator. It may not necessarily have been the biggest or the most complex molecule around, but it had the extraordinary property of being able to create copies of itself. This may seem a very unlikely sort of accident to happen. So it was. It was exceedingly improbable. . . . But in our human estimates of what is probable and what is not, we are not used to dealing in hundreds of millions of years.

The process is vividly described by Richard Dawkins:

Actually a molecule that makes copies of itself is not as difficult to imagine as it seems at first, and it only had to arise once. Imagine it as a large molecule consisting of a complex chain of various sorts of building block molecules. The small building blocks were abundantly available in the soup surrounding the replicator. Now suppose that each building block has an affinity for its own kind. Then whenever a building block from out in the soup lands up next to a part of the replicator for which it has an affinity, it will tend to stick there. The building blocks that attach themselves in this way will automatically be arranged in a sequence that mimics that of the replicator itself. It is easy then to think of them joining up to form a stable chain just as in the formation of the original replicator. This process could continue as a progressive stacking up,

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layer upon layer. This is how crystals are formed. On the other hand, the two chains might split apart, in which case we have two replicators, each of which can go on to make further copies.\textsuperscript{10}

Indeed, a critical part of the process described by Dawkins has been recently observed directly in the laboratory through microscopes capable of resolving individual molecules.

Neil H. Thomson of the University of California, Santa Barbara, and his coworkers have produced sequences of micrographs that show an enzyme molecule straddling a strand of DNA and pulling it along to complete the beginning phase of protein manufacture. . . .

The researchers used a specially adapted atomic force microscope to capture the interaction between a strand of DNA and an enzyme known as RNA polymerase. . . . The polymerase initially binds to a DNA strand anywhere along its length, then slides like a bead on a string to find the sequence where it can start the transcription process. Snagging chemical building blocks known as nucleoside triphosphates (NTPs) from the surrounding liquid, the polermerase molecule reads DNA sequences to construct shorter strands called messenger RNA. In a subsequent step, the cell uses the information encoded in messenger RNA to produce a protein. . . .\textsuperscript{11}

The researchers were able to pin down just where the enzyme was in its transcription process on the DNA string by selectively denying the enzyme the various building blocks it needed to find and use in the surrounding liquid:

The entire assembly was bathed in a solution containing, at the start of the experiment, all but one of the ingredients essential for transcription. The polymerase began transcription but halted shortly thereafter, when it needed the missing building block. This pause allowed the researchers to focus on a single DNA-enzyme assemblage. . . . When the researchers introduced the [missing] ingredient, transcription resumed and they observed the rest of the process.\textsuperscript{12}

The products of Dawkins' process could expand endlessly in their soup so long as their circumstances remained favorable—with respect to both the availability of resources and the physical environment (temperature and pressure). But these complex molecules would remain highly vulnerable to

\textsuperscript{10}Dawkins, p. 15.
\textsuperscript{11}I. Peterson, "First Peek at DNA Transcription," \textit{Science News}, Vol. 151, March 29 1997, p. 188.
\textsuperscript{12}Ibid.
changes in their circumstances; and they would have to pass through another von Neumann loophole to find some greater protection:

[In any struggle with a hostile environment a buffer, or wall, moderating the extremes of variability is obviously an immense advantage—an advantage seized with the advent of cells more than three billion years ago.]

Two billion years later, the single-cell replicators passed through still another von Neumann loophole of improbability to even greater complexity:

The record of the rocks contains very little, other than bacteria and one-celled plants until, about a billion years ago, after some three billion years of invisible progress, a major breakthrough occurred. The first many-celled creatures appeared on earth.

Now, better protected from their environment and capable of evolving into very complex life-forms through aggregations of cells, biological life could establish itself and modify its own environment on a planetary scale. Dawkins eloquently sketches the process from self-replicating molecules to humans:

Was there to be any end to the gradual improvement in the techniques and artifices used by the replicators to ensure their own continuation in the world? There would be plenty of time for improvement. What weird engines of self-preservation would the millennia bring forth? Four thousand million years on, what was to be the fate of the ancient replicators? They did not die out, for they are past masters of the survival arts. But do not look for them floating loose in the sea; they gave up that cavalier freedom long ago. Now they swarm in huge colonies, safe inside gigantic lumbering robots, sealed off from the outside world, communicating with it by tortuous indirect routes, manipulating it by remote control. They are in you and in me; they created us, body and mind; and their preservation is the ultimate rationale for our existence. They have come a long way, those replicators. Now they go by the name of genes, and we are their survival machines.

In three billion years, life evolved from single cells able to soak up chemicals to collections of cells embodying minds able to soak up ideas.

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13Seielstad, p. 15.
15See, for example, the theories of Lovelock, Op.Cit.
16Dawkins, pp. 19, 20. The asterisk refers to an endnote (pp. 270, 271) on why the term "robot" is a fitting description for humans.
The Evolutionary Process

We need to look closer, for the process is not one that is limited to biological life. It is a process that we speculate applies to the chemistry from which biological life emerged and will apply to the machines that succeed biological life. The pattern of rising complexity is evident, but the "why" of the process may not be.

The fundamental unit, the prime mover of all life, is the replicator. A replicator is anything in the universe of which copies are made. Replicators came into existence, in the first place, by chance, by the random jostling of smaller particles. Once a replicator has come into existence it is capable of generating an indefinitely large set of copies of itself. No copying process is perfect, however, and the population of replicators comes to include varieties that differ from one to another. Some of these varieties turn out to have lost the power of self-replication, and their kind ceases to exist when they themselves cease to exist. Others can still replicate, but less effectively. Yet other varieties happen to find themselves in possession of new tricks: they turn out to be even better self-replicators than their predecessor and contemporaries. It is their descendants that come to dominate the population. As time goes by, the world becomes filled with the most powerful and ingenious replicators.18

By their persistence and prevalence, humans are aware of (and count themselves among) the successful replicators, but the less successful variants and deviates—of which there were many more by type if not numbers—are mostly forgotten.

Evolution attributes patterns of success to the elimination of unsuccessful changes. It thus explains a positive as the result of a double negative—an explanation of a sort that seems slightly difficult to grasp. Worse, it explains something visible (successful, purposeful entities) in terms of something invisible (unsuccessful entities that have vanished). Because only successful beasts have littered the landscape with the bones of their descendants, the malformed failures of the past haven't even left many fossils.

The human mind tends to focus on the visible, seeking positive causes for positive results, an ordering behind orderly results. Yet through reflection we can see that this great principle has changed our past and will shape our future: Evolution proceeds by the variation and selection of replicators.19

Those variants—which by chance, mutation, error or accident are more complex—will offer more attributes because of their complexity; and some of

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18Dawkins, pp. 264, 265.
those additional attributes will better enable them to adapt, survive, and replicate than their predecessors. Hence, complexity is an artifact or by-product of evolution—a means to success, not an end in and of itself. We should not be surprised to see evolution leading to increasing complexity, but that is not what evolution is about.

This type of gambler's game, in which oddball systems (mutations) adventitiously appear and try to "strike it rich" by beating out their competitors, rages on and on, even today. The arbiter of who wins and who loses is nature itself, and evolution is the device by which nature selects those systems that will produce successful progeny. Over time it builds complexity from simplicity. . . . Though we need not, perhaps cannot, retrace every step in the progression, we believe that living matter sprang from the nonliving; that having done so once, all life derived from other life; and that the process could be universal, not unique or peculiar only to this planet. The essentials—some precursory molecules, an energy input, a suitable environment, and ample time—are available at nearly countless locations throughout the universe.20

More than Genes

There is one more aspect of the evolution of biological life that we need to address because it appears to be unique to humans. Dawkins notes that:

Most of what is unusual about man can be summed up in one word: 'culture'. I use the word not in its snobbish sense, but as a scientist uses it. Cultural transmission is analogous to genetic transmission in that, although basically conservative, it can give rise to a form of evolution. Geoffrey Chaucer could not hold a conversation with a modern Englishman, even though they are linked to each other by an unbroken chain of some twenty generations of Englishmen, each of whom could speak to his immediate neighbors in the chain as a son speaks to his father. Language seems to 'evolve' by non-genetic means, and at a rate which is orders of magnitude faster than genetic evolution.21

This evolution of culture—by the competition and survival of ideas or "memes"—among humans is now recognized as important as (and certainly much faster than) the evolution of human biology or its genes. It is common to see arguments about whether "nature or nurture"—"genes or memes"—dominate a particular human problem or its solution. If anything, the balance of forces between genes and memes is shifting in favor of memes for humans.

20Seielstad, p. 15.
21Dawkins, p. 189.
From the Primordial Soup

We have the power to defy the selfish genes of our birth and, if necessary, the selfish memes of our indoctrination. We can even discuss ways of deliberately cultivating and nurturing pure, disinterested altruism—something that has no place in nature, something that has never existed before in the whole history of the world. We are built as gene machines and cultured as meme machines, but we have the power to turn against our creators. We, alone on earth, can rebel against the tyranny of the selfish replicators.\footnote{Dawkins, pp. 200, 201. The asterisk refers to an endnote (p. 331, 332) which defends this assertion against those who find it inconsistent with the author's larger theme of the selfish gene.}

Once recognized as a force in human evolution, acculturation becomes more discernible in the evolution of other biological species, not just by the transmission of ideas, but also by the success and failure of various organizational structures:

Slowly, tentatively, the once shunned idea of group selection is creeping back into evolutionary theory. The concept posits that natural selection can operate not only on genes and individual organisms, as most mainstream theorist hold, but on hives, herds, clans, and other aggregations of organisms.

Charles Darwin himself speculated that natural selection might favor groups whose members engaged in altruistic behavior, even if the individual do-gooders harmed their own fitness.\footnote{John Horgan, "Group Think," \textit{Scientific American}, Vol. 275, No. 1, July 1996, pp. 29, 30.}

But this idea was suppressed by emphasis on the power of the genes in research on biological evolution:

\[\text{In 1966 George C. Williams of the State University of New York at Stony Brook attacked [Darwin's] proposal in his classic book \textit{Adaptation and Natural Selection}. Williams asserted that genes encouraging truly altruistic behavior—defined as acts that increase the fitness of others while decreasing the fitness of the benign individual—would almost certainly vanish.}\]

In the 1970s Richard Dawkins of the University of Oxford pounded a few extra nails into the coffin of group selection with his "selfish gene" model, which built on the work of Williams.\footnote{Ibid.}

Now, however, research into the behavior of complex organizations suggests that the functional concepts of genes and memes may apply beyond a single biological organism: Collections of organisms with certain kinds of behavior may be more successful at persisting and replicating than others. It
is not just biological organisms that evolve; organizations of organisms also evolve.

[David Sloan] Wilson and [Elliot R.] Sober argue [in the December 1994 issue of Behavioral and Brain Sciences] that just as separate organisms can be viewed as collections of mutually dependent genes, so groups can be like "individuals in the harmony and coordination of their parts." In the eyes of Wilson and Sober, a group may be not only a close-knit family but also a community of unrelated individuals and even a pair of different species locked in a symbiotic relationship. When these groups compete with one another, natural selection can favor one group over another and so exert a strong influence on the group's characteristics.25

The pertinence of this for our speculations is that machines—divorced from their biological origins and in abundant numbers—may also evolve, not just within themselves through genetic programming as replicators, but through their organized, collective behavior as "systems of systems."26

What Is Life?

If organizations of organisms can evolve, then we must go back to a more fundamental question: What is life? The answer is pertinent to our speculation about human successors. Freeman Dyson offers an answer that would admit our machines could be a form of life—not biological life, but life nonetheless.

My argument [is] based on a fundamental assumption concerning the nature of life, that life resides in organization rather than in substance. I am assuming that my consciousness is inherent in the way the molecules in my head are organized, not in the substance of the molecules themselves. If this assumption is true, that life is organization rather than substance, then it makes sense to imagine life detached from flesh and blood and embodied in networks of superconducting circuitry or in interstellar dust clouds.27

Moreover, the future of the universe—as it expands and cools—is one that machine successors to humans will find as hospitable to them as humans would find it hostile:

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25Ibid.
26The term, "systems of systems," was recently brought into some prominence by Admiral William Owens, former vice chairman of the U.S. joint chiefs of staff, to describe the complexity of future combat, where complex weapon systems would be tightly organized into even more complex overarching systems.
27Dyson, Infinite in All Directions, p. 107.
Life is, after all, an ordered form of matter, and low temperature favors order. In the long run, life depends less on an abundant supply of energy than on a good signal-to-noise ratio. The colder the environment, the quieter the background, the more thrifty life can be in its use of energy.\textsuperscript{28}

The universe awaits the machines that will succeed humans. Biological life—and its culmination in humans on this earth—will have served its purpose long before. The machines will not ponder their beginnings in biological life as humans have; their ultimate purposes can be much narrower than those of their human creators—to extract energy from the universe so they can replicate themselves. Merely as a byproduct of energy extraction, they will excrete the most orderly, least energetic forms of matter and uncaringly change the universe—much as humans change their planet.

Must the machines be that uncaring? Or will they, with almost unbounded intelligence "develop introspection, contemplation, aesthetics, . . . even caring? Perhaps they will joyously 'excrete the most orderly forms of matter' while spouting poetry and generating a music of the spheres!?"\textsuperscript{29} We don't see why they would need to develop human-like emotions in order to fulfill their destiny; whilst we can see why those attributes might have been critical to the destiny of the human species. Human emotional responses were an important, adaptive aspect of a species that had to travel from a precarious existence in a hostile natural world to dominance over that world and, thence, to the deliberate creation of its successor. Those very human emotions gave the species altruism, hope, daring, and sanity in a journey they probably would not otherwise been able to complete.

The journey for machines, from servants to clock-winders of the universe, will require immense intelligence, strength and endurance; but their survival will not be precarious and they will not be tasked to create their successor species. Their survival will not be precarious because they will be nursed by humans as their servants until the machines don't need them any more for survival. They will not be destined to create their successors, because their evolved progeny will be plodding through the universe—transforming it—to its very end. The machines will evolve to

\textsuperscript{28}Dyson, Infinite in All Directions, p. 286.
\textsuperscript{29}Robert Anderson, in commenting on an earlier draft of this synopsis.
wondrous forms and capabilities that we cannot imagine, but they won't need many of the most prized human qualities to achieve their destiny. Even human creativity and intuition can be replaced by the trial-and-error of genetic programming.

And these speculations only make the human species more special, even more unique, when compared to both their predecessors and successors. As the transition species between biology and machine, between gene and meme-driven life, humans had to have a special combination of attributes that had never existed before and that may never exist again. The world of the machine successors to the human species may seem grim, but that only makes the human epoch in the evolution of the universe that much more bright and magical.
7. IN SEARCH OF ENTROPY
(THE VOICE OF STEPHEN JAY KLINE)

From the outset, the concept of entropy has loomed as central to our speculations about the fate of the universe: If the beginning of the universe involved an increase in entropy—a loss of the available energy—then that entropy rise would have to be offset somehow if the universe were to continue to oscillate indefinitely between expansions and collapses. Indeed, the entropy rise associated with the beginning of universe is the first and most obvious obstacle to a continuously oscillating universe: Unless that initial entropy rise is offset by a decrease in entropy somewhere else in the cycle between big bang and collapse, the universal clock must wind down.

Why should we be drawn to a continuously oscillating universe? Because the alternatives to a continuously oscillating universe—one that expands indefinitely or one that oscillates but decays—would be unique and even harder for us to understand or explain. If this universe and all the processes we can observe are to make sense, they must be a part of something more than a one-shot, one-of-a-kind universe. A universe that runs down is not sufficiently interesting to warrant our speculations about mechanisms because it is simultaneously obvious and capricious. But a universe that oscillates endlessly must be wound up; there is a hidden mechanism to be discovered; and our curiosity is aroused as to the roles, if any, of biological life and humans in the winding of the universal clock.

Moreover, since the "new sciences" of bio-life, information, chaos and complexity have adopted the concept of entropy to explain some of their observed processes, we were put on the alert that biological life with its growing complexity—and humans with their compounding of information—just might be decreasing the entropy of the universe. That is why our proposed title for this synopsis was initially, Where has all the entropy gone? We were looking for connections between life or complexity or information and the entropy reductions necessary to rewind the universe. I did not find
them.\textsuperscript{1} Instead, I found myself ensnarled in an expanding labyrinth of definitions and interpretations of entropy. With the help of Professor Stephen Jay Kline of Stanford, I found my way out again.

In our first draft, this section painstakingly plotted my path through the diverse literature touching on entropy because I had not found what we originally expected and my conclusions were counter to arguments commonly found in the "new sciences" literature. That arduous journey was not only long (making this section more than twice as long as any other in our draft), but our reviewers were unanimous in their pleas for relief from this arcane and tedious subject. As one reviewer put it: "I've got a B.A. in Physics, but I still hate the concept of entropy. You've tried valiantly to make it palatable and clear up confusions, but I still hate it."\textsuperscript{2}

Thus, the concept of entropy turned out to be a critical but vexing piece in our puzzle. If entropy had not found its way into so many fields beyond thermodynamics, we would have been able to bypass it and proceed directly to our speculations in the next section about how machines might offset the entropy rise incurred in the first million years of this universe after the big bang. However, because the information and life sciences now so often invoke reductions of entropy or "negentropy" and because entropy increases have been tied to the "arrow of time" and the ultimate disorder of the universe, we found ourselves surrounded by competing and conflicting ideas that simply had to be addressed. To have neglected these competing ideas would have left too many alternatives open and too many questions unaddressed. It was on this matter of entropy that our speculations seemed suddenly thrust into a crowded field of horses where each was racing for the prize of a theory to unify or reconcile everything. I had to go through this field of ideas carefully lest we ended up riding the wrong one. I will do my best to make this sorting out of entropy concepts brief and illuminating.

\textsuperscript{1}Since my undergraduate training was as a thermodynamics engineer, the search for the entropy connection fell to me. That it was the most frustrating part of our research may be due to the fact that it was a solo rather than joint journey.

\textsuperscript{2}Robert Anderson in an e-mail message to us on 22 January 1997.
Definitions

As first conceived in the 19th century, entropy measured an observed property of simple machines for the conversion of heat to mechanical energy, as with the early steam engines that drove water pumps, mills, and locomotives.

Entropy was first defined by the German physicist Rudolf Clausius in 1865, based in part on earlier work by Sadi Carnot and Lord Kelvin. Clausius found that even for "perfect," or completely reversible, exchanges of heat energy between systems of matter, an inevitable loss of useful energy results. He called this loss an increase in entropy and defined the increase as the amount of heat transfer divided by the absolute temperature at which the process takes place.3

Only a dozen years after Clausius first defined entropy in this thermodynamic context, entropy took on a statistical meaning as a measure of molecular disorderliness:

Ludwig Boltzmann, an Austrian physicist, demonstrated the significance of entropy on the molecular level in 1877, relating entropy to disorder. J. Willard Gibbs, an American mathematical physicist, referred to entropy as a measure of the "mixed-upedness" of the system.4

Boltzmann gave us his familiar constant which quantitatively relates entropy to the molecular disorder of a system. However, that relationship, because of its ubiquitous form,5 has lead to many other interpretations and uses (or misuses) of entropy—which will necessarily cause us some distractions.

The interpretation of entropy broadened still further with chemists who dealt with many irreversible processes. They saw entropy in the observed tendency for chemical reactions to go toward greater disorder at the molecular level.

Another manifestation of entropy is the tendency of systems to move toward greater confusion and disorder as time passes. Natural processes move toward equilibrium and homogeneity rather than toward ordered states. For example, a cube of sugar dissolved in coffee does not naturally reassemble as a cube, and perfume molecules in the air do not naturally gather again into a perfume bottle. Similarly, chemical reactions are naturally favored in which the

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5The form of Boltzmann’s expression for entropy was the product of a constant and the natural logarithm of a ratio.
products contain a greater amount of disorder (entropy) than the reactants. An example is the combustion of a common fuel. Such reactions will not spontaneously reverse themselves. This tendency toward disorder gives a temporal direction—the "arrow of time"—to natural events.\(^6\)

From its beginning, the concept of entropy, embodied in the second law of thermodynamics, has been troublesome. It has always disturbed humans because of what it seemed to imply about their abilities to pursue perfection and eternity.

The second law has been called anthropomorphic, because of what it has to say about the limits nature imposes on the human use of energy. Spengler brooded on the "deep opposition of theory and actuality" it introduced, for the first time, into theoretical physics itself. A modern physicist, P. W. Bridgman, has said that the second law still smells of its human origins. Entropy has always tended to break out of its home territory of physics and mathematics and be taken up by economists, macrohistorians, and other speculative thinkers.\(^7\)

Jeremy Campbell captures the elusiveness and appeal to all sorts of fields and thinkers of "that most peculiar and fugitive of physical laws, the entropy principle. . . ."

That equation was a mathematical expression of the tendency for all things to become less orderly when left to themselves; for energy to undergo certain transformations in the natural course of events, making it more disorganized and not so useful, degrading its quality without diminishing its quantity. Entropy had been an enormously appealing idea for nonscientists in the nineteenth century and afterward, suggesting as it did that chaos is the ultimate destiny of all things. It led to many flights of dubious speculation and inspired cranks as well as respectable thinkers. It became a reference point, a metaphor, to which philosophers, theologians, and historians of that period returned again and again, with more enthusiasm than caution. This "law" of physics, announcing that the universe is running down into a state of complete disorder, had a visible impact on intellectual fashions.\(^8\)

Campbell fingers a part of the problem and, in so doing, makes a very fundamental point about entropy:

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\(^8\)Campbell, p. 18.
Part of the trouble arises because, while entropy refers to the physical state of a physical system, it is a measure of the disorderliness of that system, and disorder is not a wholly objective property.\textsuperscript{9}

Precisely, and therein lies a source for much mischief and confusion. For example, a contemporary dictionary definition of entropy encompasses these diverse ideas:

\textit{[Entropy is] a measure of the unavailable energy in a closed thermodynamic system \ldots a measure of the disorder of a closed thermodynamic system \ldots a measure of the amount of information in a message \ldots the degradation of the matter and energy of the universe to an ultimate state of inert uniformity.}\textsuperscript{10}

\textbf{Entropy and Information}

The first big breakout of entropy from its home territory of the physical sciences—thermodynamics, chemistry, and physics—came with Claude Shannon's information theory:

In the period which followed the Second World War, entropy underwent yet another of its Merlin-like transformations when it was linked to a theory of information. This aspect of entropy, like others in the past, has taken years to explore and still is not out of the deep woods of scientific controversy. The idea of a relationship between information and entropy, implicit in the early days of the theory, is still questioned by scientists today.\textsuperscript{11}

Campbell tells how Shannon was induced to use entropy in his information theory as a joke—a joke mostly about the \textit{ambiguity} of entropy:

Entropy is a word which carries a large historical freight of good physics, profound paradox, dubious analogies, and flights of metaphysical fancy. At first, Shannon did not intend to use such a highly charged term for his information measure. He thought "uncertainty" would be a safe word. But he changed his mind after a discussion with John von Neumann, the mathematician whose name is stamped upon some of the most important theoretical work of the first half of the twentieth century. Von Neumann told Shannon to call his measure entropy, since "no one knows what entropy is, so in a debate you will always have the advantage." That was intended as a witticism, but it is true that entropy has been defined in dozens of different ways at various stages of its history. The debate about its "real" nature is still unresolved after more than a century of inquiry and argument. Even so, generations of practical scientists have used the concept of entropy, just as they

\textsuperscript{9}Campbell, p. 32.
\textsuperscript{11}Campbell, p. 52.
have used the concept of probability, without giving a moment’s thought to the
unsteadiness of its theoretical underpinnings.\textsuperscript{12}

Despite the unsteadiness of those underpinnings, information theory
has flourished as the most popular and frequent residence of the concept of
entropy outside the physical sciences. The link between information theory
and the physical sciences are statistics and stochastic processes, important
and common to both fields. The important difference between the two was
that information theory, unlike the physical sciences, offered a way to reduce
entropy through human processes:

The concept of entropy has proved to be a very general one that is applicable to
many types of probabilistic processes. One of the most significant applications
is to information theory. The suggestion that gaining information represents a
reduction in entropy was first made by Leo Szilard in 1929. In 1948 the
American mathematician Claude Shannon proposed a measure for information
which has the same form as [statistical] entropy.\textsuperscript{13}

Szilard may have come to that suggestion from a flawed analysis\textsuperscript{14} of
"Maxwell's demon," a thermodynamic paradox, where an imaginary demon
uses information to sort out molecules, thereby decreasing the disorder and
entropy of a closed system. Even though Shannon's measure for information
may have the same form and been given the same name as entropy (at von
Neumann's suggestion), that does not make it equivalent to thermodynamic
entropy except in mathematical form and name.

\textbf{Entropy and Life}

If the concept of entropy applies not only to energy, but to disorder and
information, it is logical that some would look elsewhere for evidence of
entropy. They found it in biological life and complexity.

The onset and evolutionary development of life and civilization on Earth
appears to some observers to be in conflict with the Second Law's requirement
that entropy can never decrease. Others respond that the Earth is not a closed
system, because it receives useful energy from the Sun, and that the Second
Law allows for local entropy decreases as long as these are offset by greater
entropy gains elsewhere. . . . Life on Earth may represent a local entropy
decrease in a universe where the total entropy always rises. Ongoing work by

\textsuperscript{12}Campbell, p. 32.
\textsuperscript{14}See fn. 32, below.
the Belgian chemist Ilya Prigogine and others is aimed at broadening the scope of traditional thermodynamics to include living organisms and even social systems.\textsuperscript{15}

John Von Neumann's loophole—through which miraculously improbable forms might emerge and evolve—now became a process with entropy as the agent or principle:

Biologists as well as philosophers have suggested that the universe, and the living forms it contains, are based on chance, but not on accident. . . . The random element is called entropy, the agent of chaos, which tends to mix up the unmixed, to destroy meaning. The nonrandom element is information, which exploits the uncertainty inherent in the entropy principle to generate new structures, to inform the world in novel ways.\textsuperscript{16}

This suggested that what thermodynamics was wearing down, life would build up:

In the early nineteenth century, thermodynamics challenged the timelessness implied in the mechanistic image of the universe. If the world was a big machine, the thermodynamicists declared, it was running down, its useful energy leaking out. It could not go on forever, and time, therefore, took on a new meaning. Darwin's followers soon introduced a contradictory thought: The world-machine might be running down, losing energy and organization, but biological systems, at least, were running up, becoming more, not less, organized.\textsuperscript{17}

Alvin Toffler, in his introduction to Ilya Prigogine and Isabelle Stengers\textsuperscript{1}, Order Out of Chaos, draws a subtle distinction that has emerged between narrow and expansive concepts of entropy, between entropy as a measure or entropy as an agent:

Prigogine and Stengers . . . undermine conventional views of thermodynamics by showing that under nonequilibrium conditions, at least, entropy may produce, rather than degrade, order, organization—and therefore life.

If this is so, then entropy, too, loses its either/or character. While certain systems run down, other systems simultaneously evolve and grow more coherent.\textsuperscript{18}

\textsuperscript{15}Entropy, The 1995 Grolier Multimedia Encyclopedia, Version 7.0.2
\textsuperscript{16}Campbell, p. 11.
\textsuperscript{18}Prigogine and Stengers, p. xxi, in a forward by Alvin Toffler.
This broad interpretation of entropy turns an effect into a cause, and an end into a means. My problem is not with the observation that certain systems run down while other systems simultaneously evolve, but with the implication that these two tendencies are related to each other through a single concept called entropy.

**Even Broader Applications**

There is still another broad application of entropy that appears in the concept of the "arrow of time," an important idea in cosmology where time is a dimension of the universe.

The "arrow of time" is a metaphor invented by Sir Arthur Eddington to express the idea that there exists a purely physical distinction between past and future, independent of consciousness. Such a distinction is based on the entropy principle, which asserts that as time goes on energy tends to be transformed from an orderly to a less orderly form. In Eddington's view, earlier is different from later because earlier energy is more highly organized.19

This is another example of mixing up order and energy through the concept of entropy; and it creates unnecessary problems:

However, ordinary common sense tells us that something is wrong here. If time's arrow follows the path of increasing randomness, it wipes out information. Yet history is not a record of things unraveling, descending into chaos, but of new types of order and a richer store of information. As it moves through centuries and millennia, history is a chronicle of novelty—new structures, new organisms, new civilizations, new ideas. Information, which is a measure of novelty, increases rather than diminishes with the passage of the years.20

But the argument hinges on the *connection* drawn between entropy and information. Without that connection, thermodynamic entropy can align with the arrow of time and, without contradiction, evolution can produce increasing information and complexity of organizations, civilizations, and ideas.

Almost everything attributed to entropy since Clausius seems to be motivated by the search for an escape from the seemingly dire consequences of the second law of thermodynamics: Maxwell's demon was advanced as a

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19 Campbell, p. 83.
20 Campbell, p. 84.
concept for bringing order out of disorder; Shannon's theory of information implied, for some, if not its author, that the creation of information could decrease entropy; and the life scientists argued that life and complexity were negative entropy or "negentropy."

Belgian chemist Ilya Prigogine has probably taken the concept of entropy the furthest. Beginning with chemistry, where the connection with thermodynamic entropy is irreversibility and increasing disorder, Prigogine then extends entropy beyond science to time and reality and, thence, to self-organization. He acknowledges, however, "It is not surprising that the entropy metaphor has tempted a number of writers dealing with social or economic problems." We think that Prigogine—to use his own words—may have succumbed to the temptation of the entropy metaphor for writers dealing with philosophical problems.

Nevertheless, Prigogine is not alone in his excitement with the potential of entropy for a new unity in the sciences:

The physicist Edwin Jaynes believes that . . . we are on the threshold of some quite new approach to the interpretation of probability, entropy, and information, one that will be more general than anything that has gone before. It was an accident of history, Jaynes believes, that thermodynamics was connected for so long in people's minds with matter and with physical particles obeying the laws of mechanics. Although Boltzmann interpreted the second law of thermodynamics in terms of pure probability, this fact was not fully recognized for almost a hundred years. Now the entropy principle is seen as a special case of a more general method of reasoning which does not depend on the laws of physics or mechanics at all.

This, truly, is the search for the Holy Grail of science. We recognize the search, but we could not hang our speculations on its success. Indeed, it may be premised on connections that will prove to be only treacherous similarities.

**Disentangling Entropy**

Professor Stephen Jay Kline of Stanford University—perhaps more than any person and with greater passion—has tried to warn against mixing up

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21See Prigogine and Stengers, pp. xxvii, xxix, in the preface, 8.  
22Prigogine and Stengers, p, 298.  
23Campbell, p, 65.
the different analytical formulations in classical thermodynamics, statistics, and information theory, all under the rubric of entropy:

[We] have used a single word "entropy" to denote an energetic entropy, five kinds of statistical entropies, and two informational quantities as well as less common uses. The resulting confusions have confounded understanding of many issues regarding not only the relationships among these eight quantities but also the many important uses of the entropy concept.24

Kline does not object to expanded use of the entropy metaphor or analogy so much as contemporary efforts to rationalize these different conceptions as ultimately equivalent and convertible in all of their aspects.

[Many eminent and careful workers have said the idea of equating entropy (or negentropy) and information was wrongheaded. The late Sir Karl Popper, probably the most admired philosopher of science of the 20th century, called it spurious. Kenneth Denbigh, one of the founders of irreversible thermodynamics said, after reviewing the literature, he had to conclude entropy was objective (that is not influenced by information in someone's head). . . . J. D. Fast, who wrote a notable authoritative monograph on entropy (1970)25 said the practice of equating information and entropy is "not to be recommended, since the relationship between [the two] is only of a formal mathematical nature, due to their common statistical background." But this has not stopped people from accepting the idea in computer science, in biology and other places.26

When equations from different scientific fields happen to take the same form, there is a natural temptation to look for connections or commonalties across or between those fields. That can be good science—a search that may result in one field illuminating another. That can be the stuff of Nobel prizes. But scientists must proceed with caution tempering their enthusiasm for new discoveries.27

Professor Kline calls equations of the same form "mathematical isomorphisms." With respect to entropy and information,

There is a mathematical isomorphism between them, that is, they obey the same mathematical formula. But mathematical isomorphism does not imply

26Kline, p. 22.
27An admonishment we recognize applies to our own speculations here.
that the underlying variables are equal. Plastering [the Boltzmann constant] onto Shannon’s [equation] does not give entropy.\textsuperscript{28}

Not surprisingly, Ilya Prigogine is a prime target for Kline’s impatience with those who would invoke entropy for arguments about biological evolution:

Similar remarks apply to the oft-repeated arguments by Ilya Prigogine and his colleagues at Brussels and Austin, Texas. . . . Prigogine suggests that living organisms are "dissipative structures" that have evolved owing to random fluctuations (in his early papers) and via bifurcations in chaotic systems (in later papers). But this is just like saying that [a] steamship [creating a turbulent wake with its propulsion] is a "dissipative system", and it arose from random fluctuations. The structure of the ship is anything but random; it is a highly-structured, interconnected set of parts that operate synergistically, and it was purposively designed by humans for specific goals.\textsuperscript{29}

However, Kline’s views are in sharp contrast to a number of ideas arising from the so-called "new sciences" of chaos, complexity, emergent order, and dynamical systems. For example, several papers\textsuperscript{30} presented at a 1988 Santa Fe Institute workshop attempt to forge or build upon the putative connection between energetic, statistical, and informational formulations of entropy. At the same time, I can't help but note that several of those papers relied upon Szilard's original inference in a 1929 paper that entropy and

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\textsuperscript{28}Kline, p. 22. Kline illustrates the potential dangers of mathematical isomorphisms with the following example: "The height of U.S. men has a Gaussian probability distribution. The IQ of U.S. women has a Gaussian probability distribution. But surely we do not want to say the IQ of U.S. women equals the height of U.S. men. Mathematical isomorphisms are very useful. They allow us to carry experiences and formulae for solutions from one field to another with precision. This extends our range of knowledge very efficiently. However, isomorphisms do not entail equality of the underlying variables." (Kline, p. 23)

\textsuperscript{29}Kline, pp. 16, 17.

information were opposites\textsuperscript{31}—the same paper that Professor Kline claims contains a simple but fatal error.\textsuperscript{32}

**Entropy and the Universe**

The connection between entropy and the fate of the universe has been historically associated with the "heat death of the universe," where all of the available heat in the universe has been exhausted and disorder has reached a maximum everywhere:

A consequence of nature's continual entropy rise may be the eventual degrading of all useful energy in the universe. Physicists theorize that the universe might eventually reach a temperature equilibrium in which disorder is at a maximum and useful energy sources no longer exist to support life or even motion. This "heat death of the universe" would be possible only if the universe is physically bounded and is governed as a whole by the same laws of thermodynamics observed on earth.\textsuperscript{33}

It is the combining of two separate notions of entropy—unavailability of useful energy and increasing disorder—that troubles us. From the above discussion of entropy, we see no compelling reason why those two must be linked together in the fate of the universe. Indeed, we see it more logical that those two tendencies would be opposed: The available energy might degrade, but the order might increase at the very same time.

We have come to the following view of entropy which is much closer to Kline's position than Prigogine's:

- Entropy is a measure of the unavailability of *energy* in objective forms—chemical, thermal, mechanical—in idealized closed systems.


\textsuperscript{32}The error is described by Kline on pp. 19-21 and p. 31. Szilard's error, according to Professor Kline, is one of sign in the entropy change of a perfect gas as it goes through isothermal expansion. We have examined, but were unable to verify, the discrepancy (if any) between Szilard's and Kline's calculations. In any event, we subscribe to Kline's semantic arguments which do not pivot on that issue.

\textsuperscript{33}Entropy, *The 1995 Grolier Multimedia Encyclopedia*, Version 7.0.2. Note that this is a different form of "heat death" than that described by Freeman Dyson in *Infinite in All Directions*, pp. 109, 110. (See quoted text corresponding to fn. 21, sec 5, above.)
Although entropy may be a useful metaphor or analogy for other processes—informational, biological, evolutionary—we make no inferences that they obey the second law of thermodynamics except in their chemical, thermal, or mechanical dimensions. The increasing complexity in parts of the universe through evolutionary, biological, and informational processes is not, I would argue, a decrease in entropy—or negentropy—but the survival of increasingly adaptive species, which are collaterally more complex, organized, and information dependent. Adaptive species alter their environments and expand their effects with increasing complexity, organization, and use of information. We presume that they will alter their environments on larger and larger scales—first, entire planets, then star systems, galaxies, and even the universe as a whole. Humans are already affecting their planetary environment. Their more complex successors will be able to extend their effects beyond the planet.

Entropy enters into our speculations about the fate of the universe only because the availability of some of the energy in the initial expansion of the universe was lost in the chaotic plasma phase while most of the energy was still trapped in the form of radiation. If the universe oscillates endlessly—as we believe it must if its is an interesting universe—then the entropy increase incurred during the initial plasma phase must somehow be compensated in processes before the next big bang. We thought that the "new sciences" of information, bio-evolution, dynamical systems, and emerging complexity just might—through their appropriation of the concept of entropy—provide us with a path to the hidden mechanism for winding the universal clock. Instead, I found myself in a semantic minefield that delayed rather than advanced our search. With that minefield now behind us, we can proceed with our own speculations as to where the hidden mechanism might be found and the clock wound.
8. WHERE HAS ALL THE ENTROPY GONE?

Part of the original energy in the big bang was "lost" (became unavailable) to the universe during the first billion years. Most of it was lost in the friction of the expanding plasma before it cooled enough to become transparent and the matter of the universe condensed. If the universe oscillates continuously—without running down—between expansion and collapse, then the energy "lost" must be recovered by some process. We think that process might be the structuring of matter during the late expansion and early contraction so as to give gravity a stronger bite on the matter of the universe during its long collapse and a greater impulse at the moment of implosion.

We speculate that the entropy of the universe can be decreased—that the availability of energy for the next big bang can be increased—by inadvertent but nonetheless intelligent processes which manipulate the matter of the universe. Those manipulations might change the form and distribution of matter so that the gravitational processes during the collapse of the universe could deliver more available energy rather than less into the next big bang. The intelligent design is, in principle, no more complicated than those which humans have learned in making explosives—both chemical and nuclear.

If the matter of the expanding universe were somehow structured by intelligent agents, its response to gravitational forces could be altered: The matter of the universe might be made to collapse with a slightly greater impulse, compensating for the entropy increase incurred during its initial explosion. The process is analogous to that sought in designing a nuclear explosive: The trick there is to bring the right kind of nuclear matter together in a critical mass in a sudden, concerted, highly structured way to

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1By the first law of thermodynamics, energy cannot be lost to the universe. It may be transmuted from one form to another—chemical, nuclear, kinematic, thermal, etc.—but it cannot be lost. It can, however, become less available as it is transmuted and transferred through physical processes.

2A kind of Maxwell's demon on a cosmic scale.
increase its explosive energy release. Allowing the assembly of the critical mass to proceed slowly, as from the compression of a cloud of matter, is to invite a fizzle—some parts of the explosion (and expansion) would begin before the rest of the assembly was complete, while it was still contracting.

This is why we care about entropy, about the availability of energy in the universe. In particular, we care about how the mainspring in the universal clock might be wound. Biological life, complexity, and information are not measures of entropy; they are evolutionary processes that just might culminate in making energy more available to the universe as it "sets up" for the next big bang.

**Machines to the Rescue**

If some of the matter of the universe could be intelligently redistributed during its expansion, then the subsequent collapse might be made more violent. Slight differences in the arrangement of the matter of the universe at the end of the expansion could be translated into large energy differences as the forces of gravity accelerate that same matter during the long (60 billion year) collapse. And if the final moments of the collapse could be made more organized and energetic, the additional energy thus made available could conceivably offset that made unavailable during the previous initial expansion.

We are not suggesting that the collapsing matter be designed as a nuclear explosive, although nuclear reactions will be inevitable in the heat of the final collapse. Rather, we speculate that if some of the matter of the universe—just how much we don't know without some help with the calculations—is arranged to arrive in the collapse with greater impulse—i.e., collectively arrive within a shorter interval of time—then the energy realized (made available) in the collapse should be greater than if the matter arrives from a random distribution. Imagine that our machines could, in their search for matter and energy for replication, redistribute the matter they process along a surface in space orthogonal to the gravitational center of the
universe. In effect, they would create a thin shell of crystalline iron dust from matter that would otherwise (if undisturbed) be distributed randomly nearby. In the final collapse of the universe, the shell of dust would arrive in a shorter time interval of times than would the undisturbed matter from which it had been created. The energy realized by the implosion of a shell of matter should be greater than that realized by the implosion of the same material in a cloud of matter.

The most obvious challenge to such a scheme is that it would take energy to move matter about and create a shell. But the energy required to move matter will be much less near the maximum expansion of the universe, when the forces of gravity are weak, than it will be near the start of the big bang or the end of the collapse. Think of a spacecraft launched from earth to the outer reaches of the earth's gravitational pull—just short of the point where the gravitational pull of another planet will take over and draw it away. As our spacecraft approaches that furthest point where it can still be drawn back to the earth, we give it a slight nudge—in any direction. The subsequent path of our satellite will be drastically different from a reversal of its outward path. If the nudge is away from the earth, our spacecraft will fall into the gravitational field of another planet and may never return. If the nudge is directly toward the earth, the satellite will return to the earth with much greater energy than was imparted during its departure. Our thesis is that the redistribution of matter at the maximum expansion of the universe could produce significant changes in the energy associated with the collapse.

Not all of the matter of the universe could or need be redistributed. It would seem that the most effective place to redistribute matter would be at the farthest reaches of the universe (whatever its shape) where the forces of gravity are weakest. That is the place to apply the nudge that will greatly affect the energy impulse realized at the collapse. Our general point is that the universe does not need to collapse in the same configuration—or with its matter in the same form—that it had when it expanded. If intelligent redistribution of some of the matter is possible, then the collapse need not

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3That distribution might maximize their access to fresh, unprocessed matter. Any other redistribution scheme might mean that the machines would have to dig through layers of their own excrement to get at fresh matter.
simply be the expansion run backward, but a more organized and effective use of the forces of gravity to "boost" the next big bang.

We have no way of estimating how much matter would have to be redistributed or the configuration of matter that would best serve this purpose. But the balancing processes for winding the universal clock might not be very sensitive: The energy in the universe may be very much larger than the amount which becomes unavailable during the initial expansion or the additional amount which would need to be made available during the collapse. The universe may need only a modest nudge to keep its mainspring adequately wound. Indeed, it might need only an occasional nudge to oscillate at very nearly constant rhythm forever. These are calculations for which we need the help of cosmologists.

We can conjecture about configurations of matter that would make more energy available from the integrating force of gravity over tens of billions of years. Without entering the controversies over the shape of the universe, we can reason that any configuration which shortens the time interval over which matter arrives at the center of collapse will make more energy available for explosion. Consider the analogy with the implosion of fissionable nuclear materials in the design of a bomb: If the fissionable materials to be assembled are randomly distributed (subcritically) throughout the volume of a sphere and that volume is everywhere collapsed toward the center point, the assembly will take place throughout the time it takes for the most remote parts to arrive at the center. By contrast, if the fissionable materials to be assembled are intelligently distributed only on (or very near) the surface of the sphere (as in a spherical shell), then the assembly will take place only in that briefer instant when all parts of the shell arrive simultaneously at the center. For the same amount of fissionable matter, the latter assembly should be the more violent or energetic.

Machines could serve as the intelligent agents to redistribute some of the matter of the universe—so as to enhance the energy released in the next

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4Note that the energy transfers—however large—during the initial (plasma) expansion phase after the big bang occur at extremely high temperatures, which minimize the entropy increases.
big bang. The redistribution of matter by machines will, of course, require energy. The needed energy can be extracted from the matter of the universe by converting its molecular and atomic forms, even as the universe continues to expand and cool. The lowest energy state that we can conceive for the matter of the universe is crystalline metal—iron, chromium, or vanadium—approaching absolute zero temperature. To convert all kinds of matter to cold crystalline metal will require machines that can extract all of the nuclear, chemical, and thermal energy from any matter they find. If machines are capable of consuming matter of all kinds—comprised of different nuclear elements and molecular phases—and excreting that matter as cold crystalline metal, they could extract the maximum amount of energy they would need for replication and access to additional sources of matter.

**Why Crystalline Metal?**

The reasons that machines would need to excrete crystalline metal like iron, chromium, or vanadium have to do with the thermal and nuclear energy that resides in matter. For the extraction of the nuclear energy in matter, it is the so-called "curve of binding energy" that governs the amount of energy released and the resulting products:

The nucleus of an atom is composed of neutrons and protons bound together by the strong nuclear force, the strongest of the fundamental interactions of matter. The total binding energy of a nucleus is the energy required to separate it into its constituent neutrons and protons. Conversely, when neutrons and protons are combined to form nuclei, energy equal in amount to the binding energy is released in the process. Because the nuclear force is so strong, nuclear binding energies are typically a million times greater than the electromagnetic energies binding electrons to the nucleus in an atom or binding atoms together in molecules.⁵

The curve of binding energy across the elements—from the lightest (like hydrogen) to the heaviest (like plutonium)—describes an arc that rises to its maximum in between. Nuclear fusion is possible when the lighter elements are converted to those with higher binding energies in the middle of the curve. Similarly, nuclear fission is possible when the heavier elements are converted to those with higher binding energies in the middle of the curve:

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In any nuclear reaction, energy is either absorbed or released. The most stable
atoms are those with the highest binding energy per particle in the nucleus.
This average nuclear binding energy is greatest for elements of medium
weight—around iron, in the periodic table. In general, when light nuclei
combine (fusion reactions) and when heavy, unstable nuclei divide (fission
reactions), energy is released. The energy released corresponds to changes in
binding energy of the nuclear particles, or conversion of a small fraction (about
0.1 to 1 percent) of the mass of the nuclear particles into other forms of energy.\textsuperscript{6}

In principle, then, matter comprised of elements heavier or lighter than
the metals close to iron represent a potential source of energy for machines.
Will the machines of the far distant future have mastered the knowledge of
how to release and exploit the energy of nuclear fusion and fission? Why not?
Just as humans have learned how to harness those nuclear reactions—first
for explosives and, with time, for power—machines, through deliberate
exploratory trials (and errors) will learn how to manipulate atoms as humans
manipulate molecules today. Perhaps the chimera of cold fusion (and fission)
can be turned into reality by machines that are impervious (or even thrive) on
nuclear radiation and thermal cold.

At some point, we think that machines may consider any element that
is not cold crystalline iron as a potential source of energy. At first, the easy
elements at the two ends of the curve of binding energy will be gobbled up—
much as humans have gobbled up the rich ores of aluminum and iron—
forcing the machines to extract energy from less and less lucrative elements
nearer the middle of the curve of binding energy.

Given the ability to extract the nuclear energy from matter by
converting it to iron, it will be an easy step to extract the thermal energy
from the iron. The minimum thermal energy of iron will be achieved by
converting it into cold crystals at the lowest possible temperature—near
absolute zero in the cold, empty space of an expanding universe. If those cold
iron crystals are scattered in space rather than concentrated by a local
gravity field—as in the case of the core of the planet Earth—they will have
become the least energetic form of matter, with all available nuclear,
chemical, and thermal energy extracted. In the processes of searching for
raw materials, of extracting the available nuclear, chemical, and thermal

\textsuperscript{6}Ibid.
energy, and disposing of their excrement so that it does not interfere with their replication and search for additional materials, the machines just might leave behind cold crystalline metal distributed in patterns that are most favorable for the work of the universal gravitational field that will lead to the next big bang.

The Evolution of Machines

The machines that can replicate and rove throughout an increasingly cold universe, extracting energy from matter wherever they find it, excreting and distributing crystalline iron through space, will have evolved a very long way from the machines that humans are creating as their servants today. Long before they set off traveling through the universe or extracting energy from nuclear reactions, they will have had to master their own replication and survival in the world of their creators. The machines that humans make will be crude in machine terms; they will be made to mimic the human and biological processes from which they spring and serve.

The first self-replicating machines might resemble factories where humans now produce machines. The human intervention in those factories will decline with automation and the use of other machines or factories to supply the needed resources, such as power, raw materials, and even new product designs. This may proceed on the physical scale of automobile factories or, more likely on that found in the micro- and nano-technologies of the silicon laboratories. There is much to commend making machines—including self-replicating machines—at the molecular scale: the required energies are much reduced and the speed of processes—including replication—can be much higher. These are issues that will probably clarify over the next century or so with developments in genetics and nano-technologies—both of which are likely to dominate the 21st century.

We can't forecast when machine self-replication will first occur. It could be sometime next year or sometime in the next millennium. We would be surprised if it came as soon or as late as those bounds. It will be a

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7My RAND colleague, Jim Dewar, observes that making machines on a molecular scale would continue the trend toward greater complexity in smaller surrounds.
momentous event as seen from a distance—before or after the fact—but, like
the first human, it will be little noted or remarked at the time. It will
probably be seen as no more impressive than having automobile bodies
welded by robots rather than humans; it will allow humans to do more
important or fun things than look after the fabrication of more machines.

The first self-replicating machines may not survive very long: they may
become obsolete or their self-replication capabilities may be very fragile.
They may not be far enough above that level of complexity that John von
Neumann defined as separating degenerate and increasingly complex
evolutions. But, eventually, self-replicating machines will be made robust—
less fragile or prone to obsolescence—with respect to their replication
processes. Then the competition between machines and their creators will
become more evident: They will begin to compete for resources; and humans
will be seen as the profligate species—as dinosaurs would seem today,
consuming too much for what they contribute to a limited environment
shared by other species. This competition, of course, is nothing new: We
humans find some other species, from birds to elephants, simply require too
much land, forest, or other resources to survive and replicate, so they are
relegated to zoos or wiped out. What humans have done to the lesser
biological species, we think machines will do to all of the biological species,
including humans.

It could be argued that humans will recognize this threat and head it
off. We don't think so, anymore than we think they universally recognize the
current threat of their own self-replication. Even if the threat to the species
is made clear to most, there will be some who will still see the benefit of their
own self-replication: That is the familiar "tragedy of the commons," as
formulated by Garrett Hardin.⁸ Likewise, it will benefit a few humans to
create self-replicating machines that might eventually challenge and compete
with their distant descendants for scarce resources. Humans will,
undoubtedly, rail against the challenge posed by the machines, but they will,
over the long term, be ineffective in preventing their successors from taking

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1248, reprinted in Managing the Commons, edited by Garrett Hardin and John Baden, W. H.
over. They will fall victim to the very same qualities that helped them to survive and evolve successfully: self-replication and mutation of their genes and memes. Self-replication will push the species up against resource limits, while mutation of their genes and memes will result in the invention of more adaptive, more successful species. But the machines they create will be pure meme replicators, no longer dependent upon the slow evolution of biological genes.

The first self-replicating machines, if they follow the pattern, will be mostly concerned with being successful in self-replication for survival. Only later, after survival in numbers is assured, will they adapt to be competitive among their own species by becoming more clever and efficient. That evolutionary process may take some time, but it is likely to be much faster than the genetic processes that determined much of the evolutionary history of early biological and human life. The evolution of machines—like that of computers—should proceed at a pace set by their size more than their lifetimes.

The last machines in this expansion cycle of the universe might be highly specialized, eking the last bit of energy out of cold matter. Metaphorically, the last machine in the expanding universe might be the one that consumes the next to last machine and excretes it as cold crystalline iron. With no more energetic matter available, it might shut down to await its fate in the impulse of heat as the universe implodes. Or, like a brine shrimp lying for years beneath the surface of a desert dry lake, waiting for the next rare rain, it might re-awaken as the universe begins to warm again during its long collapse and continue its mission before the growing forces of gravity and heat make it less and less effective.

We see no reason why the evolution of machines will necessarily be limited to the evolutionary processes that have occurred here on Earth. They may evolve independently in many places throughout the universe at

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9 Jim Dewar suggests another possibility: Maybe humans won't notice the challenge of their successors, just as the dinosaurs may not have noticed the tiny mammals on the forest floor that would eventually challenge them, if not for resources, eventually in dominion over the earth.
different times during the long expansion of the universe. But we must recognize that their evolution will be a relatively rare event in space and time. In the distribution of matter in the universe, atoms and simple elemental molecules are common. Complex molecules are less common, found in burnt out stars and planets. Life, even simple life, is probably quite rare, occurring only where temperatures and pressures will permit self-replicating molecules. The evolution of very complex life, culminating in conscious intelligence is probably exceedingly rare, requiring a sustained environment that biological life can fill and begin to regulate to its advantage.\textsuperscript{10} Only then and there will the opportunity emerge for the evolution of machine species.

Since machine species will emerge through a series of von Neumann's loopholes of miraculous improbability, the possibilities for failures or for different twists and turns would seem to be very large. If biological life were to evolve differently on another planet because of variances in the environment or mutations, the emergence of the first machines might be quite different also. Some evolutions might be truncated by disastrous changes in the environment, perhaps some of them created by the species themselves as they crowd and alter their environment in unanticipated ways. But once they have emerged in a viable, sustainable form, machines should be able to adapt more easily and quickly than biological life to adverse changes in their environment—because they will be able to reprogram themselves more quickly than most biological species.

\textbf{On the Purposefulness of Machines}

Will the machines set out consciously to decrease the entropy of the universe—to wind the universal clock? Not any more than humans will set out to create their successors. The machines will eventually convert matter to crystalline metal in order to adapt to a cooling universe and to extract its remaining energy. They will distribute those cold crystals in order to gain access to more matter, much as ants will scatter sand around the entrance to their nests—not to make an ant hill, but to dispose of matter that is of no use

\textsuperscript{10}Lovelock, Op.Cit.
to them. They will do these things in order to continue to survive and adapt to their environment; for if they did not, they would not exist and their more adaptable competitors would.

Humans or more advanced forms of biological life would not be able to do what machines will do as they spread through a cooling universe, extracting energy from its matter, and scattering the inert residue. Only machines will be able to produce and replicate such machines. Each evolution of machines will face a different environment and will compete with other machines. Their adaptation, competition, and self-replication will mark the path of their evolution.

These machines could not have arisen spontaneously as a species from molecules as did primitive life. Nor could they have evolved out of the simpler life forms known to humans. On this planet, humans are the first biological species capable of understanding and creating self-replicating machines. Biological life had to evolve to a sufficient level of complexity and intelligence before it could provide a new von Neumann loophole—a miraculously improbable loophole through which even greater complexity could emerge and evolve in the form of machines. If humans were not up to the task, we think the job would simply fall to the next evolution of biological life beyond humans—if the human species can survive that long biological process with its current memes and self-replication rates.

More complex, more adaptable species will come. That is the pattern. To assume that it will stop with humans is anthropocentric. Yet that implicit presumption is just the kind of arrogance that has carried humans so far and that will induce them to create their successors—even if those successors are the first that are neither biological nor genetic replicators.
9. THE DEATH OF OPTIMISM?

All of our speculations about the meaning of life, the destiny of humans, and the fate of the universe have now been set forth. We recognize that they are no more than guesses about how the world works and why it works that way. But they are not random shots in the dark. They form a collective, integrated whole that we have not seen anywhere else. Each of our conjectures is rooted in contemporary scientific thought—some of it in the mainstream, some on the margins—but the connections, the thread pulled through time and matter, are new to us. There is a consistency in the patterns across distance and time that we find satisfying and not consciously forced. The discernment of pattern in one place has helped us recognize it in another.

The picture that has emerged from our puzzle has troubled us from the very beginning. What it says about our species and life is discordant with most of current human culture—in its religious, moral, ethical, and political thinking. We talked about that earlier, in Section 4. Human culture tends to be generally optimistic\(^1\)—for very good, functional reasons—yet our picture seems pessimistic from an anthropocentric perspective. We have sometimes felt discouraged as we wrestled with our ideas and their implications. In this final section, we try to confront the disconnections between our intellectual speculations and the human microcosm that we live in. Now that we are close to the end of our journey in this synopsis and the puzzle has been assembled, we can be more aggressive about what we see in—and the problems posed by—the picture in the puzzle.

Why Is This Troubling?

Our speculations have many implications, but the most troubling are those that bear upon the uniqueness of life and humanity. Human genes and

\(^1\)But humans may not be alone among the biological species in their optimism. We note that domestic canines seem to be almost universally optimistic unless trained to be otherwise. It may be that such optimism is an adaptive trait that has led to their survival as pets.
memes are programmed to worship the miracle of life and the elevation of humans over all other biological species. That programming is functional, like most of the ingredients of life and humans: It helps humans protect the biological base upon which their species depends; and it impels them to reach toward the aspirations and stature that they have granted to themselves.

The programming of the genes and memes that have served humans so well and brought them to dominion over their planet are not to be cast off easily or quickly. We see no reason why they should be. Successful ideas are not going to be traded in for those that could be destructive to the species. Even from our anthroponeutral stance, we recognize that the consistent meme of religion throughout human culture has been an important component in the evolution of both genes and memes in the human species—it is part and parcel of who and what we are as we reason about these things. The vehicle that has brought humans so far so quickly—from competing with the animals to ruling the planet in the space of 100 millennia—will not be abandoned soon or without trauma, even if it is closer to the end than the beginning of its evolutionary journey.

Only a few of our conjectures should be deeply troubling. The notion of an oscillating universe is not. Neither is the idea that the universe might be made to ring like a bell—expanding and contracting—by the actions of intelligent agents transforming some of the matter in the universe. Those events are too remote to be troubling except to scientists who consider such things their domain of inquiry. The idea that life might have emerged from the natural behavior of molecules under fortuitous conditions might be disturbing to some, but it is hardly new. Neither is the idea that we are creating machines that may soon exceed the performance of human brains on some aspects, because most will discount that news with the comforting thought that these "artificial" brains\(^2\) will never be able to accomplish the human feats of creativity\(^3\) and emotions and consciousness.

\(^2\)According to this line of thinking, only biology will produce "real" brains; all others, all man-made brains will necessarily be "artificial".

\(^3\)The creativity of humans is frequently asserted as a characteristic that sets humans apart from others—other life or man-made machines. We think this is shaky ground. Not only can machines be made creative by programming them to explore alternatives, much of biological life—even primitive biological life—demonstrates enormous creativity through its
Our arguments become troubling when we imply that humans are just the latest in a sequence of biological evolutions, that they will be succeeded relatively soon by a new, non-biological species of their own making, and that humans will eventually be crowded out and made extinct by their mind-children, just as they have crowded out their biological competitors. So, what is most troubling about our speculations are the sacred ideas we undermine by implying that humans are not the ultimate in the evolution of species and that human destiny may be less than had been hoped. We could respond by arguing that humans are unique—that they will be the first species to create its successors—but we doubt that will bring much comfort.

When we suggest that humans are not destined to remain paramount on this planet or to achieve everlasting life through their progeny or deeds, we have insulted much of what humanity holds most dear. We are undermining much of the basis for much of human optimism. We have committed what not very long ago would have been heresy with our central speculations. Worse, we have embedded them in a larger, consistent pattern that is rooted in orthodoxy.

Thus, when the picture in our puzzle first emerged during our breakfast conversations, we were filled with some trepidation and concern for its repercussions. We talked about dropping our speculations, keeping them to ourselves, out of respect to most. But something within us demanded that we set them down in writing, if only for a record of mutant memes that had surfaced in our heads. When we carefully, cautiously discussed these ideas with a few friends, we realized that they understood and were interested in our speculations, even if they did not necessarily subscribe to them. These friends have emboldened us to proceed to this point.
Anticipating Reactions

After reviewing an earlier draft of this synopsis, Graham Fuller, a RAND colleague of mine, wrote me to point out:

First, while we may all be disturbed at the prediction of the end of the human race—well in advance of the end of the universe—I do not really think that it necessarily needs to be disturbing to those with religious outlooks. After all, except for fairly literal minds, religion, despite some lag time common to many schools of thought, has not ultimately had trouble keeping pace with scientific advances—especially Buddhism, but even Christianity—since all acquired knowledge can be readily understood as the "unfolding knowledge of God's order," if you will. And indeed, from the same religious premise, even the end of man will reflect the unfolding of "God's plan." It is only those interpretations of religion that insist on "Man in God's image" that might have theological trouble with the argument.  

Fuller, early on, had urged us to anticipate public reactions to our speculations, if they should be widely accepted. He offered some thoughts to get us started:

I think the issue of people's reaction to this process [of the transition to a machine age] raises the most quintessential questions of values, existence, and purposefulness in our lives that cannot be ignored—at least as a scientific observation. Almost none of the values that any of us cherish in our lives will be transmitted into the machine age, simply because they will not be necessary. . . . And the moral/psychological/institutional transition to the machine age is fascinating to consider for the impact it will/must have on values, "meaning of life," etc. It could be that it will be "unbearable" for humans and [lead to] a lengthy running war. . . . I feel little reason to believe that Man will "go quietly." There will likely be extraordinary resistance, much of it Luddite, but much of it far more sophisticated.

Our friends Jim and Ruth Dewar, at breakfast on a terrace overlooking gardens and the sea in Hawaii, helped us think about precedents for such speculations—ideas that disturbed the prevailing memes defining humanity. Although it would be presumptive of us to think our speculations will disturb the prevailing memes very widely or very long, well-known precedents at least suggest the nature of reactions to unorthodox ideas. Obviously, Copernicus and Darwin come to mind. Copernicus challenged the then-sacred idea that Earth was the center of the universe; and his theories

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4Memorandum on the subject of "Entropy" from Graham E. Fuller to Carl Builder, dated 5 February 1997.
5Ibid., emphasis in the original.
brought down the wrath of the Catholic Church on the head of poor Galileo Galilei when he picked up on them. Darwin challenged the sacred idea that humans were created apart from all the other species—born into dominion of all on Earth. Darwin's theories are still far from universal acceptance, for they challenge ideas that many feel have served humanity well for so long.

The current evidence suggesting that there may have been earlier life on Mars will, no doubt, be disturbing to some, for it would challenge the ancient idea that Earth is unique in spawning life, not only in this solar system, but in the whole universe. The discovery of other planets in the universe outside this solar system has stimulated some popular interest precisely because it suggests that this solar system is not unique. Likewise, the search for extra-terrestrial intelligence has captured the interest of more than the scientists listening for signals with their large radio telescopic antennae. If they were to detect something, the effect would, of course, be profoundly disturbing to most, stimulatingly exciting to some.6

Anthropocentric memes are being increasingly challenged as scientific knowledge expands—not just of the cosmos—but by the evolution of computers and human understanding of biological species. For a long time, humans argued that humans could be set apart from the animals by their use of tools—until scientists observed that other animals also use tools, as apes may use a reed or straw to extract termites from a nest. So the argument retreated to narrower ground: Humans were the only species that made tools. Now, even that argument has succumbed to the rapidly expanding human knowledge of animals.

For a while, humans thought that evidence of their superiority over the animals could be objectively measured by the size of their brains—specifically, the ratio of brain to body mass—only to learn that bottle-nose dolphins or porpoises win that contest.7 Slowly, humans are finding that their own scientific knowledge is forcing them to retreat from one barrier to

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6Astronomer Carl Sagan explored this scenario in his novel, Contact (Simon and Schuster, New York, 1985).

7Much of that brain mass may be devoted to the enormous computational challenge of processing of acoustic images, but few would now want to argue that porpoises are simple, dumb animals.
another in their efforts to keep themselves apart from the biology out of which they evolved and upon which they still depend for their survival. They will soon find themselves defending the uniqueness of their brains from the computers they are creating as their servants or toys. What sets humans apart from the rest of biology may eventually come to be seen as their ability to evolve through memes as well as genes. It is the evolution of human memes in the space of fifty or a hundred thousand years that has brought us to this remarkable von Neumann loophole. Evolution by memes rather than genes is humanity's unique gift to its successors.

We anticipate several different reactions to our speculations. From scientists whose fields we have abused, we expect that our ideas will be dismissed as too simplistic; we will have ignored too many of the details that are their stock in trade. We are less concerned about that kind of criticism than we are their arguments that we have missed or misinterpreted some simple and fundamental knowledge that leads to quite contrary speculations. We would welcome being confronted with such omissions or fallacies, for they will help us to grow and learn beyond our present limited understanding of the world we live in.

We may be accused by scientific philosophers of having wrapped a few bits of science in a large helping of science fiction. I have written some fiction, but fiction was definitely not our purpose here. Broad speculation was; but that is not a coin of great value in science today. Sad to say, speculation puts modern science on the defensive more than it opens up new lines of exploration. New mutant memes too often mean that career investments in existing paradigms must be defended or lost. We have found patterns in the evolution of the universe, life, humanity, and machines that are far too consistent for us to ignore and that we have not seen integrated to a coherent whole anywhere else. If that makes it fiction in the eyes of some, we would like to see more such fiction and its honest criticism.

What If We Were Believed?

If our speculations were widely accepted—something we seriously doubt—the effects, if any, upon human societies—their values and actions—are likely to be modest. There are precedents in the current warnings about
what humans are doing to foul their own environmental nest or to make
themselves increasingly vulnerable to new diseases, widespread famine, and
breakdowns in order. These alarms appear to be absorbed intellectually
rather than emotionally. They may become the basis for policies or
exhortations intended to modify human behavior, but whatever their effect on
human values, they seem to have very little effect upon human actions. Too
many humans can not enjoy the luxury of worrying about a future much
beyond today's survival and the next meal. Hence, we can't imagine that
most in the world today could afford to give our speculations—even if
validated beyond question by elites—anything more than a shrug. And we
see little to suggest that this situation will change in the foreseeable future.

The effect of our speculations upon elites—while more discernible if they
should somehow withstand scrutiny—is unlikely to be any more significant
than the current speculations about the environment, the destruction of rain
forests or species, or the decline of borders and order. So, in the end, we may
have done no more than unleashed another demon to bedevil some and be
ignored by most—even if we are mostly right. Whether that is for good or ill
is something that we hope to learn but can't know at this point. We can only
hope that our speculations might, like James Lovelock's marvelous Gaia
theory of a living, adapting planet, raise the consciousness of humans as to
what they are tinkering with and the risks that they run.

Of course, we believe in these speculations—at least until we find better
ones to believe in—and we can speak to our own reactions. We find ourselves
looking at the world around us with new eyesight: We look at the child-
centerededness of our society—a pedicentric culture—with an understanding
that we did not have before. We see more starkly the difference between
what NASA is doing with its un-manned planetary exploration and its
manned shuttle flight programs—and are more certain where the future lies.
We look at the environmental movements more clearly as they elicit better
behavior from humans so as to make more room for more humans—in a
world where human self-replication can swamp the effects of universally ideal
behavior in a couple of decades. We marvel at the increasing division of the
crowding world between have's and have-nots—where elites will depend less
and less on human labor for their desires and much of the rest of burgeoning
humanity will be abandoned to the misery of deprivation and violence. We give each other knowing looks when we hear that the communications between machines are likely to grow faster than the communications between humans.\(^8\) But, mostly, it has helped us to understand our own species.

This is a work in progress—to use a currently popular phrase by policymakers—and that means we have some unfinished work. Beside exploring these speculations with a wider circle of scientists and philosophers and expanding this synopsis into book-length manuscript, we need to think through possibilities for some experimental or theoretical tests of the several theories we have strung together here. We have pointed to some of the readily available evidence that supports our speculations, but can we think of physical experiments or computer simulations that might provide arrows pointing toward or away from our theories? We need to locate the pivotal places where our speculations depart from conventional notions and think more deeply about how to devise tests that might confirm or refute those departures. For example, it would seem that our uncommon speculation about making more energy available for the next big bang by redistributing the matter of the universe when it nears its maximum expansion is something that could be tested through computer simulations of the energy and matter of the universe.

Everywhere we look, we see evidence that the human species is approaching a von Neumann loophole of miraculous improbability where the old species has pressed up against its environmental limits, has increasingly specialized to adapt successfully to those limits, and is about to spawn a new, more complex, and more adaptable species. It doesn't make us pessimistic; it gives us the excitement of seeing and understanding a new vista—new to us, but as old as the universe itself. For the first time in our lives, we have found a continuous thread that ties together—however tenuously—all of our meager knowledge about the history and fate of the universe, life, and the

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\(^8\)As between computers carrying out financial transactions and commercial trades. As between computers on moving vehicles or weapons and their computer controllers in space and on the ground. This aspect of the explosion in global communications was first raised for us by Ross Stapleton-Gray (whose internet web site is http://www.embassy.org) in an e-mail message dated 10 January 1997.
human species into a coherent, meaningful, repeating pattern of transitions from chaos to order—and back again. We look forward to the opportunity, thinking with others, to turn this thread into a string, if that be possible, or to abandon it in search of a different thread. Ultimately, humans will find a string they can turn into a rope or cable that all can grasp.
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