Notes

Prologue: The Power of Ideas

1. My mother is a talented artist specializing in watercolor paintings. My father was a noted musician, conductor of the Bell Symphony, founder and former chairman of the Queensborough College Music Department.
2. The Tom Swift Jr. series, which was launched in 1954 by Grosset and Dunlap and written by a series of authors under the pseudonym Victor Appleton, continued until 1971. The teenage Tom Swift, along with his pal Bud Barclay, raced around the universe exploring strange places, conquering bad guys, and using exotic gadgets such as house-sized spacecraft, a space station, a flying lab, a cycloplane, an electric hydrolung, a diving seacopter, and a repellatron (which repelled things; underwater, for example, it would repel water, thus forming a bubble in which the boys could live).

   The first nine books in the series are *Tom Swift and His Flying Lab* (1954), *Tom Swift and His Jetmarine* (1954), *Tom Swift and His Rocket Ship* (1954), *Tom Swift and His Giant Robot* (1954), *Tom Swift and His Atomic Earth Blaster* (1954), *Tom Swift and His Outpost in Space* (1955), *Tom Swift and His Diving Seacopter* (1956), *Tom Swift in the Caves of Nuclear Fire* (1956), and *Tom Swift on the Phantom Satellite* (1956).
3. The program was called Select. Students filled out a three-hundred-item questionnaire. The computer software, which contained a database of about two million pieces of information on three thousand colleges, selected six to fifteen schools that matched the student's interests, background, and academic standing. We processed about ten thousand students on our own and then sold the program to the publishing company Harcourt, Brace, and World.
4. *The Age of Intelligent Machines*, published in 1990 by MIT Press, was named Best Computer Science Book by the Association of American Publishers. The book explores the development of artificial intelligence and predicts a range of philosophic, social, and economic impacts of intelligent machines. The narrative is complemented by twenty-three articles on AI from thinkers such as Sherry Turkle, Douglas Hofstadter, Marvin Minsky, Seymour Papert, and George Gilder. For the entire text of the book, see http://www.KurzweilAI.net/aim.

5. Key measures of capability (such as price-performance, bandwidth, and capacity) increase by multiples (that is, the measures are multiplied by a factor for each increment of time) rather than being added to linearly.
6. Douglas R. Hofstadter, *Gödel, Escher, Bach: An Eternal Golden Braid* (New York: Basic Books, 1979).

Chapter One: The Six Epochs

1. According to the Transtopia site (http://transtopia.org/faq.html#1.11), "Singularitarian" was "originally defined by Mark Plus ('91) to mean 'one who believes the concept of a Singularity.' " Another definition of this term is " 'Singularity activist' or 'friend of the Singularity'; that is, one who acts so as to bring about a Singularity [Mark Plus, 1991; *Singularitarian Principles,* Eliezer Yudkowsky, 2000]." There is not universal agreement on this definition, and many Transhumanists are still Singularitarians in the original sense—that is, "believers in the Singularity concept" rather than "activists" or "friends."

   Eliezer S. Yudkowsky, in *The Singularitarian Principles*, version 1.0.2 (January 1, 2000), http://yudkowsky.net/sing/principles.ext.html, proposed an alternate definition: "A Singularitarian is someone who believes that technologically creating a greater-than-human intelligence is desirable, and who works to that end. A Singularitarian is friend, advocate, defender, and agent of the future known as the Singularity."

   My view: one can advance the Singularity and in particular make it more likely to represent a constructive advance of knowledge in many ways and in many spheres of human discourse—for example, advancing democracy, combating totalitarian and fundamentalist belief systems and ideologies, and creating knowledge in all of its diverse forms: music, art, literature, science, and technology. I regard a Singularitarian as someone who understands the transformations that are coming in this century and who has reflected on their implications for his or her own life.
2. We will examine the doubling rates of computation in the next chapter. Although the number of transistors per unit cost has doubled every two years, transistors have been getting progressively faster, and there have been many other levels of innovation and improvement. The overall power of computation per unit cost has recently been doubling every year. In particular, the amount of computation (in computations per second) that can be brought to bear to a computer chess machine doubled every year during the 1990s.
3. John von Neumann, paraphrased by Stanislaw Ulam, "Tribute to John von Neumann," *Bulletin of the American Mathematical Society* 64.3, pt. 2 (May 1958): 1–49. Von Neumann (1903–1957) was born in Budapest into a Jewish banking family and came to Princeton University to teach mathematics in 1930. In 1933 he became one of the six original professors in the new Institute for Advanced Study

in Princeton, where he stayed until the end of his life. His interests were far ranging: he was the primary force in defining the new field of quantum mechanics; along with coauthor Oskar Morgenstern, he wrote *Theory of Games and Economic Behavior*, a text that transformed the study of economics; and he made significant contributions to the logical design of early computers, including building MANIAC (Mathematical Analyzer, Numeral Integrator, and Computer) in the late 1930s.

Here is how Oskar Morgenstern described von Neumann in the obituary "John von Neumann, 1903–1957," in the *Economic Journal* (March 1958: 174): "Von Neumann exercised an unusually large influence upon the thought of other men in his personal relations. . . . His stupendous knowledge, the immediate response, the unparalleled intuition held visitors in awe. He would often solve their problems before they had finished stating them. His mind was so unique that some people have asked themselves—they too eminent scientists—whether he did not represent a new stage in human mental development."

4. See notes 20 and 21 in chapter 2.
5. The conference was held February 19–21, 2003, in Monterey, California. Among the topics covered were stem-cell research, biotechnology, nanotechnology, cloning, and genetically modified food. For a list of books recommended by conference speakers, see http://www.thefutureoflife.com/books.htm.
6. The Internet, as measured by the number of nodes (servers), was doubling every year during the 1980s but was only tens of thousands of nodes in 1985. This grew to tens of millions of nodes by 1995. By January 2003, the Internet Software Consortium (http://www.isc.org/ds/host-count-history.html) counted 172 million Web hosts, which are the servers hosting Web sites. That number represents only a subset of the total number of nodes.
7. At the broadest level, the anthropic principle states that the fundamental constants of physics must be compatible with our existence; if they were not, we would not be here to observe them. One of the catalysts for the development of the principle is the study of constants, such as the gravitational constant and the electromagnetic-coupling constant. If the values of these constants were to stray beyond a very narrow range, intelligent life would not be possible in our universe. For example, if the electromagnetic-coupling constant were stronger, there would be no bonding between electrons and other atoms. If it were weaker, electrons could not be held in orbit. In other words, if this single constant strayed outside an extremely narrow range, molecules would not form. Our universe, then, appears to proponents of the anthropic principle to be fine-tuned for the evolution of intelligent life. (Detractors such as Victor Stenger claim the fine-tuning is not so fine after all; there are compensatory mechanisms that would support a wider window for life to form under different conditions.)

   The anthropic principle comes up again in the context of contemporary cosmology theories that posit multiple universes (see notes 8 and 9, below), each with its own set of laws. Only in a universe in which the laws allowed thinking beings to exist could we be here asking these questions.

One of the seminal texts in the discussion is John Barrow and Frank Tipler, *The Anthropic Cosmological Principle* (New York: Oxford University Press, 1988). See also Steven Weinberg, "A Designer Universe?" at http://www.physlink.com/Education/essay_weinberg.cfm.

8. According to some cosmological theories, there were multiple big bangs, not one, leading to multiple universes (parallel multiverses or "bubbles"). Different physical constants and forces apply in the different bubbles; conditions in some (or at least one) of these bubbles support carbon-based life. See Max Tegmark, "Parallel Universes," *Scientific American* (May 2003): 41–53; Martin Rees, "Exploring Our Universe and Others," *Scientific American* (December 1999): 78–83; Andrei Linde, "The Self-Reproducing Inflationary Universe," *Scientific American* (November 1994): 48–55.
9. The "many worlds" or multiverse theory as an interpretation of quantum mechanics was developed to solve a problem presented by quantum mechanics and then has been combined with the anthropic principle. As summarized by Quentin Smith:

> A serious difficulty associated with the conventional or Copenhagen interpretation of quantum mechanics is that it cannot be applied to the general relativity space-time geometry of a closed universe. A quantum state of such a universe is describable as a wave function with varying spatial-temporal amplitude; the probability of the state of the universe being found at any given point is the square of the amplitude of the wave function at that point. In order for the universe to make the transition from the superposition of many points of varying probabilities to one of these points—the one in which it actually is—a measuring apparatus must be introduced that collapses the wave function and determines the universe to be at that point. But this is impossible, for there is nothing outside the universe, no external measuring apparatus, that can collapse the wave function.
>
> A possible solution is to develop an interpretation of quantum mechanics that does not rely on the notion of external observation or measurement that is central to the Copenhagen interpretation. A quantum mechanics can be formulated that is internal to a closed system.
>
> It is such an interpretation that Hugh Everett developed in his 1957 paper, "Relative State Formulation of Quantum Mechanics." Each point in the superposition represented by the wave function is regarded as actually containing one state of the observer (or measuring apparatus) and one state of the system being observed. Thus "with each succeeding observation (or interaction), the observer state 'branches' into a number of different states. Each branch represents a different outcome of the measurement and the corresponding eigenstate for the object-system state. All branches exist simultaneously in the superposition after any given sequence of observations."

> Each branch is causally independent of each other branch, and consequently no observer will ever be aware of any "splitting" process. The world will seem to each observer as it does in fact seem.
>
> Applied to the universe as a whole, this means that the universe is regularly dividing into numerous different and causally independent branches, consequent upon the measurement-like interactions among its various parts. Each branch can be regarded as a separate world, with each world constantly splitting into further worlds.

Given that these branches—the set of universes—will include ones both suitable and unsuitable for life, Smith continues, "At this point it can be stated how the strong anthropic principle in combination with the many-worlds interpretation of quantum mechanics can be used in an attempt to resolve the apparent problem mentioned at the beginning of this essay. The seemingly problematic fact that a world with intelligent life is actual, rather than one of the many lifeless worlds, is found not to be a fact at all. If worlds with life and without life are both actual, then it is not surprising that this world is actual but is something to be expected."

Quentin Smith, "The Anthropic Principle and Many-Worlds Cosmologies," *Australasian Journal of Philosophy* 63.3 (September 1985), available at http://www.qsmithwmu.com/the_anthropic_principle_and_many-worlds_cosmologies.htm.

10. See chapter 4 for a complete discussion of the brain's self-organizing principles and the relationship of this principle of operation to pattern recognition.
11. With a "linear" plot (where all graph divisions are equal), it would be impossible to visualize all of the data (such as billions of years) in a limited space (such as a page of this book). A logarithmic ("log") plot solves that by plotting the order of magnitude of the values rather than the actual values, allowing you to see a wider range of data.
12. Theodore Modis, professor at DUXX, Graduate School in Business Leadership in Monterrey, Mexico, attempted to develop a "precise mathematical law that governs the evolution of change and complexity in the Universe." To research the pattern and history of these changes, he required an analytic data set of significant events where the events equate to major change. He did not want to rely solely on his own list, because of selection bias. Instead, he compiled thirteen multiple independent lists of major events in the history of biology and technology from these sources:

Carl Sagan, *The Dragons of Eden: Speculations on the Evolution of Human Intelligence* (New York: Ballantine Books, 1989). Exact dates provided by Modis.

American Museum of Natural History. Exact dates provided by Modis.

The data set "important events in the history of life" in the *Encyclopaedia Britannica.*

Educational Resources in Astronomy and Planetary Science (ERAPS), University of Arizona, http://ethel.as.arizona.edu/~collins/astro/subjects/evolve-26.html.

Paul D. Boyer, biochemist, winner of the 1997 Nobel Prize, private communication. Exact dates provided by Modis.

J. D. Barrow and J. Silk, "The Structure of the Early Universe," *Scientific American* 242.4 (April 1980): 118–28.

J. Heidmann, *Cosmic Odyssey: Observatoir de Paris*, trans. Simon Mitton (Cambridge, U.K.: Cambridge University Press, 1989).

J. W. Schopf, ed., *Major Events in the History of Life*, symposium convened by the IGPP Center for the Study of Evolution and the Origin of Life, 1991 (Boston: Jones and Bartlett, 1991).

Phillip Tobias, "Major Events in the History of Mankind," chap. 6 in Schopf, *Major Events in the History of Life.*

David Nelson, "Lecture on Molecular Evolution I," http://drnelson.utmem.edu/evolution.html, and "Lecture Notes for Evolution II," http://drnelson.utmem.edu/evolution2.html.

G. Burenhult, ed., *The First Humans: Human Origins and History to 10,000 BC* (San Francisco: HarperSanFrancisco, 1993).

D. Johanson and B. Edgar, *From Lucy to Language* (New York: Simon & Schuster, 1996).

R. Coren, *The Evolutionary Trajectory: The Growth of Information in the History and Future of Earth*, World Futures General Evolution Studies (Amsterdam: Gordon and Breach, 1998).

These lists date from the 1980s and 1990s, with most covering the known history of the universe, while three focus on the narrower period of hominoid evolution. The dates used by some of the older lists are imprecise, but it is the events themselves, and the relative locations of these events in history, that are of primary interest.

Modis then combined these lists to find clusters of major events, his "canonical milestones." This resulted in 28 canonical milestones from the 203 milestone events in the lists. Modis also used another independent list by Coren as a check to see if it corroborated his methods. See T. Modis, "Forecasting the Growth of Complexity and Change," *Technological Forecasting and Social Change* 69.4 (2002); http://ourworld.compuserve.com/homepages/tmodis/TedWEB.htm.

13. Modis notes that errors can arise from variations in the size of lists and from variations in dates assigned to events (see T. Modis, "The Limits of Complexity and Change," *The Futurist* [May–June 2003], http://ourworld.compuserve.com/homepages/tmodis/Futurist.pdf). So he used clusters of dates to define his canonical milestones. A milestone represents an average, with known errors assumed to be the standard deviation. For events without multiple sources, he "arbitrarily assign[ed] the average error as error." Modis also points out other sources of error—cases where precise dates are unknown or where there is the possibility of inappropriate assumption of equal importance for each data point—which are not caught in the standard deviation.

Note that Modis's date of 54.6 million years ago for the dinosaur extinction is not far enough back.

14. Typical interneuronal reset times are on the order of five milliseconds, which allows for two hundred digital-controlled analog transactions per second. Even accounting for multiple nonlinearities in neuronal information processing, this is on the order of a million times slower than contemporary electronic circuits, which can switch in less than one nanosecond (see the analysis of computational capacity in chapter 2).
15. A new analysis by Los Alamos National Lab researchers of the relative concentrations of radioactive isotopes in the world's only known natural nuclear reactor (at Oklo in Gabon, West Africa) has found a decrease in the fine-structure constant, or alpha (the speed of light is inversely proportional to alpha), over two billion years. That translates into a small increase in the speed of light, although this finding clearly needs to be confirmed. See "Speed of Light May Have Changed Recently," *New Scientist,* June 30, 2004, http://www.newscientist.com/news/news.jsp?id=ns99996092. See also http://www.sciencedaily.com/releases/2005/05/050512120842.htm.
16. Stephen Hawking declared at a scientific conference in Dublin on July 21, 2004, that he had been wrong in a controversial assertion he made thirty years ago about black holes. He had said information about what had been swallowed by a black hole could never be retrieved from it. This would have been a violation of quantum theory, which says that information is preserved. "I'm sorry to disappoint science fiction fans, but if information is preserved there is no possibility of using black holes to travel to other universes," he said. "If you jump into a black hole, your mass energy will be returned to our universe, but in a mangled form, which contains the information about what you were like, but in an unrecognizable state." See Dennis Overbye, "About Those Fearsome Black Holes? Never Mind," *New York Times*, July 22, 2004.
17. An event horizon is the outer boundary, or perimeter, of a spherical region surrounding the singularity (the black hole's center, characterized by infinite density and pressure). Inside the event horizon, the effects of gravity are so strong that not even light can escape, although there is radiation emerging from the surface owing to quantum effects that cause particle-antiparticle pairs to form, with one of the pair being pulled into the black hole and the other being emitted as radiation (so-called Hawking radiation). This is the reason why these regions are called "black holes," a term invented by Professor John Wheeler. Although black holes were originally predicted by German astrophysicist Kurt Schwarzschild in 1916 based on Einstein's theory of general relativity, their existence at the centers of galaxies has only recently been experimentally demonstrated. For further reading, see Kimberly Weaver, "The Galactic Odd Couple," http://www.scientificamerican.com, June 10, 2003; Jean-Pierre Lasota, "Unmasking Black Holes," *Scientific American* (May 1999): 41–47; Stephen Hawking, *A Brief History of Time: From the Big Bang to Black Holes* (New York: Bantam, 1988).

18. Joel Smoller and Blake Temple, "Shock-Wave Cosmology Inside a Black Hole," *Proceedings of the National Academy of Sciences* 100.20 (September 30, 2003): 11216–18.
19. Vernor Vinge, "First Word," *Omni* (January 1983): 10.
20. Ray Kurzweil, *The Age of Intelligent Machines* (Cambridge, Mass.: MIT Press, 1989).
21. Hans Moravec, *Mind Children: The Future of Robot and Human Intelligence* (Cambridge, Mass.: Harvard University Press, 1988).
22. Vernor Vinge, "The Coming Technological Singularity: How to Survive in the Post-Human Era," VISION-21 Symposium, sponsored by the NASA Lewis Research Center and the Ohio Aerospace Institute, March 1993. The text is available at http://www.KurzweilAI.net/vingesing.
23. Ray Kurzweil, *The Age of Spiritual Machines: When Computers Exceed Human Intelligence* (New York: Viking, 1999).
24. Hans Moravec, *Robot: Mere Machine to Transcendent Mind* (New York: Oxford University Press, 1999).
25. Damien Broderick, two works: *The Spike: Accelerating into the Unimaginable Future* (Sydney, Australia: Reed Books, 1997) and *The Spike: How Our Lives Are Being Transformed by Rapidly Advancing Technologies*, rev. ed. (New York: Tor/Forge, 2001).
26. One of John Smart's overviews, "What Is the Singularity," can be found at http://www.KurzweilAI.net/meme/frame.html?main=/articles/art0133.html; for a collection of John Smart's writings on technology acceleration, the Singularity, and related issues, see http://www.singularitywatch.com and http://www.Accelerating.org.

    John Smart runs the "Accelerating Change" conference, which covers issues related to "artificial intelligence and intelligence amplification." See http://www.accelerating.org/ac2005/index.html.
27. An emulation of the human brain running on an electronic system would run much faster than our biological brains. Although human brains benefit from massive parallelism (on the order of one hundred trillion interneuronal connections, all potentially operating simultaneously), the reset time of the connections is extremely slow compared to contemporary electronics.
28. See notes 20 and 21 in chapter 2.
29. See the appendix, "The Law of Accelerating Returns Revisited," for a mathematical analysis of the exponential growth of information technology as it applies to the price-performance of computation.
30. In a 1950 paper published in *Mind: A Quarterly Review of Psychology and Philosophy*, the computer theoretician Alan Turing posed the famous questions "Can a machine think? If a computer could think, how could we tell?" The answer to the second question is the Turing test. As the test is currently defined, an expert committee interrogates a remote correspondent on a wide range of topics such as love,

current events, mathematics, philosophy, and the correspondent's personal history to determine whether the correspondent is a computer or a human. The Turing test is intended as a measure of *human* intelligence; failure to pass the test does not imply a lack of intelligence. Turing's original article can be found at http://www.abelard.org/turpap/turpap.htm; see also the *Stanford Encyclopedia of Philosophy,* http://plato.stanford.edu/entries/turing-test, for a discussion of the test.

There is no set of tricks or algorithms that would allow a machine to pass a properly designed Turing test without actually possessing intelligence at a fully human level. Also see Ray Kurzweil, "A Wager on the Turing Test: Why I Think I Will Win," http://www.KurzweilAI.net/turingwin.

31. See John H. Byrne, "Propagation of the Action Potential," *Neuroscience Online,* https://oac22.hsc.uth.tmc.edu/courses/nba/s1/i3-1.html: "The propagation velocity of the action potentials in nerves can vary from 100 meters per second (580 miles per hour) to less than a tenth of a meter per second (0.6 miles per hour)."

    Also see Kenneth R. Koehler, "The Action Potential," http://www.rwc.uc.edu/koehler/biophys/4d.html: "The speed of propagation for mammalian motor neurons is 10–120 m/s, while for nonmyelinated sensory neurons it's about 5–25 m/s (nonmyelinated neurons fire in a continuous fashion, without the jumps; ion leakage allows effectively complete circuits but slows the rate of propagation)."

32. A 2002 study published in *Science* highlighted the role of the beta-catenin protein in the horizontal expansion of the cerebral cortex in humans. This protein plays a key role in the folding and grooving of the surface of the cerebral cortex; it is this folding, in fact, that increases the surface area of this part of the brain and makes room for more neurons. Mice that overproduced the protein developed wrinkled, folded cerebral cortexes with substantially more surface area than the smooth, flat cerebral cortexes of control mice. Anjen Chenn and Christopher Walsh, "Regulation of Cerebral Cortical Size by Control of Cell Cycle Exit in Neural Precursors," *Science* 297 (July 2002): 365–69.

    A 2003 comparison of cerebral-cortex gene-expression profiles for humans, chimpanzees, and rhesus macaques showed a difference of expression in only ninety-one genes associated with brain organization and cognition. The study authors were surprised to find that 90 percent of these differences involved upregulation (higher activity). See M. Cacares et al., "Elevated Gene Expression Levels Distinguish Human from Non-human Primate Brains," *Proceedings of the National Academy of Sciences* 100.22 (October 28, 2003): 13030–35.

    However, University of California–Irvine College of Medicine researchers have found that gray matter in specific regions in the brain is more related to IQ than is overall brain size and that only about 6 percent of all the gray matter in the brain appears related to IQ. The study also discovered that because these regions related to intelligence are located throughout the brain, a single "intelligence center," such as the frontal lobe, is unlikely. See "Human Intelligence Determined by Volume and Location of Gray Matter Tissue in Brain," University of California–Irvine news release (July 19, 2004), http://today.uci.edu/news/release_detail.asp?key=1187.

A 2004 study found that human nervous system genes displayed accelerated evolution compared with nonhuman primates and that all primates had accelerated evolution compared with other mammals. Steve Dorus et al., "Accelerated Evolution of Nervous System Genes in the Origin of *Homo sapiens*," *Cell* 119 (December 29, 2004): 1027–40. In describing this finding, the lead researcher, Bruce Lahn, states, "Humans evolved their cognitive abilities not due to a few accidental mutations, but rather from an enormous number of mutations acquired through exceptionally intense selection favoring more complex cognitive abilities." Catherine Gianaro, *University of Chicago Chronicle* 24.7 (January 6, 2005).

A single mutation to the muscle fiber gene MYH16 has been proposed as one change allowing humans to have much larger brains. The mutation made ancestral humans' jaws weaker, so that humans did not require the brain-size limiting muscle anchors found in other great apes. Stedman et al., "Myosin Gene Mutation Correlates with Anatomical Changes in the Human Lineage," *Nature* 428 (March 25, 2004): 415–18.

33. Robert A. Freitas Jr., "Exploratory Design in Medical Nanotechnology: A Mechanical Artificial Red Cell," *Artificial Cells, Blood Substitutes, and Immobil. Biotech.* 26 (1998): 411–30; http://www.foresight.org/Nanomedicine/Respirocytes.html; see also the Nanomedicine Art Gallery images (http://www.foresight.org/Nanomedicine/Gallery/Species/Respirocytes.html) and award-winning animation (http://www.phleschbubble.com/album/beyondhuman/respirocyte01.htm) of the respirocytes.
34. Foglets are the conception of the nanotechnology pioneer and Rutgers professor J. Storrs Hall. Here is a snippet of his description: "Nanotechnology is based on the concept of tiny, self-replicating robots. The Utility Fog is a very simple extension of the idea: Suppose, instead of building the object you want atom by atom, the tiny robots [foglets] linked their arms together to form a solid mass in the shape of the object you wanted? Then, when you got tired of that avant-garde coffee table, the robots could simply shift around a little and you'd have an elegant Queen Anne piece instead." J. Storrs Hall, "What I Want to Be When I Grow Up, Is a Cloud," *Extropy,* Quarters 3 and 4, 1994. Published on KurzweilAI.net July 6, 2001: http://www.KurzweilAI.net/foglets. See also J. Storrs Hall, "Utility Fog: The Stuff That Dreams Are Made Of," in *Nanotechnology: Molecular Speculations on Global Abundance*, B. C. Crandall, ed. (Cambridge, Mass.: MIT Press, 1996). Published on KurzweilAI.net July 5, 2001: http://www.KurzweilAI.net/utilityfog.
35. Sherry Turkle, ed., "Evocative Objects: Things We Think With," forthcoming.
36. See the "Exponential Growth of Computing" figure in chapter 2 (p. 70). Projecting the double exponential growth of the price-performance of computation to the end of the twenty-first century, one thousand dollars' worth of computation will provide 10^{60} calculations per second (cps). As we will discuss in chapter 2, three different analyses of the amount of computing required to functionally emulate

the human brain result in an estimate of 10^{15} cps. A more conservative estimate, which assumes that it will be necessary to simulate all of the nonlinearities in every synapse and dendrite, results in an estimate of 10^{19} cps for neuromorphic emulation of the human brain. Even taking the more conservative figure, we get a figure of 10^{29} cps for the approximately 10^{10} humans. Thus, the 10^{60} cps that can be purchased for one thousand dollars circa 2099 will represent 10^{31} (ten million trillion trillion) human civilizations.

37. The invention of the power loom and the other textile automation machines of the early eighteenth century destroyed the livelihoods of the cottage industry of English weavers, who had passed down stable family businesses for hundreds of years. Economic power passed from the weaving families to the owners of the machines. As legend has it, a young and feebleminded boy named Ned Ludd broke two textile factory machines out of sheer clumsiness. From that point on, whenever factory equipment was found to have mysteriously been damaged, anyone suspected of foul play would say, "But Ned Ludd did it." In 1812 the desperate weavers formed a secret society, an urban guerrilla army. They made threats and demands of factory owners, many of whom complied. When asked who their leader was, they replied, "Why, General Ned Ludd, of course." Although the Luddites, as they became known, initially directed most of their violence against the machines, a series of bloody engagements erupted later that year. The tolerance of the Tory government for the Luddites ended, and the movement dissolved with the imprisonment and hanging of prominent members. Although they failed to create a sustained and viable movement, the Luddites have remained a powerful symbol of opposition to automation and technology.
38. See note 34 above.

Chapter Two: A Theory of Technology Evolution: The Law of Accelerating Returns

1. John Smart, Abstract to "Understanding Evolutionary Development: A Challenge for Futurists," presentation to World Futurist Society annual meeting, Washington, D.C., August 3, 2004.
2. That epochal events in evolution represent increases in complexity is Theodore Modis's view. See Theodore Modis, "Forecasting the Growth of Complexity and Change," *Technological Forecasting and Social Change* 69.4 (2002), http://ourworld.compuserve.com/homepages/tmodis/TedWEB.htm.
3. Compressing files is a key aspect of both data transmission (such as a music or text file over the Internet) and data storage. The smaller the file is, the less time it will take to transmit and the less space it will require. The mathematician Claude Shannon, often called the father of information theory, defined the basic theory of data compression in his paper "A Mathematical Theory of Communication," *The Bell System Technical Journal* 27 (July–October 1948): 379–423, 623–56. Data

compression is possible because of factors such as redundancy (repetition) and probability of appearance of character combinations in data. For example, silence in an audio file could be replaced by a value that indicates the duration of the silence, and letter combinations in a text file could be replaced with coded identifiers in the compressed file.

Redundancy can be removed by lossless compression, as Shannon explained, which means there is no loss of information. There is a limit to lossless compression, defined by what Shannon called the entropy rate (compression increases the "entropy" of the data, which is the amount of actual information in it as opposed to predetermined and thus predictable data structures). Data compression removes redundancy from data; lossless compression does it without losing data (meaning that the exact original data can be restored). Alternatively, lossy compression, which is used for graphics files or streaming video and audio files, does result in information loss, though that loss is often imperceptible to our senses.

Most data-compression techniques use a code, which is a mapping of the basic units (or symbols) in the source to a code alphabet. For example, all the spaces in a text file could be replaced by a single code word and the number of spaces. A compression algorithm is used to set up the mapping and then create a new file using the code alphabet; the compressed file will be smaller than the original and thus easier to transmit or store. Here are some of the categories into which common lossless-compression techniques fall:

- Run-length compression, which replaces repeating characters with a code and a value representing the number of repetitions of that character (examples: PackBits and PCX).
- Minimum redundancy coding or simple entropy coding, which assigns codes on the basis of probability, with the most frequent symbols receiving the shortest codes (examples: Huffman coding and arithmetic coding).
- Dictionary coders, which use a dynamically updated symbol dictionary to represent patterns (examples: Lempel-Ziv, Lempel-Ziv-Welch, and DEFLATE).
- Block-sorting compression, which reorganizes characters rather than using a code alphabet; run-length compression can then be used to compress the repeating strings (example: Burrows-Wheeler transform).
- Prediction by partial mapping, which uses a set of symbols in the uncompressed file to predict how often the next symbol in the file appears.

4. Murray Gell-Mann, "What Is Complexity?" in *Complexity*, vol. 1 (New York: John Wiley and Sons, 1995).
5. The human genetic code has approximately six billion (about 10^{10}) bits, not considering the possibility of compression. So the 10^{27} bits that theoretically can be stored in a one-kilogram rock is greater than the genetic code by a factor of 10^{17}. See note 57 below for a discussion of genome compression.
6. Of course, a human, who is also composed of an enormous number of particles, contains an amount of information comparable to a rock of similar weight when

we consider the properties of all the particles. As with the rock, the bulk of this information is not needed to characterize the state of the person. On the other hand, much more information is needed to characterize a person than a rock.

7. See note 175 in chapter 5 for an algorithmic description of genetic algorithms.
8. Humans, chimpanzees, gorillas, and orangutans are all included in the scientific classification of hominids (family *Hominidae*). The human lineage is thought to have diverged from its great ape relatives five to seven million years ago. The human genus *Homo* within the *Hominidae* includes extinct species such as *H. erectus* as well as modern man (*H. sapiens*).

   In chimpanzee hands, the fingers are much longer and less straight than in humans, and the thumb is shorter, weaker, and not as mobile. Chimps can flail with a stick but tend to lose their grip. They cannot pinch hard because their thumbs do not overlap their index fingers. In the modern human, the thumb is longer, and the fingers rotate toward a central axis, so you can touch all the tips of your fingers to the tip of your thumb, a quality that is called full opposability. These and other changes gave humans two new grips: the precision and power grips. Even prehominoid hominids such as the *Australopithecine* from Ethiopia called Lucy, who is thought to have lived around three million years ago, could throw rocks with speed and accuracy. Since then, scientists claim, continual improvements in the hand's capacity to throw and club, along with associated changes in other parts of the body, have resulted in distinct advantages over other animals of similar size and weight. See Richard Young, "Evolution of the Human Hand: The Role of Throwing and Clubbing," *Journal of Anatomy* 202 (2003): 165–74; Frank Wilson, *The Hand: How Its Use Shapes the Brain, Language, and Human Culture* (New York: Pantheon, 1998).
9. The Santa Fe Institute has played a pioneering role in developing concepts and technology related to complexity and emergent systems. One of the principal developers of paradigms associated with chaos and complexity is Stuart Kauffman. Kauffman's *At Home in the Universe: The Search for the Laws of Self-Organization and Complexity* (Oxford: Oxford University Press, 1995) looks "at the forces for order that lie at the edge of chaos."

   In his book *Evolution of Complexity by Means of Natural Selection* (Princeton: Princeton University Press, 1988), John Tyler Bonner asks the questions "How is it that an egg turns into an elaborate adult? How is it that a bacterium, given many millions of years, could have evolved into an elephant?"

   John Holland is another leading thinker from the Santa Fe Institute in the emerging field of complexity. His book *Hidden Order: How Adaptation Builds Complexity* (Reading, Mass.: Addison-Wesley, 1996) includes a series of lectures that he presented at the Santa Fe Institute in 1994. See also John H. Holland, *Emergence: From Chaos to Order* (Reading, Mass.: Addison-Wesley, 1998) and Mitchell Waldrop, *Complexity: The Emerging Science at the Edge of Order and Chaos* (New York: Simon & Schuster, 1992).
10. The second law of thermodynamics explains why there is no such thing as a

perfect engine that uses all the heat (energy) produced by burning fuel to do work: some heat will inevitably be lost to the environment. This same principle of nature holds that heat will flow from a hot pan to cold air rather than in reverse. It also posits that closed ("isolated") systems will spontaneously become more disordered over time—that is, they tend to move from order to disorder. Molecules in ice chips, for example, are limited in their possible arrangements. So a cup of ice chips has less entropy (disorder) than the cup of water the ice chips become when left at room temperature. There are many more possible molecular arrangements in the glass of water than in the ice; greater freedom of movement equals higher entropy. Another way to think of entropy is as multiplicity. The more ways that a state could be achieved, the higher the multiplicity. Thus, for example, a jumbled pile of bricks has a higher multiplicity (and higher entropy) than a neat stack.

11. Max More articulates the view that "advancing technologies are combining and cross-fertilizing to accelerate progress even faster." Max More, "Track 7 Tech Vectors to Take Advantage of Technological Acceleration," *ManyWorlds,* August 1, 2003.

12. For more information, see J. J. Emerson et al., "Extensive Gene Traffic on the Mammalian X Chromosome," *Science* 303.5657 (January 23, 2004): 537–40, http://www3.uta.edu/faculty/betran/science2004.pdf; Nicholas Wade, "Y Chromosome Depends on Itself to Survive," *New York Times*, June 19, 2003; and Bruce T. Lahn and David C. Page, "Four Evolutionary Strata on the Human X Chromosome," *Science* 286.5441 (October 29, 1999): 964–67, http://inside.wi.mit.edu/page/Site/Page%20PDFs/Lahn_and_Page_strata_1999.pdf.

    Interestingly, the second X chromosome in girls is turned off in a process called X inactivation so that the genes on only one X chromosome are expressed. Research has shown that the X chromosome from the father is turned off in some cells and the X chromosome from the mother in other cells.

13. Human Genome Project, "Insights Learned from the Sequence," http://www.ornl.gov/sci/techresources/Human_Genome/project/journals/insights.html. Even though the human genome has been sequenced, most of it does not code for proteins (the so-called junk DNA), so researchers are still debating how many genes will be identified among the three billion base pairs in human DNA. Current estimates suggest less than thirty thousand, though during the Human Genome Project estimates ranged as high as one hundred thousand. See "How Many Genes Are in the Human Genome?" (http://www.ornl.gov/sci/techresources/Human_Genome/faq/genenumber.shtml) and Elizabeth Pennisi, "A Low Number Wins the GeneSweep Pool," *Science* 300.5625 (June 6, 2003): 1484.

14. Niles Eldredge and the late Stephen Jay Gould proposed this theory in 1972 (N. Eldredge and S. J. Gould, "Punctuated Equilibria: An Alternative to Phyletic Gradualism," in T. J. M. Schopf, ed., *Models in Paleobiology* [San Francisco: Freeman, Cooper], pp. 82–115). It has sparked heated discussions among paleontolo-

gists and evolutionary biologists ever since, though it has gradually gained acceptance. According to this theory, millions of years may pass with species in relative stability. This stasis is then followed by a burst of change, resulting in new species and the extinction of old (called a "turnover pulse" by Elisabeth Vrba). The effect is ecosystemwide, affecting many unrelated species. Eldredge and Gould's proposed pattern required a new perspective: "For no bias can be more constricting than invisibility—and stasis, inevitably read as absence of evolution, had always been treated as a non-subject. How odd, though, to define the most common of all palaeontological phenomena as beyond interest or notice!" S. J. Gould and N. Eldredge, "Punctuated Equilibrium Comes of Age," *Nature* 366 (November 18, 1993): 223–27.

See also K. Sneppen et al., "Evolution As a Self-Organized Critical Phenomenon," *Proceedings of the National Academy of Sciences* 92.11 (May 23, 1995): 5209–13; Elisabeth S. Vrba, "Environment and Evolution: Alternative Causes of the Temporal Distribution of Evolutionary Events," *South African Journal of Science* 81 (1985): 229–36.

15. As I will discuss in chapter 6, if the speed of light is not a fundamental limit to rapid transmission of information to remote portions of the universe, then intelligence and computation will continue to expand exponentially until they saturate the potential of matter and energy to support computation throughout the entire universe.
16. Biological evolution continues to be of relevance to humans, however, in that disease processes such as cancer and viral diseases use evolution against us (that is, cancer cells and viruses evolve to counteract specific countermeasures such as chemotherapy drugs and antiviral medications respectively). But we can use our human intelligence to outwit the intelligence of biological evolution by attacking disease processes at sufficiently fundamental levels and by using "cocktail" approaches that attack a disease in several orthogonal (independent) ways at once.
17. Andrew Odlyzko, "Internet Pricing and the History of Communications," AT&T Labs Research, revised version February 8, 2001, http://www.dtc.umn.edu/~odlyzko/doc/history.communications1b.pdf.
18. Cellular Telecommunications and Internet Association, Semi-Annual Wireless Industry Survey, June 2004, http://www.ctia.org/research_statistics/index.cfm/AID/10030.
19. Electricity, telephone, radio, television, mobile phones: FCC, www.fcc.gov/Bureaus/Common_Carrier/Notices/2000/fc00057a.xls. Home computers and Internet use: Eric C. Newburger, U.S. Census Bureau, "Home Computers and Internet Use in the United States: August 2000" (September 2001), http://www.census.gov/prod/2001pubs/p23-207.pdf. See also "The Millennium Notebook," *Newsweek*, April 13, 1998, p. 14.
20. The paradigm-shift rate, as measured by the amount of time required to adopt new communications technologies, is currently doubling (that is, the amount of

time for mass adoption—defined as being used by a quarter of the U.S. population—is being cut in half) every nine years. See also note 21.

21. The "Mass Use of Inventions" chart in this chapter on p. 50 shows that the time required for adoption by 25 percent of the U.S. population steadily declined over the past 130 years. For the telephone, 35 years were required compared to 31 for the radio—a reduction of 11 percent, or 0.58 percent per year in the 21 years between these two inventions. The time required to adopt an invention dropped 0.60 percent per year between the radio and television, 1.0 percent per year between television and the PC, 2.6 percent per year between the PC and the mobile phone, and 7.4 percent per year between the mobile phone and the World Wide Web. Mass adoption of the radio beginning in 1897 required 31 years, while the Web required a mere 7 years after it was introduced in 1991—a reduction of 77 percent over 94 years, or an average rate of 1.6 percent reduction in adoption time per year. Extrapolating this rate for the entire twentieth century results in an overall reduction of 79 percent for the century. At the current rate of reducing adoption time of 7.4 percent each year, it would take only 20 years at today's rate of progress to achieve the same reduction of 79 percent that was achieved in the twentieth century. At this rate, the paradigm-shift rate doubles (that is, adoption times are reduced by 50 percent) in about 9 years. Over the twenty-first century, eleven doublings of the rate will result in multiplying the rate by 2^{11}, to about 2,000 times the rate in 2000. The increase in rate will actually be greater than this because the current rate will continue to increase as it steadily did over the twentieth century.
22. Data from 1967–1999, Intel data, see Gordon E. Moore, "Our Revolution," http://www.sia-online.org/downloads/Moore.pdf. Data from 2000–2016, International Technology Roadmap for Semiconductors (ITRS) 2002 Update and 2004 Update, http://public.itrs.net/Files/2002Update/2002Update.pdf and http://www.itrs.net/Common/2004Update/2004_00_Overview.pdf.
23. The ITRS DRAM cost is the cost per bit (packaged microcents) at production. Data from 1971–2000: VLSI Research Inc. Data from 2001–2002: ITRS, 2002 Update, Table 7a, Cost-Near-Term Years, p. 172. Data from 2003–2018: ITRS, 2004 Update, Tables 7a and 7b, Cost-Near-Term Years, pp. 20–21.
24. Intel and Dataquest reports (December 2002), see Gordon E. Moore, "Our Revolution," http://www.sia-online.org/downloads/Moore.pdf.
25. Randall Goodall, D. Fandel, and H. Huffet, "Long-Term Productivity Mechanisms of the Semiconductor Industry," Ninth International Symposium on Silicon Materials Science and Technology, May 12–17, 2002, Philadelphia, sponsored by the Electrochemical Society (ECS) and International Sematech.
26. Data from 1976–1999: E. R. Berndt, E. R. Dulberger, and N. J. Rappaport, "Price and Quality of Desktop and Mobile Personal Computers: A Quarter Century of History," July 17, 2000, http://www.nber.org/~confer/2000/si2000/berndt.pdf. Data from 2001–2016: ITRS, 2002 Update, On-Chip Local Clock in Table 4c: Performance and Package Chips: Frequency On-Chip Wiring Levels—Near-Term Years, p. 167.

27. See note 26 for clock speed (cycle times) and note 24 for cost per transistor.
28. Intel transistors on microprocessors: *Microprocessor Quick Reference Guide,* Intel Research, http://www.intel.com/pressroom/kits/quickrefyr.htm. See also Silicon Research Areas, Intel Research, http://www.intel.com/research/silicon/mooreslaw.htm.
29. Data from Intel Corporation. See also Gordon Moore, "No Exponential Is Forever . . . but We Can Delay 'Forever,' " presented at the International Solid State Circuits Conference (ISSCC), February 10, 2003, ftp://download.intel.com/research/silicon/Gordon_Moore_ISSCC_021003.pdf.
30. Steve Cullen, "Semiconductor Industry Outlook," InStat/MDR, report no. IN0401550SI, April 2004, http://www.instat.com/abstract.asp?id=68&SKU=IN0401550SI.
31. World Semiconductor Trade Statistics, http://wsts.www5.kcom.at.
32. Bureau of Economic Analysis, U.S. Department of Commerce, http://www.bea.gov/bea/dn/home/gdp.htm.
33. See notes 22–24 and 26–30.
34. International Technology Roadmap for Semiconductors, 2002 update, International Sematech.
35. "25 Years of Computer History," http://www.compros.com/timeline.html; Linley Gwennap, "Birth of a Chip," *BYTE* (December 1996), http://www.byte.com/art/9612/sec6/art2.htm; "The CDC 6000 Series Computer," http://www.moorecad.com/standardpascal/cdc6400.html; "A Chronology of Computer History," http://www.cyberstreet.com/hcs/museum/chron.htm; Mark Brader, "A Chronology of Digital Computing Machines (to 1952)," http://www.davros.org/misc/chronology.html; Karl Kempf, "Electronic Computers Within the Ordnance Corps," November 1961, http://ftp.arl.mil/~mike/comphist/61ordnance/index.html; Ken Polsson, "Chronology of Personal Computers," http://www.islandnet.com/~kpolsson/comphist; "The History of Computing at Los Alamos," http://bang.lanl.gov/video/sunedu/computer/comphist.html (requires password); the Machine Room, http://www.machine-room.org; Mind Machine Web Museum, http://www.userwww.sfsu.edu/~hl/mmm.html; Hans Moravec, computer data, http://www.frc.ri.cmu.edu/~hpm/book97/ch3/processor.list; "PC Magazine Online: Fifteen Years of PC Magazine," http://www.pcmag.com/article2/0,1759,23390,00.asp; Stan Augarten, *Bit by Bit: An Illustrated History of Computers* (New York: Ticknor and Fields, 1984); International Association of Electrical and Electronics Engineers (IEEE), *Annals of the History of the Computer* 9.2 (1987): 150–53 and 16.3 (1994): 20; Hans Moravec, *Mind Children: The Future of Robot and Human Intelligence* (Cambridge, Mass.: Harvard University Press, 1988); René Moreau, *The Computer Comes of Age* (Cambridge, Mass.: MIT Press, 1984).
36. The plots in this chapter labeled "Logarithmic Plot" are technically semilogarithmic plots in that one axis (time) is on a linear scale, and the other axis is on a logarithmic scale. However, I am calling these plots "logarithmic plots" for simplicity.
37. See the appendix, "The Law of Accelerating Returns Revisited," which provides a

mathematical derivation of why there are two levels of exponential growth (that is, exponential growth over time in which the rate of the exponential growth—the exponent—is itself growing exponentially over time) in computational power as measured by MIPS per unit cost.

38. Hans Moravec, "When Will Computer Hardware Match the Human Brain?" *Journal of Evolution and Technology* 1 (1998), http://www.jetpress.org/volume1/moravec.pdf.
39. See note 35 above.
40. Achieving the first MIPS per $1,000 took from 1900 to 1990. We're now doubling the number of MIPS per $1,000 in about 400 days. Because current price-performance is about 2,000 MIPS per $1,000, we are adding price-performance at the rate of 5 MIPS per day, or 1 MIPS about every 5 hours.
41. "IBM Details Blue Gene Supercomputer," *CNET News,* May 8, 2003, http://news.com.com/2100-1008_3-1000421.html.
42. See Alfred North Whitehead, *An Introduction to Mathematics* (London: Williams and Norgate, 1911), which he wrote at the same time he and Bertrand Russell were working on their seminal three-volume *Principia Mathematica*.
43. While originally projected to take fifteen years, "the Human Genome Project was finished two and a half years ahead of time and, at $2.7 billion in FY 1991 dollars, significantly under original spending projections": http://www.ornl.gov/sci/techresources/Human_Genome/project/50yr/press4_2003.shtml.
44. Human Genome Project Information, http://www.ornl.gov/sci/techresources/Human_Genome/project/privatesector.shtml; Stanford Genome Technology Center, http://sequence-www.stanford.edu/group/techdev/auto.html; National Human Genome Research Institute, http://www.genome.gov; Tabitha Powledge, "How Many Genomes Are Enough?" *Scientist,* November 17, 2003, http://www.biomedcentral.com/news/20031117/07.
45. Data from National Center for Biotechnology Information, "GenBank Statistics," revised May 4, 2004, http://www.ncbi.nlm.nih.gov/Genbank/genbankstats.html.
46. Severe acute respiratory syndrome (SARS) was sequenced within thirty-one days of the virus being identified by the British Columbia Cancer Agency and the American Centers for Disease Control. The sequencing from the two centers differed by only ten base pairs out of twenty-nine thousand. This work identified SARS as a coronavirus. Dr. Julie Gerberding, director of the CDC, called the quick sequencing "a scientific achievement that I don't think has been paralleled in our history." See K. Philipkoski, "SARS Gene Sequence Unveiled," *Wired News,* April 15, 2003, http://www.wired.com/news/medtech/0,1286,58481,00.html?tw=wn_story_related.

    In contrast, the efforts to sequence HIV began in the 1980s. HIV 1 and HIV 2 were completely sequenced in 2003 and 2002 respectively. National Center for Biotechnology Information, http://www.ncbi.nlm.nih.gov/genomes/framik.cgi?db=genome&gi=12171; HIV Sequence Database maintained by the Los Alamos National Laboratory, http://www.hiv.lanl.gov/content/hiv-db/HTML/outline.html.

47. Mark Brader, "A Chronology of Digital Computing Machines (to 1952)," http://www.davros.org/misc/chronology.html; Richard E. Matick, *Computer Storage Systems and Technology* (New York: John Wiley and Sons, 1977); University of Cambridge Computer Laboratory, EDSAC99, http://www.cl.cam.ac.uk/UoCCL/misc/EDSAC99/statistics.html; Mary Bellis, "Inventors of the Modern Computer: The History of the UNIVAC Computer—J. Presper Eckert and John Mauchly," http://inventors.about.com/library/weekly/aa062398.htm; "Initial Date of Operation of Computing Systems in the USA (1950–1958)," compiled from 1968 OECD data, http://members.iinet.net.au/~dgreen/timeline.html; Douglas Jones, "Frequently Asked Questions about the DEC PDP-8 computer," ftp://rtfm.mit.edu/pub/usenet/alt.sys.pdp8/PDP-8_Frequently_Asked_Questions_%28posted_every_other_month%29; *Programmed Data Processor-1 Handbook*, Digital Equipment Corporation (1960–1963), http://www.dbit.com/~greeng3/pdp1/pdp1.html#INTRODUCTION; John Walker, "Typical UNIVAC® 1108 Prices: 1968," http://www.fourmilab.ch/documents/univac/config1108.html; Jack Harper, "LISP 1.5 for the Univac 1100 Mainframe," http://www.frobenius.com/univac.htm; Wikipedia, "Data General Nova," http://www.answers.com/topic/data-general-nova; Darren Brewer, "Chronology of Personal Computers 1972–1974," http://uk.geocities.com/magoos_universe/comp1972.htm; www.pricewatch.com; http://www.jc-news.com/parse.cgi?news/pricewatch/raw/pw-010702; http://www.jc-news.com/parse.cgi?news/pricewatch/raw/pw-020624; http://www.pricewatch.com (11/17/04); http://sharkyextreme.com/guides/WMPG/article.php/10706_2227191_2; *Byte* advertisements, September 1975–March 1998; *PC Computing* advertisements, March 1977–April 2000.
48. Seagate, "Products," http://www.seagate.com/cda/products/discsales/index; *Byte* advertisements, 1977–1998; *PC Computing* advertisements, March 1999; Editors of Time-Life Books, *Understanding Computers: Memory and Storage*, rev. ed. (New York: Warner Books, 1990); "Historical Notes about the Cost of Hard Drive Storage Space," http://www.alts.net/ns1625/winchest.html; "IBM 305 RAMAC Computer with Disk Drive," http://www.cedmagic.com/history/ibm-305-ramac.html; John C. McCallum, "Disk Drive Prices (1955–2004)," http://www.jcmit.com/diskprice.htm.
49. James DeRose, *The Wireless Data Handbook* (St. Johnsbury, Vt.: Quantrum, 1996); First Mile Wireless, http://www.firstmilewireless.com/; J. B. Miles, "Wireless LANs," *Government Computer News* 18.28 (April 30, 1999), http://www.gcn.com/vol18_no28/guide/514-1.html; *Wireless Week* (April 14, 1997), http://www.wirelessweek.com/toc/4%2F14%2F1997; Office of Technology Assessment, "Wireless Technologies and the National Information Infrastructure," September 1995, http://infoventures.com/emf/federal/ota/ota95-tc.html; Signal Lake, "Broadband Wireless Network Economics Update," January 14, 2003, http://www.signallake.com/publications/broadbandupdate.pdf; BridgeWave Communications communication, http://www.bridgewave.com/050604.htm.
50. Internet Software Consortium (http://www.isc.org), ISC Domain Survey: Number of Internet Hosts, http://www.isc.org/ds/host-count-history.html.

51. Ibid.
52. Average traffic on Internet backbones in the U.S. during December of each year is used to estimate traffic for the year. A. M. Odlyzko, "Internet Traffic Growth: Sources and Implications," *Optical Transmission Systems and Equipment for WDM Networking II,* B. B. Dingel, W. Weiershausen, A. K. Dutta, and K.-I. Sato, eds., *Proc. SPIE* (The International Society for Optical Engineering) 5247 (2003): 1–15, http://www.dtc.umn.edu/~odlyzko/doc/oft.internet.growth.pdf; data for 2003–2004 values: e-mail correspondence with A. M. Odlyzko.
53. Dave Kristula, "The History of the Internet" (March 1997, update August 2001), http://www.davesite.com/webstation/net-history.shtml; Robert Zakon, "Hobbes' Internet Timeline v8.0," http://www.zakon.org/robert/internet/timeline; *Converge Network Digest*, December 5, 2002, http://www.convergedigest.com/Daily/daily.asp?vn=v9n229&fecha=December%2005,%202002; V. Cerf, "Cerf's Up," 2004, http://global.mci.com/de/resources/cerfs_up/.
54. H. C. Nathanson et al., "The Resonant Gate Transistor," *IEEE Transactions on Electron Devices* 14.3 (March 1967): 117–33; Larry J. Hornbeck, "128 x 128 Deformable Mirror Device," *IEEE Transactions on Electron Devices* 30.5 (April 1983): 539–43; J. Storrs Hall, "Nanocomputers and Reversible Logic," *Nanotechnology* 5 (July 1994): 157–67; V. V. Aristov et al., "A New Approach to Fabrication of Nanostructures," *Nanotechnology* 6 (April 1995): 35–39; C. Montemagno et al., "Constructing Biological Motor Powered Nanomechanical Devices," *Nanotechnology* 10 (1999): 225–31, http://www.foresight.org/Conferences/MNT6/Papers/Montemagno/; Celeste Biever, "Tiny 'Elevator' Most Complex Nanomachine Yet," *NewScientist.com News Service,* March 18, 2004, http://www.newscientist.com/article.ns?id=dn4794.
55. ETC Group, "From Genomes to Atoms: The Big Down," p. 39, http://www.etcgroup.org/documents/TheBigDown.pdf.
56. Ibid., p. 41.
57. Although it is not possible to determine precisely the information content in the genome, because of the repeated base pairs it is clearly much less than the total uncompressed data. Here are two approaches to estimating the compressed information content of the genome, both of which demonstrate that a range of thirty to one hundred million bytes is conservatively high.

    1. In terms of the uncompressed data, there are three billion DNA rungs in the human genetic code, each coding two bits (since there are four possibilities for each DNA base pair). Thus, the human genome is about 800 million bytes uncompressed. The noncoding DNA used to be called "junk DNA," but it is now clear that it plays an important role in gene expression. However, it is very inefficiently coded. For one thing, there are massive redundancies (for example, the sequence called "ALU" is repeated hundreds of thousands of times), which compression algorithms can take advantage of.

With the recent explosion of genetic data banks, there is a great deal of interest in compressing genetic data. Recent work on applying standard data compression algorithms to genetic data indicates that reducing the data by 90 percent (for bit-perfect compression) is feasible: Hisahiko Sato et al., "DNA Data Compression in the Post Genome Era," *Genome Informatics* 12 (2001): 512–14, http://www.jsbi.org/journal/GIW01/GIW01P130.pdf.

Thus we can compress the genome to about 80 million bytes without loss of information (meaning we can perfectly reconstruct the full 800-million-byte uncompressed genome).

Now consider that more than 98 percent of the genome does not code for proteins. Even after standard data compression (which eliminates redundancies and uses a dictionary lookup for common sequences), the algorithmic content of the noncoding regions appears to be rather low, meaning that it is likely that we could code an algorithm that would perform the same function with fewer bits. However, since we are still early in the process of reverse engineering the genome, we cannot make a reliable estimate of this further decrease based on a functionally equivalent algorithm. I am using, therefore, a range of 30 to 100 million bytes of compressed information in the genome. The top part of this range assumes only data compression and no algorithmic simplification.

Only a portion (although the majority) of this information characterizes the design of the brain.

2. Another line of reasoning is as follows. Though the human genome contains around 3 billion bases, only a small percentage, as mentioned above, codes for proteins. By current estimates, there are 26,000 genes that code for proteins. If we assume those genes average 3,000 bases of useful data, those equal only approximately 78 million bases. A base of DNA requires only two bits, which translate to about 20 million bytes (78 million bases divided by four). In the protein-coding sequence of a gene, each "word" (codon) of three DNA bases translates into one amino acid. There are, therefore, 4^3 (64) possible codon codes, each consisting of three DNA bases. There are, however, only 20 amino acids used plus a stop codon (null amino acid) out of the 64. The rest of the 43 codes are used as synonyms of the 21 useful ones. Whereas 6 bits are required to code for 64 possible combinations, only about 4.4 ($\log_2 21$) bits are required to code for 21 possibilities, a savings of 1.6 out of 6 bits (about 27 percent), bringing us down to about 15 million bytes. In addition, some standard compression based on repeating sequences is feasible here, although much less compression is possible on this protein-coding portion of the DNA than in the so-called junk DNA, which has massive redundancies. So this will bring the

figure probably below 12 million bytes. However, now we have to add information for the noncoding portion of the DNA that controls gene expression. Although this portion of the DNA comprises the bulk of the genome, it appears to have a low level of information content and is replete with massive redundancies. Estimating that it matches the approximately 12 million bytes of protein-coding DNA, we again come to approximately 24 million bytes. From this perspective, an estimate of 30 to 100 million bytes is conservatively high.

58. Continuous values can be represented by floating-point numbers to any desired degree of accuracy. A floating-point number consists of two sequences of bits. One "exponent" sequence represents a power of 2. The "base" sequence represents a fraction of 1. By increasing the number of bits in the base, any desired degree of accuracy can be achieved.
59. Stephen Wolfram, *A New Kind of Science* (Champaign, Ill.: Wolfram Media, 2002).
60. Early work on a digital theory of physics was also presented by Frederick W. Kantor, *Information Mechanics* (New York: John Wiley and Sons, 1977). Links to several of Kantor's papers can be found at http://w3.execnet.com/kantor/pm00.htm (1997); http://w3.execnet.com/kantor/1b2p.htm (1989); and http://w3.execnet.com/kantor/ipoim.htm (1982). Also see at http://www.kx.com/listbox/k/msg05621.html.
61. Konrad Zuse, "Rechnender Raum," *Elektronische Datenverarbeitung*, 1967, vol. 8, pp. 336–44. Konrad Zuse's book on a cellular automaton–based universe was published two years later: *Rechnender Raum, Schriften zur Datenverarbeitung* (Braunschweig, Germany: Friedrich Vieweg & Sohn, 1969). English translation: *Calculating Space,* MIT Technical Translation AZT-70-164-GEMIT, February 1970. MIT Project MAC, Cambridge, MA 02139. PDF.
62. Edward Fredkin quoted in Robert Wright, "Did the Universe Just Happen?" *Atlantic Monthly,* April 1988, 29–44, http://digitalphysics.org/Publications/Wri88a/html.
63. Ibid.
64. Many of Fredkin's results come from studying his own model of computation, which explicitly reflects a number of fundamental principles of physics. See the classic article Edward Fredkin and Tommaso Toffoli, "Conservative Logic," *International Journal of Theoretical Physics* 21.3–4 (1982): 219–53, http://www.digitalphilosophy.org/download_documents/ConservativeLogic.pdf. Also, a set of concerns about the physics of computation analytically similar to those of Fredkin's may be found in Norman Margolus, "Physics and Computation," Ph.D. thesis, MIT/LCS/TR-415, MIT Laboratory for Computer Science, 1988.
65. I discussed Norbert Wiener and Ed Fredkin's view of information as the fundamental building block for physics and other levels of reality in my 1990 book, *The Age of Intelligent Machines*.

    The complexity of casting all of physics in terms of computational transformations proved to be an immensely challenging project, but Fredkin has continued his efforts. Wolfram has devoted a considerable portion of his work over the past decade to this notion, apparently with only limited communication with some of the others in the physics community who are also pursuing the idea. Wolfram's stated goal "is not to present a specific ultimate model for physics," but in his "Note for Physicists" (which essentially equates to a grand challenge), Wolfram describes the "features that [he] believe[s] such a model will have" (*A New Kind of Science,* pp. 1043–65, http://www.wolframscience.com/nksonline/page-1043c-text).

In *The Age of Intelligent Machines*, I discuss "the question of whether the ultimate nature of reality is analog or digital" and point out that "as we delve deeper and deeper into both natural and artificial processes, we find the nature of the process often alternates between analog and digital representations of information." As an illustration, I discussed sound. In our brains, music is represented as the digital firing of neurons in the cochlea, representing different frequency bands. In the air and in the wires leading to loudspeakers, it is an analog phenomenon. The representation of sound on a compact disc is digital, which is interpreted by digital circuits. But the digital circuits consist of thresholded transistors, which are analog amplifiers. As amplifiers, the transistors manipulate individual electrons, which can be counted and are, therefore, digital, but at a deeper level electrons are subject to analog quantum-field equations. At a yet deeper level, Fredkin and now Wolfram are theorizing a digital (computational) basis to these continuous equations.

It should be further noted that if someone actually does succeed in establishing such a digital theory of physics, we would then be tempted to examine what sorts of deeper mechanisms are actually implementing the computations and links of the cellular automata. Perhaps underlying the cellular automata that run the universe are yet more basic analog phenomena, which, like transistors, are subject to thresholds that enable them to perform digital transactions. Thus, establishing a digital basis for physics will not settle the philosophical debate as to whether reality is ultimately digital or analog. Nonetheless, establishing a viable computational model of physics would be a major accomplishment.

So how likely is this? We can easily establish an existence proof that a digital model of physics is feasible, in that continuous equations can always be expressed to any desired level of accuracy in the form of discrete transformations on discrete changes in value. That is, after all, the basis for the fundamental theorem of calculus. However, expressing continuous formulas in this way is an inherent complication and would violate Einstein's dictum to express things "as simply as possible, but no simpler." So the real question is whether we can express the basic relationships that we are aware of in more elegant terms, using cellular-automata algorithms. One test of a new theory of physics is whether it is capable of making verifiable predictions. In at least one important way, that might be a difficult challenge for a cellular automata–based theory because lack of predictability is one of the fundamental features of cellular automata.

Wolfram starts by describing the universe as a large network of nodes. The nodes do not exist in "space," but rather space, as we perceive it, is an illusion created by the smooth transition of phenomena through the network of nodes. One can easily imagine building such a network to represent "naive" (Newtonian) physics by simply building a three-dimensional network to any desired degree of granularity. Phenomena such as "particles" and "waves" that appear to move through space would be represented by "cellular gliders," which are patterns that are advanced through the network for each cycle of computation. Fans of the game *Life* (which is based on cellular automata) will recognize the common phenomenon of gliders and the diversity of patterns that can move smoothly through a cellular-automaton network. The speed of light, then, is the result of the clock speed of the celestial computer, since gliders can advance only one cell per computational cycle.

Einstein's general relativity, which describes gravity as perturbations in space itself, as if our three-dimensional world were curved in some unseen fourth dimension, is also straightforward to represent in this scheme. We can imagine a four-dimensional network and can represent apparent curvatures in space in the same way that one represents normal curvatures in three-dimensional space. Alternatively, the network can become denser in certain regions to represent the equivalent of such curvature.

A cellular-automata conception proves useful in explaining the apparent increase in entropy (disorder) that is implied by the second law of thermodynamics. We have to assume that the cellular-automata rule underlying the universe is a class 4 rule (see main text)—otherwise the universe would be a dull place indeed. Wolfram's primary observation that a class 4 cellular automaton quickly produces apparent randomness (despite its determinate process) is consistent with the tendency toward randomness that we see in Brownian motion and that is implied by the second law.

Special relativity is more difficult. There is an easy mapping from the Newtonian model to the cellular network. But the Newtonian model breaks down in special relativity. In the Newtonian world, if a train is going eighty miles per hour and you drive along it on a parallel road at sixty miles per hour, the train will appear to pull away from you at twenty miles per hour. But in the world of special relativity, if you leave Earth at three quarters of the speed of light, light will still appear to you to move away from you at the full speed of light. In accordance with this apparently paradoxical perspective, both the size and subjective passage of time for two observers will vary depending on their relative speed. Thus, our fixed mapping of space and nodes becomes considerably more complex. Essentially, each observer needs his or her own network. However, in considering special relativity, we can essentially apply the same conversion to our "Newtonian" network as we do to Newtonian space. However, it is not clear that we are achieving greater simplicity in representing special relativity in this way.

A cellular-node representation of reality may have its greatest benefit in understanding some aspects of the phenomenon of quantum mechanics. It could provide an explanation for the apparent randomness that we find in quantum phenomena. Consider, for example, the sudden and apparently random creation of particle-antiparticle pairs. The randomness could be the same sort of randomness that we see in class 4 cellular automata. Although predetermined, the behavior of class 4 automata cannot be anticipated (other than by running the cellular automata) and is effectively random.

This is not a new view. It's equivalent to the "hidden variables" formulation of quantum mechanics, which states that there are some variables that we cannot otherwise access that control what appears to be random behavior that we can observe. The hidden-variables conception of quantum mechanics is not inconsistent with the formulas for quantum mechanics. It is possible but is not popular with quantum physicists because it requires a large number of assumptions to work out in a very particular way. However, I do not view this as a good argument against it. The existence of our universe is itself very unlikely and requires many assumptions to all work out in a very precise way. Yet here we are.

A bigger question is, How could a hidden-variables theory be tested? If based on cellular-automata-like processes, the hidden variables would be inherently unpredictable, even if deterministic. We would have to find some other way to "unhide" the hidden variables.

Wolfram's network conception of the universe provides a potential perspective on the phenomenon of quantum entanglement and the collapse of the wave function. The collapse of the wave function, which renders apparently ambiguous properties of a particle (for example, its location) retroactively determined, can be viewed from the cellular-network perspective as the interaction of the observed phenomenon with the observer itself. As observers, we are not outside the network but exist inside it. We know from cellular mechanics that two entities cannot interact without both being changed, which suggests a basis for wave-function collapse.

Wolfram writes, "If the universe is a network, then it can in a sense easily contain threads that continue to connect particles even when the particles get far apart in terms of ordinary space." This could provide an explanation for recent dramatic experiments showing nonlocality of action in which two "quantum entangled" particles appear to continue to act in concert with each other even though separated by large distances. Einstein called this "spooky action at a distance" and rejected it, although recent experiments appear to confirm it.

Some phenomena fit more neatly into this cellular automata–network conception than others. Some of the suggestions appear elegant, but as Wolfram's "Note for Physicists" makes clear, the task of translating all of physics into a consistent cellular-automata–based system is daunting indeed.

Extending his discussion to philosophy, Wolfram "explains" the apparent phenomenon of free will as decisions that are determined but unpredictable. Since there is no way to predict the outcome of a cellular process without actually running the process, and since no simulator could possibly run faster than the universe itself, there is therefore no way to reliably predict human decisions. So even though our decisions are determined, there is no way to preidentify what they will be. However, this is not a fully satisfactory examination of the concept. This observation concerning the lack of predictability can be made for the outcome of most physical processes—such as where a piece of dust will fall on the ground. This view thereby equates human free will with the random descent of a piece of dust. Indeed, that appears to be Wolfram's view when he states that the process in the human brain is "computationally equivalent" to those taking place in processes such as fluid turbulence.

Some of the phenomena in nature (for example, clouds, coastlines) are characterized by repetitive simple processes such as cellular automata and fractals, but intelligent patterns (such as the human brain) require an evolutionary process (or alternatively, the reverse engineering of the results of such a process). Intelligence is the inspired product of evolution and is also, in my view, the most powerful "force" in the world, ultimately transcending the powers of mindless natural forces.

In summary, Wolfram's sweeping and ambitious treatise paints a compelling but ultimately overstated and incomplete picture. Wolfram joins a growing community of voices that maintain that patterns of information, rather than matter and energy, represent the more fundamental building blocks of reality. Wolfram has added to our knowledge of how patterns of information create the world we experience, and I look forward to a period of collaboration between Wolfram and his colleagues so that we can build a more robust vision of the ubiquitous role of algorithms in the world.

The lack of predictability of class 4 cellular automata underlies at least some of the apparent complexity of biological systems and does represent one of the important biological paradigms that we can seek to emulate in our technology. It does not explain all of biology. It remains at least possible, however, that such methods can explain all of physics. If Wolfram, or anyone else for that matter, succeeds in formulating physics in terms of cellular-automata operations and their patterns, Wolfram's book will have earned its title. In any event, I believe the book to be an important work of ontology.

66. Rule 110 states that a cell becomes white if its previous color was, and its two neighbors are, all black or all white, or if its previous color was white and the two neighbors are black and white, respectively; otherwise, the cell becomes black.
67. Wolfram, *New Kind of Science*, p. 4, http://www.wolframscience.com/nksonline/page-4-text.
68. Note that certain interpretations of quantum mechanics imply that the world is not based on deterministic rules and that there is an inherent quantum randomness to every interaction at the (small) quantum scale of physical reality.

69. As discussed in note 57 above, the uncompressed genome has about six billion bits of information (order of magnitude = 10^{10} bits), and the compressed genome is about 30 to 100 million bytes. Some of this design information applies, of course, to other organs. Even assuming all of 100 million bytes applies to the brain, we get a conservatively high figure of 10^9 bits for the design of the brain in the genome. In chapter 3, I discuss an estimate for "human memory on the level of individual interneuronal connections," including "the connection patterns and neurotransmitter concentrations" of 10^{18} (billion billion) bits in a mature brain. This is about a billion (10^9) times more information than that in the genome which describes the brain's design. This increase comes about from the self-organization of the brain as it interacts with the person's environment.
70. See the sections "Disdisorder" and "The Law of Increasing Entropy Versus the Growth of Order" in my book *The Age of Spiritual Machines: When Computers Exceed Human Intelligence* (New York: Viking, 1999), pp. 30–33.
71. A universal computer can accept as input the definition of any other computer and then simulate that other computer. This does not address the speed of simulation, which might be relatively slow.
72. C. Geoffrey Woods, "Crossing the Midline," *Science* 304.5676 (June 4, 2004): 1455–56; Stephen Matthews, "Early Programming of the Hypothalamo-Pituitary-Adrenal Axis," *Trends in Endocrinology and Metabolism* 13.9 (November 1, 2002): 373–80; Justin Crowley and Lawrence Katz, "Early Development of Ocular Dominance Columns," *Science* 290.5495 (November 17, 2000): 1321–24; Anna Penn et al., "Competition in the Retinogeniculate Patterning Driven by Spontaneous Activity," *Science* 279.5359 (March 27, 1998): 2108–12.
73. The seven commands of a Turing machine are: (1) Read Tape, (2) Move Tape Left, (3) Move Tape Right, (4) Write 0 on the Tape, (5) Write 1 on the Tape, (6) Jump to Another Command, and (7) Halt.
74. In what is perhaps the most impressive analysis in his book, Wolfram shows how a Turing machine with only two states and five possible colors can be a universal Turing machine. For forty years, we've thought that a universal Turing machine had to be more complex than this. Also impressive is Wolfram's demonstration that rule 110 is capable of universal computation, given the right software. Of course, universal computation by itself cannot perform useful tasks without appropriate software.
75. The "nor" gate transforms two inputs into one output. The output of "nor" is true if and only if neither A *nor* B is true.
76. See the section "A *nor* B: The Basis of Intelligence?" in *The Age of Intelligent Machines* (Cambridge, Mass.: MIT Press, 1990), pp. 152–57, http://www.KurzweilAI.net/meme/frame.html?m=12.
77. United Nations Economic and Social Commission for Asia and the Pacific, "Regional Road Map Towards an Information Society in Asia and the Pacific," ST/ESCAP/2283, http://www.unescap.org/publications/detail.asp?id=771; Eco-

nomic and Social Commission for Western Asia, "Regional Profile of the Information Society in Western Asia," October 8, 2003, http://www.escwa.org.lb/information/publications/ictd/docs/ictd-03-11-e.pdf; John Enger, "Asia in the Global Information Economy: The Rise of Region-States, The Role of Telecommunications," presentation at the International Conference on Satellite and Cable Television in Chinese and Asian Regions, Communication Arts Research Institute, Fu Jen Catholic University, June 4–6, 1996.

78. See "The 3 by 5 Initiative," Fact Sheet 274, December 2003, http://www.who.int/mediacentre/factsheets/2003/fs274/en/print.html.
79. Technology investments accounted for 76 percent of 1998 venture-capital investments ($10.1 billion) (PricewaterhouseCoopers news release, "Venture Capital Investments Rise 24 Percent and Set Record at $14.7 Billion, PricewaterhouseCoopers Finds," February 16, 1999). In 1999, technology-based companies cornered 90 percent of venture-capital investments ($32 billion) (PricewaterhouseCoopers news release, "Venture Funding Explosion Continues: Annual and Quarterly Investment Records Smashed, According to PricewaterhouseCoopers Money Tree National Survey," February 14, 2000). Venture-capital levels certainly dropped during the high-tech recession; but in just the second quarter of 2003, software companies alone attracted close to $1 billion (PricewaterhouseCoopers news release, "Venture Capital Investments Stabilize in Q2 2003," July 29, 2003). In 1974 in all U.S. manufacturing industries forty-two firms received a total of $26.4 million in venture-capital disbursements (in 1974 dollars, or $81 million in 1992 dollars). Samuel Kortum and Josh Lerner, "Assessing the Contribution of Venture Capital to Innovation," *RAND Journal of Economics* 31.4 (Winter 2000): 674–92, http://econ.bu.edu/kortum/rje_Winter'00_Kortum.pdf. As Paul Gompers and Josh Lerner say, "Inflows to venture capital funds have expanded from virtually zero in the mid-1970s. . . ." Gompers and Lerner, *The Venture Capital Cycle*, (Cambridge, Mass.: MIT Press, 1999). See also Paul Gompers, "Venture Capital," in B. Espen Eckbo, ed., *Handbook of Corporate Finance: Empirical Corporate Finance*, in the Handbooks in Finance series (Holland: Elsevier, forthcoming), chapter 11, 2005, http://mba.tuck.dartmouth.edu/pages/faculty/espen.eckbo/PDFs/Handbookpdf/CH11-VentureCapital.pdf.
80. An account of how "new economy" technologies are making important transformations to "old economy" industries: Jonathan Rauch, "The New Old Economy: Oil, Computers, and the Reinvention of the Earth," *Atlantic Monthly*, January 3, 2001.
81. U.S. Department of Commerce, Bureau of Economic Analysis (http://www.bea.doc.gov), use the following site and select Table 1.1.6: http://www.bea.doc.gov/bea/dn/nipaweb/SelectTable.asp?Selected=N.
82. U.S. Department of Commerce, Bureau of Economic Analysis, http://www.bea.doc.gov. Data for 1920–1999: Population Estimates Program, Population Division, U.S. Census Bureau, "Historical National Population Estimates: July 1,

1900 to July 1, 1999," http://www.census.gov/popest/archives/1990s/popclockest.txt; data for 2000–2004: http://www.census.gov/popest/states/tables/NST-EST2004-01.pdf.

83. "The Global Economy: From Recovery to Expansion," Results from *Global Economic Prospects 2005: Trade, Regionalism and Prosperity* (World Bank, 2004), http://globaloutlook.worldbank.org/globaloutlook/outside/globalgrowth.aspx; "World Bank: 2004 Economic Growth Lifts Millions from Poverty," *Voice of America News*, http://www.voanews.com/english/2004-11-17-voa41.cfm.
84. Mark Bils and Peter Klenow, "The Acceleration in Variety Growth," *American Economic Review* 91.2 (May 2001): 274–80, http://www.klenow.com/Acceleration.pdf.
85. See notes 84, 86, and 87.
86. U.S. Department of Labor, Bureau of Labor Statistics, news report, June 3, 2004. You can generate productivity reports at http://www.bls.gov/bls/productivity.htm.
87. Bureau of Labor Statistics, Major Sector Multifactor Productivity Index, Manufacturing Sector: Output per Hour All Persons (1996 = 100), http://data.bls.gov/PDQ/outside.jsp?survey=mp (Requires JavaScript: select "Manufacturing," "Output Per Hour All Persons," and starting year 1949), or http://data.bls.gov/cgi-bin/srgate (use series "MPU300001," "All Years," and Format 2).
88. George M. Scalise, Semiconductor Industry Association, in "Luncheon Address: The Industry Perspective on Semiconductors," *2004 Productivity and Cyclicality in Semiconductors: Trends, Implications, and Questions—Report of a Symposium (2004)* (National Academies Press, 2004), p. 40, http://www.nap.edu/openbook/0309092744/html/index.html.
89. Data from Kurzweil Applied Intelligence, now part of ScanSoft (formerly Kurzweil Computer Products).
90. eMarketer, "E-Business in 2003: How the Internet Is Transforming Companies, Industries, and the Economy—a Review in Numbers," February 2003; "US B2C E-Commerce to Top $90 Billion in 2003," April 30, 2003, http://www.emarketer.com/Article.aspx?1002207; and "Worldwide B2B E-Commerce to Surpass $1 Trillion By Year's End," March 19, 2003, http://www.emarketer.com/Article.aspx?1002125.
91. The patents used in this chart are, as described by the U.S. Patent and Trademark Office, "patents for inventions," also known as "utility" patents. The U.S. Patent and Trademark Office, Table of Annual U.S. Patent Activity, http://www.uspto.gov/web/offices/ac/ido/oeip/taf/h_counts.htm.
92. The doubling time for IT's share of the economy is twenty-three years. U.S. Department of Commerce, Economics and Statistics Administration, "The Emerging Digital Economy," figure 2, http://www.technology.gov/digeconomy/emerging.htm.
93. The doubling time for U.S. education expenditures per capita is twenty-three years. National Center for Education Statistics, Digest of Education Statistics, 2002, http://nces.ed.gov/pubs2003/digest02/tables/dt030.asp.
94. The United Nations estimated that the total global equity market capitalization in

2000 was thirty-seven trillion dollars. United Nations, "Global Finance Profile," *Report of the High-Level Panel of Financing for Development*, June 2001, http://www.un.org/reports/financing/profile.htm.

If our perception of future growth rates were to increase (compared to current expectations) by an annual compounded rate of as little as 2 percent, and considering an annual discount rate (for discounting future values today) of 6 percent, then considering the increased present value resulting from only twenty years of compounded and discounted future (additional) growth, present values should triple. As the subsequent dialogue points out, this analysis does not take into consideration the likely increase in the discount rate that would result from such a perception of increased future growth.

Chapter Three: Achieving the Computational Capacity of the Human Brain

1. Gordon E. Moore, "Cramming More Components onto Integrated Circuits," *Electronics* 38.8 (April 19, 1965): 114–17, ftp://download.intel.com/research/silicon/moorespaper.pdf.
2. Moore's initial projection in this 1965 paper was that the number of components would double every year. In 1975 this was revised to every two years. However, this more than doubles price-performance every two years because smaller components run faster (because the electronics have less distance to travel). So overall price-performance (for the cost of each transistor cycle) has been coming down by half about every thirteen months.
3. Paolo Gargini quoted in Ann Steffora Mutschler, "Moore's Law Here to Stay," ElectronicsWeekly.com, July 14, 2004, http://www.electronicsweekly.co.uk/articles/article.asp?liArticleID=36829. See also Tom Krazit, "Intel Prepares for Next 20 Years of Chip Making," *Computerworld*, October 25, 2004, http://www.computerworld.com/hardwaretopics/hardware/story/0,10801,96917,00.html.
4. Michael Kanellos, " 'High-rise' Chips Sneak on Market," CNET News.com, July 13, 2004, http://zdnet.com.com/2100-1103-5267738.html.
5. Benjamin Fulford, "Chipmakers Are Running Out of Room: The Answer Might Lie in 3-D," Forbes.com, July 22, 2002, http://www.forbes.com/forbes/2002/0722/173_print.html.
6. NTT news release, "Three-Dimensional Nanofabrication Using Electron Beam Lithography," February 2, 2004, http://www.ntt.co.jp/news/news04e/0402/040202.html.
7. László Forró and Christian Schönenberger, "Carbon Nanotubes, Materials for the Future," *Europhysics News* 32.3 (2001), http://www.europhysicsnews.com/full/09/article3/article3.html. Also see http://www.research.ibm.com/nanoscience/nanotubes.html for an overview of nanotubes.
8. Michael Bernstein, American Chemical Society news release, "High-Speed Nanotube Transistors Could Lead to Better Cell Phones, Faster Computers," April 27, 2004, http://www.eurekalert.org/pub_releases/2004-04/acs-nt042704.php.

9. I estimate a nanotube-based transistor and supporting circuitry and connections require approximately a ten-nanometer cube (the transistor itself will be a fraction of this), or 10^3 cubic nanometers. This is conservative, since single-walled nanotubes are only one nanometer in diameter. One inch = 2.54 centimeters = 2.54×10^7 nanometers. Thus, a 1-inch cube = $2.54^3 \times 10^{21} = 1.6 \times 10^{22}$ cubic nanometers. So a one-inch cube could provide 1.6×10^{19} transistors. With each computer requiring approximately 10^7 transistors (which is a much more complex apparatus than that comprising the calculations in a human interneuronal connection), we can support about 10^{12} (one trillion) parallel computers.

   A nanotube transistor–based computer at 10^{12} calculations per second (based on Burke's estimate) gives us a speed estimate of 10^{24} cps for the one-inch cube of nanotube circuitry. Also see Bernstein, "High-Speed Nanotube Transistors."

   With an estimate of 10^{16} cps for functional emulation of the human brain (see discussion later in this chapter), this gives us about 100 million (10^8) human-brain equivalents. If we use the more conservative 10^{19} cps estimate needed for neuromorphic simulation (simulating every nonlinearity in every neural component; see subsequent discussion in this chapter), a one-inch cube of nanotube circuitry would provide only one hundred thousand human-brain equivalents.
10. "Only four years ago did we measure for the first time any electronic transport through a nanotube. Now, we are exploring what can be done and what cannot in terms of single-molecule devices. The next step will be to think about how to combine these elements into complex circuits," says one of the authors, Cees Dekker, of Henk W. Ch. Postma et al., "Carbon Nanotube Single-Electron Transistors at Room Temperature," *Science* 293.5527 (July 6, 2001): 76–129, described in the American Association for the Advancement of Science news release, "Nano-transistor Switches with Just One Electron May Be Ideal for Molecular Computers, *Science* Study Shows," http://www.eurekalert.org/pub_releases/2001-07/aaft-nsw062901.php.
11. The IBM researchers solved a problem in nanotube fabrication. When carbon soot is heated to create the tubes, a large number of unusable metallic tubes are created along with the semiconductor tubes suitable for transistors. The team included both types of nanotubes in a circuit and then used electrical pulses to shatter the undesirable ones—a far more efficient approach than cherry-picking the desirable tubes with an atomic-force microscope. Mark K. Anderson, "Mega Steps Toward the Nanochip," *Wired News,* April 27, 2001, at http://www.wired.com/news/technology/0,1282,43324,00.html, referring to Philip G. Collins, Michael S. Arnold, and Phaedon Avouris, "Engineering Carbon Nanotubes and Nanotube Circuits Using Electrical Breakdown," *Science* 292.5517 (April 27, 2001): 706–9.
12. "A carbon nanotube, which looks like rolled chicken wire when examined at the atomic level, is tens of thousands of times thinner than a human hair, yet remarkably strong." University of California at Berkeley press release, "Researchers Create First Ever Integrated Silicon Circuit with Nanotube Transistors," January 5, 2004, http://www.berkeley.edu/news/media/releases/2004/01/05_nano.shtml, referring to Yu-Chih Tseng et al., "Monolithic Integration of Carbon Nanotube Devices

with Silicon MOS Technology," *Nano Letters* 4.1 (2004): 123–27, http://pubs.acs.org/cgi-bin/sample.cgi/nalefd/2004/4/i01/pdf/nl0349707.pdf.

13. R. Colin Johnson, "IBM Nanotubes May Enable Molecular-Scale Chips," *EETimes,* April 26, 2001, http://eetimes.com/article/showArticle.jhtml?articleId=10807704.
14. Avi Aviram and Mark A. Ratner, "Molecular Rectifiers," *Chemical Physics Letters* (November 15, 1974): 277–83, referred to in Charles M. Lieber, "The Incredible Shrinking Circuit," *Scientific American* (September 2001), at http://www.sciam.com and http://www-mcg.uni-r.de/downloads/lieber.pdf. The single-molecule rectifier described in Aviram and Ratner could pass current preferentially in either direction.
15. Will Knight, "Single Atom Memory Device Stores Data," NewScientist.com, September 10, 2002, http://www.newscientist.com/news/news.jsp?id=ns99992775, referring to R. Bennewitz et al., "Atomic Scale Memory at a Silicon Surface," *Nanotechnology* 13 (July 4, 2002): 499–502.
16. Their transistor is made from indium phosphide and indium gallium arsenide. University of Illinois at Urbana-Champaign news release, "Illinois Researchers Create World's Fastest Transistor—Again," http://www.eurekalert.org/pub_releases/2003-11/uoia-irc110703.php.
17. Michael R. Diehl et al., "Self-Assembled Deterministic Carbon Nanotube Wiring Networks," *Angewandte Chemie International Edition* 41.2 (2002): 353–56; C. P. Collier et al., "Electronically Configurable Molecular-Based Logic Gates," *Science* 285.5426 (July 1999): 391–94. See http://www.its.caltech.edu/~heathgrp/papers/Paperfiles/2002/diehlangchemint.pdf and http://www.cs.duke.edu/~thl/papers/Heath.Switch.pdf.
18. The "rosette nanotubes" designed by the Purdue team contain carbon, nitrogen, hydrogen, and oxygen. The rosettes self-assemble because their interiors are hydrophobic and their exteriors are hydrophilic; therefore, to protect their insides from water, the rosettes stack into nanotubes. "The physical and chemical properties of our rosette nanotubes can now be modified almost at will through a novel dial-in approach," according to lead researcher Hicham Fenniri. R. Colin Johnson, "Purdue Researchers Build Made-to-Order Nanotubes," *EETimes,* October 24, 2002, http://www.eetimes.com/article/showArticle.jhtml?articleId=18307660; H. Fenniri et al., "Entropically Driven Self-Assembly of Multichannel Rosette Nanotubes," *Proceedings of the National Academy of Sciences* 99, suppl. 2 (April 30, 2002): 6487–92; Purdue news release, "Adaptable Nanotubes Make Way for Custom-Built Structures, Wires," http://news.uns.purdue.edu/UNS/html4ever/020311.Fenniri.scaffold.html.

    Similar work has been done by scientists in the Netherlands: Gaia Vince, "Nano-Transistor Self-Assembles Using Biology," NewScientist.com, November 20, 2003, http://www.newscientist.com/news/news.jsp?id=ns99994406.
19. Liz Kalaugher, "Lithography Makes a Connection for Nanowire Devices," June 9, 2004, http://www.nanotechweb.org/articles/news/3/6/6/1, referring to Song Jin et

al., "Scalable Interconnection and Integration of Nanowire Devices Without Registration," *Nano Letters* 4.5 (2004): 915–19.

20. Chao Li et al., "Multilevel Memory Based on Molecular Devices," *Applied Physics Letters* 84.11 (March 15, 2004): 1949–51. Also see http://www.technologyreview.com/articles/rnb_051304.asp?p=1. See also http://nanolab.usc.edu/PDF%5CAPL84-1949.pdf.
21. Gary Stix, "Nano Patterning," *Scientific American* (February 9, 2004), http://www.sciam.com/print_version.cfm?articleID=000170D6-C99F-101E-861F83414B7F0000; Michael Kanellos, "IBM Gets Chip Circuits to Draw Themselves," CNET News.com, http://zdnet.com.com/2100-1103-5114066.html. See also http://www.nanopolis.net/news_ind.php?type_id=3.
22. IBM is working on chips that automatically reconfigure as needed, such as by adding memory or accelerators. "In the future, the chip you have may not be the chip you bought," said Bernard Meyerson, chief technologist, IBM Systems and Technology Group. IBM press release, "IBM Plans Industry's First Openly Customizable Microprocessor," http://www.ibm.com/investor/press/mar-2004/31-03-04-1.phtml.
23. BBC News, " 'Nanowire' Breakthrough Hailed," April 1, 2003, http://news.bbc.co.uk/1/hi/sci/tech/2906621.stm. Published article is Thomas Scheibel et al., "Conducting Nanowires Built by Controlled Self-Assembly of Amyloid Fibers and Selective Metal Deposition," *Proceedings of the National Academy of Sciences* 100.8 (April 15, 2003): 4527–32, published online April 2, 2003, http://www.pnas.org/cgi/content/full/100/8/4527.
24. Duke University press release, "Duke Scientists 'Program' DNA Molecules to Self Assemble into Patterned Nanostructures," http://www.eurekalert.org/pub_releases/2003-09/du-ds092403.php, referring to Hao Yan et al., "DNA-Templated Self-Assembly of Protein Arrays and Highly Conductive Nanowires," *Science* 301.5641 (September 26, 2003): 1882–84. See also http://www.phy.duke.edu/~gleb/Pdf_FILES/DNA_science.pdf.
25. Ibid.
26. Here is an example of the procedure to solve what's called the traveling-salesperson problem. We try to find an optimal route for a hypothetical traveler among multiple cities without having to visit a city more than once. Only certain city pairs are connected by routes, so finding the right path is not straightforward.

    To solve the traveling-salesperson problem, mathematician Leonard Adleman of the University of Southern California performed the following steps:

    1. Generate a small strand of DNA with a unique code for each city.
    2. Replicate each such strand (one for each city) trillions of times using PCR.
    3. Next, put the pools of DNA (one for each city) together in a test tube. This step uses DNA's affinity to link strands together. Longer strands will form automatically. Each such strand represents a possible route of multiple cities. The small strands representing each city link up with each other in a random fashion, so

there is no mathematical certainty that a linked strand representing the correct answer (sequence of cities) will be formed. However, the number of strands is so vast that it is virtually certain that at least one strand—and probably millions—will be formed that represents the correct answer.

The next steps use specially designed enzymes to eliminate the trillions of strands that represent wrong answers, leaving only the strands representing the correct answer:

4. Use molecules called "primers" to destroy those DNA strands that do not start with the start city, as well as those that do not end with the end city; then replicate the surviving strands, using PCR.
5. Use an enzyme reaction to eliminate those DNA strands that represent a travel path greater than the total number of cities.
6. Use an enzyme reaction to destroy those strands that do not include city 1. Repeat for each of the cities.
7. Now, each of the surviving strands represents the correct answer. Replicate these surviving strands (using PCR) until there are billions of such strands.
8. Using a technique called electrophoresis, read out the DNA sequence of these correct strands (as a group). The readout looks like a set of distinct lines, which specifies the correct sequence of cities.

See L. M. Adleman, "Molecular Computation of Solutions to Combinatorial Problems," *Science* 266 (1994): 1021–24.

27. Charles Choi, "DNA Computer Sets Guinness Record," http://www.upi.com/view.cfm?StoryID=20030224-045551-7398r. See also Y. Benenson et al., "DNA Molecule Provides a Computing Machine with Both Data and Fuel," *Proceedings of the National Academy of Sciences* 100.5 (March 4, 2003): 2191–96, available at http://www.pubmedcentral.nih.gov/articlerender.fcgi?tool=pubmed&pubmedid=12601148; Y. Benenson et al., "An Autonomous Molecular Computer for Logical Control of Gene Expression," *Nature* 429.6990 (May 27, 2004): 423–29 (published online, April 28, 2004), available at http://www.wisdom.weizmann.ac.il/~udi/ShapiroNature2004.pdf.
28. Stanford University news release, " 'Spintronics' Could Enable a New Generation of Electronic Devices, Physicists Say," http://www.eurekalert.org/pub_releases/2003-08/su-ce080803.php, referring to Shuichi Murakami, Naoto Nagaosa, and Shou-Cheng Zhang, "Dissipationless Quantum Spin Current at Room Temperature," *Science* 301.5638 (September 5, 2003): 1348–51.
29. Celeste Biever, "Silicon-Based Magnets Boost Spintronics," NewScientist.com, March 22, 2004, http://www.newscientist.com/news/news.jsp?id=ns99994801, referring to Steve Pearton, "Silicon-Based Spintronics," *Nature Materials* 3.4 (April 2004): 203–4.
30. Will Knight, "Digital Image Stored in Single Molecule," NewScientist.com, December 1, 2002, http://www.newscientist.com/news/news.jsp?id=ns99993129,

referring to Anatoly K. Khitrin, Vladimir L. Ermakov, and B. M. Fung, "Nuclear Magnetic Resonance Molecular Photography," *Journal of Chemical Physics* 117.15 (October 15, 2002): 6903–6.

31. Reuters, "Processing at the Speed of Light," *Wired News*, http://www.wired.com/news/technology/0,1282,61009,00.html.
32. To date, the largest number to be factored is one of 512 bits, according to RSA Security.
33. Stephan Gulde et al., "Implementation of the Deutsch-Jozsa Algorithm on an Ion-Trap Quantum Computer," *Nature* 421 (January 2, 2003): 48–50. See http://heart-c704.uibk.ac.at/Papers/Nature03–Gulde.pdf.
34. Since we are currently doubling the price-performance of computation each year, a factor of a thousand requires ten doublings, or ten years. But we are also (slowly) decreasing the doubling time itself, so the actual figure is eight years.
35. Each subsequent thousandfold increase is itself occurring at a slightly faster rate. See the previous note.
36. Hans Moravec, "Rise of the Robots," *Scientific American* (December 1999): 124–35, http://www.sciam.com and http://www.frc.ri.cmu.edu/~hpm/project.archive/robot.papers/1999/SciAm.scan.html. Moravec is a professor at the Robotics Institute at Carnegie Mellon University. His Mobile Robot Laboratory explores how to use cameras, sonars, and other sensors to give robots 3-D spatial awareness. In the 1990s, he described a succession of robot generations that would "essentially [be] our off-spring, by unconventional means. Ultimately, I think they're on their own and they'll do things that we can't imagine or understand—you know, just the way children do" (Nova Online interview with Hans Moravec, October 1997, http://www.pbs.org/wgbh/nova/robots/moravec.html). His books *Mind Children: The Future of Robot and Human Intelligence* and *Robot: Mere Machine to Transcendent Mind* explore the capabilities of the current and future robot generations.

    Disclosure: The author is an investor in and on the board of directors of Moravec's robotics company, Seegrid.
37. Although instructions per second as used by Moravec and calculations per second are slightly different concepts, these are close enough for the purposes of these order-of-magnitude estimates. Moravec developed the mathematical techniques for his robot vision independent of biological models, but similarities (between Moravec's algorithms and those performed biologically) were noted after the fact. Functionally, Moravec's computations re-create what is accomplished in these neural regions, so computational estimates based on Moravec's algorithms are appropriate in determining what is required to achieve functionally equivalent transformations.
38. Lloyd Watts, "Event-Driven Simulation of Networks of Spiking Neurons," seventh Neural Information Processing Systems Foundation Conference, 1993; Lloyd Watts, "The Mode-Coupling Liouville-Green Approximation for a Two-Dimensional Cochlear Model," *Journal of the Acoustical Society of America* 108.5 (November

2000): 2266–71. Watts is the founder of Audience, Inc., which is devoted to applying functional simulation of regions of the human auditory system to applications in sound processing, including creating a way of preprocessing sound for automated speech-recognition systems. For more information, see http://www.lloydwatts.com/neuroscience.shtml.

Disclosure: The author is an adviser to Audience.

39. U.S. Patent Application 20030095667, U.S. Patent and Trademark Office, May 22, 2003.
40. The Medtronic MiniMed closed-loop artificial pancreas currently in human clinical trials is returning encouraging results. The company has announced that the device should be on the market within the next five years. Medtronic news release, "Medtronic Supports Juvenile Diabetes Research Foundation's Recognition of Artificial Pancreas as a Potential 'Cure' for Diabetes," March 23, 2004, http://www.medtronic.com/newsroom/news_2004323a.html. Such devices require a glucose sensor, an insulin pump, and an automated feedback mechanism to monitor insulin levels (International Hospital Federation, "Progress in Artificial Pancreas Development for Treating Diabetes," http://www.hospitalmanagement.net/informer/technology/tech10). Roche is also in the race to produce an artificial pancreas by 2007. See http://www.roche.com/pages/downloads/science/pdf/rtdcmannh02-6.pdf.
41. A number of models and simulations have been created based on analyses of individual neurons and interneuronal connections. Tomaso Poggio writes, "One view of the neuron is that it is more like a chip with thousands of logical-gates-equivalents rather than a single threshold element." Tomaso Poggio, private communication to Ray Kurzweil, January 2005.

    See also T. Poggio and C. Koch, "Synapses That Compute Motion," *Scientific American* 256 (1987): 46–52.

    C. Koch and T. Poggio, "Biophysics of Computational Systems: Neurons, Synapses, and Membranes," in *Synaptic Function*, G. M. Edelman, W. E. Gall, and W. M. Cowan, eds. (New York: John Wiley and Sons, 1987), pp. 637–97.

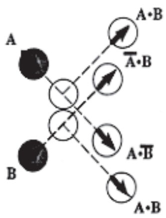
    Another set of detailed neuron-level models and simulations is being created at the University of Pennsylvania's Neuroengineering Research Lab based on reverse engineering brain function at the neuron level. Dr. Leif Finkel, head of the laboratory, says, "Right now we're building a cellular-level model of a small piece of visual cortex. It's a very detailed computer simulation which reflects with some accuracy at least the basic operations of real neurons. [My colleague Kwabena Boahen] has a chip that accurately models the retina and produces output spikes that closely match real retinae." See http://nanodot.org/article.pl?sid=01/12/18/1552221.

    Reviews of these and other models and simulations at the neuron level indicate that an estimate of 10^3 calculations per neural transaction (a single transaction involving signal transmission and reset on a single dendrite) is a reasonable upper bound. Most simulations use considerably less than this.

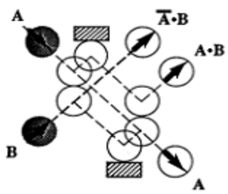
42. Plans for Blue Gene/L, the second generation of Blue Gene computers, were announced in late 2001. The new supercomputer, planned to be fifteen times faster than today's supercomputers and one twentieth the size, is being built jointly by the National Nuclear Security Agency's Lawrence Livermore National Laboratory and IBM. In 2002, IBM announced that open-source Linux had been chosen as the operating system for the new supercomputers. By July 2003, the innovative processor chips for the supercomputer, which are complete systems on chips, were in production. "Blue Gene/L is a poster child for what is possible with the system-on-a-chip concept. More than 90 percent of this chip was built from standard blocks in our technology library," according to Paul Coteus, one of the managers of the project (Timothy Morgan, "IBM's Blue Gene/L Shows Off Minimalist Server Design," *The Four Hundred*, http://www.midrangeserver.com/tfh/tfh120103-story05.html). By June 2004, the Blue Gene/L prototype systems appeared for the first time on the list of top ten supercomputers. IBM press release, "IBM Surges Past HP to Lead in Global Supercomputing," http://www.research.ibm.com/bluegene.
43. This type of network is also called peer-to-peer, many-to-many, and "multihop." In it, nodes in the network can be connected to all the other nodes or to a subset, and there are multiple paths through meshed nodes to each destination. These networks are highly adaptable and self-organizing. "The signature of a mesh network is that there is no central orchestrating device. Instead, each node is outfitted with radio communications gear and acts as a relay point for other nodes." Sebastian Rupley, "Wireless: Mesh Networks," *PC Magazine*, July 1, 2003, http://www.pcmag.com/article2/0,1759,1139094,00.asp; Robert Poor, "Wireless Mesh Networks," Sensors Online, February 2003, http://www.sensorsmag.com/articles/0203/38/main.shtml; Tomas Krag and Sebastian Büettrich, "Wireless Mesh Networking," O'Reilly Wireless DevCenter, January 22, 2004, http://www.oreillynet.com/pub/a/wireless/2004/01/22/wirelessmesh.html.
44. Carver Mead, founder of more than twenty-five companies and holder of more than fifty patents, is pioneering the new field of neuromorphic electronic systems, circuits modeled on the brain and nervous system. See Carver A. Mead, "Neuromorphic Electronic Systems," *IEEE Proceedings* 78.10 (October 1990): 1629–36. His work led to the computer touch pad and the cochlear chip used in digital hearing aids. His 1999 start-up company Foveon makes analog image-sensors that imitate the properties of film.
45. Edward Fredkin, "A Physicist's Model of Computation," Proceedings of the Twenty-sixth Recontre de Moriond, Texts of Fundamental Symmetries (1991): 283–97, http://digitalphilosophy.org/physicists_model.htm.
46. Gene Frantz, "Digital Signal Processing Trends," *IEEE Micro* 20.6 (November/December 2000): 52–59, http://csdl.computer.org/comp/mags/mi/2000/06/m6052abs.htm.
47. In 2004 Intel announced a "right hand turn" switch toward dual-core (more than one processor on a chip) architecture after reaching a "thermal wall" (or "power

wall") caused by too much heat from ever-faster single processors: http://www.intel.com/employee/retiree/circuit/righthandturn.htm.

48. R. Landauer, "Irreversibility and Heat Generation in the Computing Process," *IBM Journal of Research Development* 5 (1961): 183–91, http://www.research.ibm.com/journal/rd/053/ibmrd0503C.pdf.
49. Charles H. Bennett, "Logical Reversibility of Computation," *IBM Journal of Research Development* 17 (1973): 525–32, http://www.research.ibm.com/journal/rd/176/ibmrd1706G.pdf; Charles H. Bennett, "The Thermodynamics of Computation—a Review," *International Journal of Theoretical Physics* 21 (1982): 905–40; Charles H. Bennett, "Demons, Engines, and the Second Law," *Scientific American* 257 (November 1987): 108–16.
50. Edward Fredkin and Tommaso Toffoli, "Conservative Logic," *International Journal of Theoretical Physics* 21 (1982): 219–53, http://digitalphilosophy.org/download_documents/ConservativeLogic.pdf. Edward Fredkin, "A Physicist's Model of Computation," Proceedings of the Twenty-sixth Recontre de Moriond, Tests of Fundamental Symmetries (1991): 283–97, http://www.digitalphilosophy.org/physicists_model.htm.
51. Knight, "Digital Image Stored in Single Molecule," referring to Khitrin et al., "Nuclear Magnetic Resonance Molecular Photography"; see note 30 above.
52. Ten billion (10^{10}) humans at 10^{19} cps each is 10^{29} cps for all human brains; 10^{42} cps is greater than this by ten trillion (10^{13}).
53. Fredkin, "Physicist's Model of Computation"; see notes 45 and 50 above.
54. Two such gates are the Interaction Gate, a two-input, four-output universal, reversible-logic gate



and the Feynman Gate, a two-input, three-output reversible, universal-logic gate.



Both images are from ibid., p. 7.

55. Ibid., p. 8.
56. C. L. Seitz et al., "Hot-Clock nMOS," *Proceedings of the 1985 Chapel Hill Conference on VLSI* (Rockville, Md.: Computer Science Press, 1985), pp. 1–17, http://caltechcstr.library.caltech.edu/archive/00000365; Ralph C. Merkle, "Reversible Electronic Logic Using Switches," *Nanotechnology* 4 (1993): 21–40; S. G. Younis and T. F. Knight, "Practical Implementation of Charge Recovering Asymptotic Zero Power CMOS," *Proceedings of the 1993 Symposium on Integrated Systems* (Cambridge, Mass.: MIT Press, 1993), pp. 234–50.
57. Hiawatha Bray, "Your Next Battery," *Boston Globe,* November 24, 2003, http://www.boston.com/business/technology/articles/2003/11/24/your_next_battery.
58. Seth Lloyd, "Ultimate Physical Limits to Computation," *Nature* 406 (2000): 1047–54.

    Early work on the limits of computation was done by Hans J. Bremermann in 1962: Hans J. Bremermann, "Optimization Through Evolution and Recombination," in M. C. Yovits, C. T. Jacobi, C. D. Goldstein, eds., *Self-Organizing Systems* (Washington, D.C.: Spartan Books, 1962), pp. 93–106.

    In 1984 Robert A. Freitas Jr. built on Bremermann's work in Robert A. Freitas Jr., "Xenopsychology," *Analog* 104 (April 1984): 41–53, http://www.rfreitas.com/Astro/Xenopsychology.htm#SentienceQuotient.
59. $\pi \times$ maximum energy (10^{17} kg $\times$ meter ^{2}/second^2) / (6.6×10^{-34}) joule-seconds = ~ 5×10^{50} operations/second.
60. 5×10^{50} cps is equivalent to 5×10^{21} (5 billion trillion) human civilizations (each requiring 10^{29} cps).
61. Ten billion (10^{10}) humans at 10^{16} cps each is 10^{26} cps for human civilization. So 5×10^{50} cps is equivalent to 5×10^{24} (5 trillion trillion) human civilizations.
62. This estimate makes the conservative assumption that we've had ten billion humans for the past ten thousand years, which is obviously not the case. The actual number of humans has been increasing gradually over the past to reach about 6.1 billion in 2000. There are 3×10^7 seconds in a year, and 3×10^{11} seconds in ten thousand years. So, using the estimate of 10^{26} cps for human civilization, human thought over ten thousand years is equivalent to certainly no more than 3×10^{37} calculations. The ultimate laptop performs 5×10^{50} calculations in one second. So simulating ten thousand years of ten billion humans' thoughts would take it about 10^{-13} seconds, which is one ten-thousandth of a nanosecond.
63. Anders Sandberg, "The Physics of the Information Processing Superobjects: Daily Life Among the Jupiter Brains," *Journal of Evolution & Technology* 5 (December 22, 1999), http://www.transhumanist.com/volume5/Brains2.pdf.
64. See note 62 above; 10^{42} cps is a factor of 10^{-8} less than 10^{50} cps, so one ten-thousandth of a nanosecond becomes 10 microseconds.
65. See http://e-drexler.com/p/04/04/0330drexPubs.html for a list of Drexler's publications and patents.
66. At the rate of $\$10^{12}$ and 10^{26} cps per thousand dollars ($\$10^3$), we get 10^{35} cps per

year in the mid-2040s. The ratio of this to the 10^{26} cps for all of the biological thinking in human civilization is 10^9 (one billion).

67. In 1984 Robert A. Freitas proposed a logarithmic scale of "sentience quotient" (SQ) based on the computational capacity of a system. In a scale that ranges from −70 to 50, human brains come out at 13. The Cray 1 supercomputer comes out at 9. Freitas's sentience quotient is based on the amount of computation per unit mass. A very fast computer with a simple algorithm would come out with a high SQ. The measure I describe for computation in this section builds on Freitas's SQ and attempts to take into consideration the usefulness of the computation. So if a simpler computation is equivalent to the one actually being run, then we base the computational efficiency on the equivalent (simpler) computation. Also in my measure, the computation needs to be "useful." Robert A. Freitas Jr., "Xenopsychology," *Analog* 104 (April 1984): 41–53, http://www.rfreitas.com/Astro/Xenopsychology.htm#SentienceQuotient.
68. As an interesting aside, engravings on the side of small rocks did in fact represent an early form of computer storage. One of the earliest forms of written language, cuneiform, which was developed in Mesopotamia circa 3000 B.C., used pictorial markings on stones to store information. Agricultural records were maintained as cuneiform markings on stones placed in trays, and organized in rows and columns. These marked stones were essentially the first spreadsheet. One such cuneiform stone record is a prized artifact in my collection of historical computers.
69. One thousand (10^3) bits is less than the theoretical capacity of the atoms in the stone to store information (estimated at 10^{27} bits) by a factor of 10^{-24}.
70. 1 cps (10^0 cps) is less than the theoretical computing capacity of the atoms in the stone (estimated at 10^{42} cps) by a factor of 10^{-42}.
71. Edgar Buckingham, "Jet Propulsion for Airplanes," NACA report no. 159, in *Ninth Annual Report of NACA-1923* (Washington, D.C.: NACA, 1924), pp. 75–90. See http://naca.larc.nasa.gov/reports/1924/naca-report-159/.
72. Belle Dumé, "Microscopy Moves to the Picoscale," *PhysicsWeb*, June 10, 2004, http://physicsweb.org/article/news/8/6/6, referring to Stefan Hembacher, Franz J. Giessibl, and Jochen Mannhart, "Force Microscopy with Light-Atom Probes," *Science* 305.5682 (July 16, 2004): 380–83. This new "higher harmonic" force microscope, developed by University of Augsburg physicists, uses a single carbon atom as a probe and has a resolution that is at least three times better than that of traditional scanning tunneling microscopes. How it works: as the tungsten tip of the probe is made to oscillate at subnanometer amplitudes, the interaction between the tip atom and the carbon atom produces higher harmonic components in the underlying sinusoidal-wave pattern. The scientists measured these signals to obtain an ultrahigh-resolution image of the tip atom that showed features just 77 picometers (thousandths of a nanometer) across.
73. Henry Fountain, "New Detector May Test Heisenberg's Uncertainty Principle," *New York Times,* July 22, 2003.
74. Mitch Jacoby, "Electron Moves in Attoseconds," *Chemical and Engineering News*

82.25 (June 21, 2004): 5, referring to Peter Abbamonte et al., "Imaging Density Disturbances in Water with a 41.3-Attosecond Time Resolution," *Physical Review Letters* 92.23 (June 11, 2004): 237–401.

75. S. K. Lamoreaux and J. R. Torgerson, "Neutron Moderation in the Oklo Natural Reactor and the Time Variation of Alpha," *Physical Review* D 69 (2004): 121701–6, http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=PRVDAQ 000069000012121701000001&idtype=cvips&gifs=yes; Eugenie S. Reich, "Speed of Light May Have Changed Recently," *New Scientist,* June 30, 2004, http://www.newscientist.com/news/news.jsp?id=ns99996092.
76. Charles Choi, "Computer Program to Send Data Back in Time," UPI, October 1, 2002, http://www.upi.com/view.cfm?StoryID=20021001-125805-3380r; Todd Brun, "Computers with Closed Timelike Curves Can Solve Hard Problems," *Foundation of Physics Letters* 16 (2003): 245–53. Electronic edition, September 11, 2002, http://arxiv.org/PS_cache/gr-qc/pdf/0209/0209061.pdf.

Chapter Four: Achieving the Software of Human Intelligence: How to Reverse Engineer the Human Brain

1. Lloyd Watts, "Visualizing Complexity in the Brain," in D. Fogel and C. Robinson, eds., *Computational Intelligence: The Experts Speak* (Piscataway, N.J.: IEEE Press/Wiley, 2003), http://www.lloydwatts.com/wcci.pdf.
2. J. G. Taylor, B. Horwitz, and K. J. Friston, "The Global Brain: Imaging and Modeling," *Neural Networks* 13, special issue (2000): 827.
3. Neil A. Busis, "Neurosciences on the Internet," http://www.neuroguide.com; "Neuroscientists Have Better Tools on the Brain," *Bio IT Bulletin,* http://www.bio-it world.com/news/041503_report2345.html; "Brain Projects to Reap Dividends for Neurotech Firms," *Neurotech Reports*, http://www.neurotechreports.com/pages/brainprojects.html.
4. Robert A. Freitas Jr., *Nanomedicine*, vol. 1, *Basic Capabilities,* section 4.8.6, "Noninvasive Neuroelectric Monitoring" (Georgetown, Tex.: Landes Bioscience, 1999), pp. 115–16, http://www.nanomedicine.com/NMI/4.8.6.htm.
5. Chapter 3 analyzed this issue; see the section "The Computational Capacity of the Human Brain."
6. Speech-recognition research and development, Kurzweil Applied Intelligence, which I founded in 1982, now part of ScanSoft (formerly Kurzweil Computer Products).
7. Lloyd Watts, U.S. Patent Application, U.S. Patent and Trademark Office, 20030095667, May 22, 2003, "Computation of Multi-sensor Time Delays." Abstract: "Determining a time delay between a first signal received at a first sensor and a second signal received at a second sensor is described. The first signal is analyzed to derive a plurality of first signal channels at different frequencies and the second signal is analyzed to derive a plurality of second signal channels at different frequencies. A first feature is detected that occurs at a first time in one of the first

signal channels. A second feature is detected that occurs at a second time in one of the second signal channels. The first feature is matched with the second feature and the first time is compared to the second time to determine the time delay." See also Nabil H. Farhat, U.S. Patent Application 20040073415, U.S. Patent and Trademark Office, April 15, 2004, "Dynamical Brain Model for Use in Data Processing Applications."

8. I estimate the compressed genome at about thirty to one hundred million bytes (see note 57 for chapter 2); this is smaller than the object code for Microsoft Word and much smaller than the source code. See Word 2003 system requirements, October 20, 2003, http://www.microsoft.com/office/word/prodinfo/sysreq.mspx.
9. Wikipedia, http://en.wikipedia.org/wiki/Epigenetics.
10. See note 57 in chapter 2 for an analysis of the information content in the genome, which I estimate to be 30 to 100 million bytes, therefore less than 10^9 bits. See the section "Human Memory Capacity" in chapter 3 (p. 126) for my analysis of the information in a human brain, estimated at 10^{18} bits.
11. Marie Gustafsson and Christian Balkenius, "Using Semantic Web Techniques for Validation of Cognitive Models against Neuroscientific Data," AILS 04 Workshop, SAIS/SSLS Workshop (Swedish Artificial Intelligence Society; Swedish Society for Learning Systems), April 15–16, 2004, Lund, Sweden, www.lucs.lu.se/People/Christian.Balkenius/PDF/Gustafsson.Balkenius.2004.pdf.
12. See discussion in chapter 3. In one useful reference, when modeling neuron by neuron, Tomaso Poggio and Christof Koch describe the neuron as similar to a chip with thousands of logical gates. See T. Poggio and C. Koch, "Synapses That Compute Motion," *Scientific American* 256 (1987): 46–52. Also C. Koch and T. Poggio, "Biophysics of Computational Systems: Neurons, Synapses, and Membranes," in *Synaptic Function*, G. M. Edelman, W. E. Gall, and W. M. Cowan, eds. (New York: John Wiley and Sons, 1987), pp. 637–97.
13. On Mead, see http://www.technology.gov/Medal/2002/bios/Carver_A._Mead.pdf. Carver Mead, *Analog VLSI and Neural Systems* (Reading, Mass.: Addison-Wesley, 1986).
14. See note 172 in chapter 5 for an algorithmic description of a self-organizing neural net and note 175 in chapter 5 for a description of a self-organizing genetic algorithm.
15. See Gary Dudley et al., "Autonomic Self-Healing Systems in a Cross-Product IT Environment," proceedings of the IEEE International Conference on Autonomic Computing, New York City, May 17–19, 2004, http://csdl.computer.org/comp/proceedings/icac/2004/2114/00/21140312.pdf; "About IBM Autonomic Computing," http://www-3.ibm.com/autonomic/about.shtml; and Ric Telford, "The Autonomic Computing Architecture," April 14, 2004, http://www.dcs.st-andrews.ac.uk/undergrad/current/dates/disclec/2003–2/RicTelfordDistinguished2.pdf.
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Brain regions modeled:

Cochlea: Sense organ of hearing. Thirty thousand fibers convert motion of the stapes into spectrotemporal representations of sound.

MC: Multipolar cells. Measure spectral energy.

GBC: Globular bushy cells. Relay spikes from the auditory nerve to the lateral superior olivary complex (includes LSO and MSO). Encoding of timing and amplitude of signals for binaural comparison of level.

SBC: Spherical bushy cells. Provide temporal sharpening of time of arrival, as a preprocessor for interaural time-difference calculation (difference in time of arrival between the two ears, used to tell where a sound is coming from).

OC: Octopus cells. Detection of transients.

DCN: Dorsal cochlear nucleus. Detection of spectral edges and calibrating for noise levels.

VNTB: Ventral nucleus of the trapezoid body. Feedback signals to modulate outer hair-cell function in the cochlea.

VNLL, PON: Ventral nucleus of the lateral lemniscus; peri-olivary nuclei: processing transients from the OC.

MSO: Medial superior olive. Computing interaural time difference.

LSO: Lateral superior olive. Also involved in computing interaural level difference.

ICC: Central nucleus of the inferior colliculus. The site of major integration of multiple representations of sound.

ICx: Exterior nucleus of the inferior colliculus. Further refinement of sound localization.

SC: Superior colliculus. Location of auditory/visual merging.

MGB: Medial geniculate body. The auditory portion of the thalamus.

LS: Limbic system. Comprising many structures associated with emotion, memory, territory, et cetera.

AC: Auditory cortex.

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Tables/3.4.jpg). Thus human brain state monitoring can probably be instantaneous, at least on the timescale of human neural response, in the sense of 'nothing of significance was missed.' "

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Chapter Five: GNR: Three Overlapping Revolutions

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6. The original reports of Crick and Watson, which still make compelling reading today, may be found in James A. Peters, ed., *Classic Papers in Genetics* (Englewood Cliffs, N.J.: Prentice-Hall, 1959). An exciting account of the successes and failures that led to the double helix is given in J. D. Watson, *The Double Helix: A Personal Account of the Discovery of the Structure of DNA* (New York: Atheneum, 1968). Nature.com has a collection of Crick's papers available online at http://www.nature.com/nature/focus/crick/index.html.
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9. Mark A. Jobling and Chris Tyler-Smith, "The Human Y Chromosome: An Evolutionary Marker Comes of Age," *Nature Reviews Genetics* 4 (August 2003): 598–612; Helen Skaletsky et al., "The Male-Specific Region of the Human Y Chromosome Is a Mosaic of Discrete Sequence Classes," *Nature* 423 (June 19, 2003): 825–37.
10. Misformed proteins are perhaps the most dangerous toxin of all. Research suggests that misfolded proteins may be at the heart of numerous disease processes in the body. Such diverse diseases as Alzheimer's disease, Parkinson's disease, the human form of mad-cow disease, cystic fibrosis, cataracts, and diabetes are all

thought to result from the inability of the body to adequately eliminate misfolded proteins.

Protein molecules perform the lion's share of cellular work. Proteins are made within each cell according to DNA blueprints. They begin as long strings of amino acids, which must then be folded into precise three-dimensional configurations in order to function as enzymes, transport proteins, et cetera. Heavy-metal toxins interfere with normal function of these enzymes, further exacerbating the problem. There are also genetic mutations that predispose individuals to misformed-protein buildup.

When protofibrils begin to stick together, they form filaments, fibrils, and ultimately larger globular structures called amyloid plaque. Until recently these accumulations of insoluble plaque were regarded as the pathologic agents for these diseases, but it is now known that the protofibrils themselves are the real problem. The speed with which a protofibril is turned into insoluble amyloid plaque is inversely related to disease progression. This explains why some individuals are found to have extensive accumulation of plaque in their brains but no evidence of Alzheimer's disease, while others have little visible plaque yet extensive manifestations of the disease. Some people form amyloid plaque quickly, which protects them from further protofibril damage. Other individuals turn protofibrils into amyloid plaque less rapidly, allowing more extensive damage. These people also have little visible amyloid plaque. See Per Hammarström, Frank Schneider, and Jeffrey W. Kelly, "*Trans*-Suppression of Misfolding in an Amyloid Disease," *Science* 293.5539 (September 28, 2001): 2459–62.

11. A fascinating account of the new biology is given in Horace F. Judson, *The Eighth Day of Creation: The Makers of the Revolution in Biology* (Woodbury, N.Y.: CSHL Press, 1996).
12. Raymond Kurzweil and Terry Grossman, M.D., *Fantastic Voyage: Live Long Enough to Live Forever* (New York: Rodale, 2004). See http://www.Fantastic-Voyage.net and http://www.RayandTerry.com.
13. Raymond Kurzweil, *The 10% Solution for a Healthy Life: How to Eliminate Virtually All Risk of Heart Disease and Cancer* (New York: Crown Books, 1993).
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15. The test for "biological age," called the H-scan test, includes tests for auditory-reaction time, highest audible pitch, vibrotactile sensitivity, visual-reaction time, muscle-movement time, lung (forced expiratory) volume, visual-reaction time with decision, muscle-movement time with decision, memory (length of sequence), alternative button-tapping time, and visual accommodation. The author had this test done at Frontier Medical Institute (Grossman's health and longevity clinic), http://www.FMIClinic.com. For information on the H-scan test, see Diagnostic and Lab Testing, Longevity Institute, Dallas, http://www.lidhealth.com/diagnostic.html.

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17. Ibid.
18. Aubrey D. N. J. de Grey, "The Foreseeability of Real Anti-Aging Medicine: Focusing the Debate," *Experimental Gerontology* 38.9 (September 2003): 927–34; Aubrey D. N. J. de Grey, "An Engineer's Approach to the Development of Real Anti-Aging Medicine," *Science of Aging, Knowledge, Environment* 1 (2003): Aubrey D. N. J. de Grey et al., "Is Human Aging Still Mysterious Enough to Be Left Only to Scientists?" *BioEssays* 24.7 (July 2002): 667–76.
19. Aubrey D. N. J. de Grey, ed., *Strategies for Engineered Negligible Senescence: Why Genuine Control of Aging May Be Foreseeable*, Annals of the New York Academy of Sciences, vol. 1019 (New York: New York Academy of Sciences, June 2004).
20. In addition to providing the functions of different types of cells, two other reasons for cells to control the expression of genes are environmental cues and developmental processes. Even simple organisms such as bacteria can turn on and off the synthesis of proteins depending on environmental cues. *E. coli,* for example, can turn off the synthesis of proteins that allow it to control the level of nitrogen gas from the air when there are other, less energy-intensive sources of nitrogen in its environment. A recent study of 1,800 strawberry genes found that the expression of 200 of those genes varied during different stages of development. E. Marshall, "An Array of Uses: Expression Patterns in Strawberries, Ebola, TB, and Mouse Cells," *Science* 286.5439 (1999): 445.
21. Along with a protein-encoding region, genes include regulatory sequences called promoters and enhancers that control where and when that gene is expressed. Promoters of genes that encode proteins are typically located immediately "upstream" on the DNA. An enhancer activates the use of a promoter, thereby controlling the rate of gene expression. Most genes require enhancers to be expressed. Enhancers have been called "the major determinant of differential transcription in space (cell type) and time"; and any given gene can have several different enhancer sites linked to it (S. F. Gilbert, *Developmental Biology*, 6th ed. [Sunderland, Mass.: Sinauer Associates, 2000]; available online at www.ncbi.nlm.nih.gov/books/bv.fcgi?call=bv.View..ShowSection&rid=.0BpKYEB-SPfx18nm8QOxH).

    By binding to enhancer or promoter regions, transcription factors start or repress the expression of a gene. New knowledge of transcription factors has transformed our understanding of gene expression. Per Gilbert in the chapter "The Genetic Core of Development: Differential Gene Expression": "The gene itself is no longer seen as an independent entity controlling the synthesis of proteins. Rather, the gene both directs and is directed by protein synthesis. Natalie Anger (1992) has written, 'A series of discoveries suggests that DNA is more like a certain type of politician, surrounded by a flock of protein handlers and advisors that must vigorously massage it, twist it and, on occasion, reinvent it before the grand blueprint of the body can make any sense at all.' "

22. Bob Holmes, "Gene Therapy May Switch Off Huntington's," March 13, 2003, http://www.newscientist.com/news/news.jsp?id=ns99993493. "Emerging as a powerful tool for reverse genetic analysis, RNAi is rapidly being applied to study the function of many genes associated with human disease, in particular those associated with oncogenesis and infectious disease." J. C. Cheng, T. B. Moore, and K. M. Sakamoto, "RNA Interference and Human Disease," *Molecular Genetics and Metabolism* 80.1–2 (October 2003): 121–28. RNAi is a "potent and highly sequence-specific mechanism." L. Zhang, D. K. Fogg, and D. M. Waisman, "RNA Interference-Mediated Silencing of the S100A10 Gene Attenuates Plasmin Generation and Invasiveness of Colo 222 Colorectal Cancer Cells," *Journal of Biological Chemistry* 279.3 (January 16, 2004): 2053–62.
23. Each chip contains synthetic oligonucleotides that replicate sequences that identify specific genes. "To determine which genes have been expressed in a sample, researchers isolate messenger RNA from test samples, convert it to complementary DNA (cDNA), tag it with fluorescent dye, and run the sample over the wafer. Each tagged cDNA will stick to an oligo with a matching sequence, lighting up a spot on the wafer where the sequence is known. An automated scanner then determines which oligos have bound, and hence which genes were expressed. . . ." E. Marshall, "Do-It-Yourself Gene Watching," *Science* 286.5439 (October 15, 1999): 444–47.
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25. J. Rosamond and A. Allsop, "Harnessing the Power of the Genome in the Search for New Antibiotics," *Science* 287.5460 (March 17, 2000): 1973–76.
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27. Ibid., as reported in A. Berns, "Cancer: Gene Expression in Diagnosis," *Nature* 403 (February 3, 2000): 491–92. In another study, 1 percent of the genes studied showed reduced expression in aged muscles. These genes produced proteins associated with energy production and cell building, so a reduction makes sense given the weakening associated with age. Genes with increased expression produced stress proteins, which are used to repair damaged DNA or proteins. J. Marx, "Chipping Away at the Causes of Aging," *Science* 287.5462 (March 31, 2000): 2390.

    As another example, liver metastases are a common cause of colorectal cancer. These metastases respond differently to treatment depending on their genetic profile. Expression profiling is an excellent way to determine an appropriate mode of treatment. J. C. Sung et al., "Genetic Heterogeneity of Colorectal Cancer Liver Metastases," *Journal of Surgical Research* 114.2 (October 2003): 251.

    As a final example, researchers have had difficulty analyzing the Reed-Sternberg cell of Hodgkin's disease because of its extreme rarity in diseased tissue. Expression profiling is now providing a clue regarding the heritage of this cell. J. Cossman et al., "Reed-Sternberg Cell Genome Expression Supports a B-Cell Lineage," *Blood* 94.2 (July 15, 1999): 411–16.

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30. Gene transfer to somatic cells affects a subset of cells in the body for a period of time. It is theoretically possible also to alter genetic information in egg and sperm (germ-line) cells, for the purpose of passing on those changes to the next generations. Such therapy poses many ethical concerns and has not yet been attempted. "Gene Therapy," Wikipedia, http://en.wikipedia.org/wiki/Gene_therapy.
31. Genes encode proteins, which perform vital functions in the human body. Abnormal or mutated genes encode proteins that are unable to perform those functions, resulting in genetic disorders and diseases. The goal of gene therapy is to replace the defective genes so that normal proteins are produced. This can be done in a number of ways, but the most typical way is to insert a therapeutic replacement gene into the patient's target cells using a carrier molecule called a vector. "Currently, the most common vector is a virus that has been genetically altered to carry normal human DNA. Viruses have evolved a way of encapsulating and delivering their genes to human cells in a pathogenic manner. Scientists have tried to take advantage of this capability and manipulate the virus genome to remove the disease-causing genes and insert therapeutic genes" (Human Genome Project, "Gene Therapy," http://www.ornl.gov/TechResources/Human_Genome/medicine/gene therapy.html). See the Human Genome Project site for more information about gene therapy and links. Gene therapy is an important enough area of research that there are currently six scientific peer-reviewed gene-therapy journals and four professional associations dedicated to this topic.
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of the X's and most of its genes are normally silenced or inactivated. That way, the amount of gene expression in males and females is the same. But in cloned animals, one X-chromosome is already inactivated in the donated nucleus. It must be reprogrammed and then later inactivated again, which introduces the possibility of errors." CBC News online staff, "Genetic Defects May Explain Cloning Failures," May 27, 2002, http://www.cbc.ca/stories/2002/05/27/cloning_errors020527. That story reports on F. Xue et al., "Aberrant Patterns of X Chromosome Inactivation in Bovine Clones," *Nature Genetics* 31.2 (June 2002): 216–20.

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62. As the Scripps Research Institute points out, "The ability to dedifferentiate or reverse lineage-committed cells to multipotent progenitor cells might overcome many of the obstacles associated with using ESCs and adult stem cells in clinical applications (inefficient differentiation, rejection of allogenic cells, efficient isolation and expansion, etc.). With an efficient dedifferentiation process, it is conceivable that healthy, abundant and easily accessible adult cells could be used to generate different types of functional cells for the repair of damaged tissues and organs" (http://www.scripps.edu/chem/ding/sciences.htm).

> The direct conversion of one differentiated cell type into another—a process referred to as transdifferentiation—would be beneficial for producing isogenic [patient's own] cells to replace sick or damaged cells or tissue. Adult stem cells display a broader differentiation potential than anticipated and might contribute to tissues other than those in which they reside. As such, they could be worthy therapeutic agents. Recent advances in transdifferentiation involve nuclear transplantation, manipulation of cell culture conditions, induction of ectopic gene expression and uptake of molecules from cellular extracts. These approaches open the doors to new avenues for engineering isogenic replacement cells. To avoid unpredictable tissue transformation, nuclear reprogramming requires controlled and heritable epigenetic modifications. Considerable efforts remain to unravel the molecular processes

underlying nuclear reprogramming and evaluate stability of the changes in reprogrammed cells.

Quoted from P. Collas and Anne-Mari Håkelien, "Teaching Cells New Tricks," *Trends in Biotechnology* 21.8 (August 2003): 354–61; P. Collas, "Nuclear Reprogramming in Cell-Free Extracts," *Philosophical Transactions of the Royal Society of London*, *B* 358.1436 (August 29, 2003): 1389–95.

63. Researchers have converted human liver cells to pancreas cells in the laboratory: Jonathan Slack et al., "Experimental Conversion of Liver to Pancreas," *Current Biology* 13.2 (January 2003): 105–15. Researchers reprogrammed cells to behave like other cells using cell extracts; for example, skin cells were reprogrammed to exhibit T-cell characteristics. Anne-Mari Håkelien et al., "Reprogramming Fibroblasts to Express T-Cell Functions Using Cell Extracts," *Nature Biotechnology* 20.5 (May 2002): 460–66; Anne-Mari Håkelien and P. Collas, "Novel Approaches to Transdifferentiation," *Cloning Stem Cells* 4.4 (2002): 379–87. See also David Tosh and Jonathan M. W. Slack, "How Cells Change Their Phenotype," *Nature Reviews Molecular Cell Biology* 3.3 (March 2002): 187–94.
64. See the description of transcription factors in note 21, above.
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    According to a clinical-trial research summary (James Shapiro, "Campath-1H and One-Year Temporary Sirolimus Maintenance Monotherapy in Clinical Islet Transplantation," http://www.immunetolerance.org/public/clinical/islet/trials/shapiro2.html), "This therapy is not suitable for all patients with Type I diabetes, even if there were no limitation in islet supply, because of the potential long-term risks of cancer, life-threatening infections and drug side-effects related to the anti-rejection therapy. If tolerance [indefinite graft function without a need for long-term drugs to prevent rejection] could be achieved at minimal up-front risk, then islet transplant could be used safely earlier in the course of diabetes, and eventually in children at the time of diagnosis."
67. "Lab Grown Steaks Nearing Menu," http://www.newscientist.com/news/news.jsp?id=ns99993208, includes discussion of technical issues.
68. The halving time for feature sizes is five years in each dimension. See discussion in chapter 2.
69. An analysis by Robert A. Freitas Jr. indicates that replacing 10 percent of a person's

red blood cells with robotic respirocytes would enable holding one's breath for about four hours, which is about 240 times longer than one minute (about the length of time feasible with all biological red blood cells). Since this increase derives from replacing only 10 percent of the red blood cells, the respirocytes are thousands of times more effective.

70. Nanotechnology is "thorough, inexpensive control of the structure of matter based on molecule-by-molecule control of products and byproducts; the products and processes of molecular manufacturing, including molecular machinery" (Eric Drexler and Chris Peterson, *Unbounding the Future: The Nanotechnology Revolution* [New York: William Morrow, 1991]). According to the authors:

> Technology has been moving toward greater control of the structure of matter for millennia. . . . [P]ast advanced technologies—microwave tubes, lasers, superconductors, satellites, robots, and the like—have come trickling out of factories, at first with high price tags and narrow applications. Molecular manufacturing, though, will be more like computers: a flexible technology with a huge range of applications. And molecular manufacturing won't come trickling out of conventional factories as computers did; it will replace factories and replace or upgrade their products. This is something new and basic, not just another twentieth-century gadget. It will arise out of twentieth-century trends in science, but it will break the trend-lines in technology, economics, and environmental affairs. [chap. 1]

Drexler and Peterson outline the possible scope of the effects of the revolution: efficient solar cells "as cheap as newspaper and as tough as asphalt," molecular mechanisms that can kill cold viruses in six hours before biodegrading, immune machines that destroy malignant cells in the body at the push of a button, pocket supercomputers, the end of the use of fossil fuels, space travel, and restoration of lost species. Also see E. Drexler, *Engines of Creation* (New York: Anchor Books, 1986). The Foresight Institute has a useful list of nanotechnology FAQs (http://www.foresight.org/NanoRev/FIFAQ1.html) and other information. Other Web resources include the National Nanotechnology Initiative (http://www.nano.gov), http://nanotechweb.org, Dr. Ralph Merkle's nanotechnology page (http://www.zyvex.com/nano), and *Nanotechnology*, an online journal (http://www.iop.org/EJ/journal/0957-4484). Extensive material on nanotechnology can be found on the author's Web site at http://www.kurzweilAI.net/meme/frame.html?m=18.

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157. As quoted by Douglas Hofstadter in *Gödel, Escher, Bach: An Eternal Golden Braid* (New York: Basic Books, 1979).
158. The author runs a company, FATKAT (Financial Accelerating Transactions by

Kurzweil Adaptive Technologies), which applies computerized pattern recognition to financial data to make stock-market investment decisions, http://www.FatKat.com.

159. See discussion in chapter 2 on price-performance improvements in computer memory and electronics in general.
160. Runaway AI refers to a scenario where, as Max More describes, "superintelligent *machines,* initially harnessed for *human* benefit, soon leave us behind." Max More, "Embrace, Don't Relinquish, the Future," http://www.KurzweilAI.net/articles/art0106.html?printable=1. See also Damien Broderick's description of the "Seed AI": "A self-improving seed AI could run glacially slowly on a limited machine substrate. The point is, so long as it has the capacity to improve itself, at some point it will do so convulsively, bursting through any architectural bottlenecks to design its own improved hardware, maybe even build it (if it's allowed control of tools in a fabrication plant)." Damien Broderick, "Tearing Toward the Spike," presented at "Australia at the Crossroads? Scenarios and Strategies for the Future" (April 31–May 2, 2000), published on KurzweilAI.net May 7, 2001, http://www.KurzweilAI.net/meme/frame.html?main=/articles/art0173.html.
161. David Talbot, "Lord of the Robots," *Technology Review* (April 2002).
162. Heather Havenstein writes that the "inflated notions spawned by science fiction writers about the convergence of humans and machines tarnished the image of AI in the 1980s because AI was perceived as failing to live up to its potential." Heather Havenstein, "Spring Comes to AI Winter: A Thousand Applications Bloom in Medicine, Customer Service, Education and Manufacturing," *Computerworld*, February 14, 2005, http://www.computerworld.com/softwaretopics/software/story/0,10801,99691,00.html. This tarnished image led to "AI Winter," defined as "a term coined by Richard Gabriel for the (circa 1990–94?) crash of the wave of enthusiasm for the AI language Lisp and AI itself, following a boom in the 1980s." Duane Rettig wrote: ". . . companies rode the great AI wave in the early 80's, when large corporations poured billions of dollars into the AI hype that promised thinking machines in 10 years. When the promises turned out to be harder than originally thought, the AI wave crashed, and Lisp crashed with it because of its association with AI. We refer to it as the AI Winter." Duane Rettig quoted in "AI Winter," http://c2.com/cgi/wiki?AiWinter.
163. The General Problem Solver (GPS) computer program, written in 1957, was able to solve problems through rules that allowed the GPS to divide a problem's goals into subgoals, and then check if obtaining a particular subgoal would bring the GPS closer to solving the overall goal. In the early 1960s Thomas Evan wrote ANALOGY, a "program [that] solves geometric-analogy problems of the form A:B::C:? taken from IQ tests and college entrance exams." Boicho Kokinov and Robert M. French, "Computational Models of Analogy-Making," in L. Nadel, ed., *Encyclopedia of Cognitive Science,* vol. 1 (London: Nature Publishing Group, 2003), pp. 113–18. See also A. Newell, J. C. Shaw, and H. A.

Simon, "Report on a General Problem-Solving Program," *Proceedings of the International Conference on Information Processing* (Paris: UNESCO House, 1959), pp. 256–64; Thomas Evans, "A Heuristic Program to Solve Geometric-Analogy Problems," in M. Minsky, ed., *Semantic Information Processing* (Cambridge, Mass.: MIT Press, 1968).

164. Sir Arthur Conan Doyle, "The Red-Headed League," 1890, available at http://www.eastoftheweb.com/short-stories/UBooks/RedHead.shtml.
165. V. Yu et al., "Antimicrobial Selection by a Computer: A Blinded Evaluation by Infectious Diseases Experts," *JAMA* 242.12 (1979): 1279–82.
166. Gary H. Anthes, "Computerizing Common Sense," *Computerworld,* April 8, 2002, http://www.computerworld.com/news/2002/story/0,11280,69881,00.html.
167. Kristen Philipkoski, "Now Here's a Really Big Idea," *Wired News,* November 25, 2002, http://www.wired.com/news/technology/0,1282,56374,00.html, reporting on Darryl Macer, "The Next Challenge Is to Map the Human Mind," *Nature* 420 (November 14, 2002): 121; see also a description of the project at http://www.biol.tsukuba.ac.jp/~macer/index.html.
168. Thomas Bayes, "An Essay Towards Solving a Problem in the Doctrine of Chances," published in 1763, two years after his death in 1761.
169. SpamBayes spam filter, http://spambayes.sourceforge.net.
170. Lawrence R. Rabiner, "A Tutorial on Hidden Markov Models and Selected Applications in Speech Recognition," *Proceedings of the IEEE* 77 (1989): 257–86. For a mathematical treatment of Markov models, see http://jedlik.phy.bme.hu/~gerjanos/HMM/node2.html.
171. Kurzweil Applied Intelligence (KAI), founded by the author in 1982, was sold in 1997 for $100 million and is now part of ScanSoft (formerly called Kurzweil Computer Products, the author's first company, which was sold to Xerox in 1980), now a public company. KAI introduced the first commercially marketed large-vocabulary speech-recognition system in 1987 (Kurzweil Voice Report, with a ten-thousand-word vocabulary).
172. Here is the basic schema for a neural net algorithm. Many variations are possible, and the designer of the system needs to provide certain critical parameters and methods, detailed below.

Creating a neural-net solution to a problem involves the following steps:

- Define the input.
- Define the topology of the neural net (i.e., the layers of neurons and the connections between the neurons).
- Train the neural net on examples of the problem.
- Run the trained neural net to solve new examples of the problem.
- Take your neural-net company public.

These steps (except for the last one) are detailed below:

The Problem Input

The problem input to the neural net consists of a series of numbers. This input can be:

- In a visual pattern-recognition system, a two-dimensional array of numbers representing the pixels of an image; or
- In an auditory (e.g., speech) recognition system, a two-dimensional array of numbers representing a sound, in which the first dimension represents parameters of the sound (e.g., frequency components) and the second dimension represents different points in time; or
- In an arbitrary pattern-recognition system, an *n*-dimensional array of numbers representing the input pattern.

Defining the Topology

To set up the neural net, the architecture of each neuron consists of:

- Multiple inputs in which each input is "connected" to either the output of another neuron, or one of the input numbers.
- Generally, a single output, which is connected either to the input of another neuron (which is usually in a higher layer), or to the final output.

Set Up the First Layer of Neurons

- Create N_0 neurons in the first layer. For each of these neurons, "connect" each of the multiple inputs of the neuron to "points" (i.e., numbers) in the problem input. These connections can be determined randomly or using an evolutionary algorithm (see below).
- Assign an initial "synaptic strength" to each connection created. These weights can start out all the same, can be assigned randomly, or can be determined in another way (see below).

Set Up the Additional Layers of Neurons

Set up a total of M layers of neurons. For each layer, set up the neurons in that layer.

For layer_i:

- Create N_i neurons in layer_i. For each of these neurons, "connect" each of the multiple inputs of the neuron to the outputs of the neurons in layer_{i-1} (see variations below).
- Assign an initial "synaptic strength" to each connection created. These weights can start out all the same, can be assigned randomly, or can be determined in another way (see below).
- The outputs of the neurons in layer_M are the outputs of the neural net (see variations below).

The Recognition Trials
How Each Neuron Works

Once the neuron is set up, it does the following for each recognition trial:

- Each weighted input to the neuron is computed by multiplying the output of the other neuron (or initial input) that the input to this neuron is connected to by the synaptic strength of that connection.
- All of these weighted inputs to the neuron are summed.
- If this sum is greater than the firing threshold of this neuron, then this neuron is considered to fire and its output is 1. Otherwise, its output is 0 (see variations below).

Do the Following for Each Recognition Trial

For each layer, from $layer_0$ to $layer_M$:

For each neuron in the layer:

- Sum its weighted inputs (each weighted input = the output of the other neuron [or initial input] that the input to this neuron is connected to multiplied by the synaptic strength of that connection).
- If this sum of weighted inputs is greater than the firing threshold for this neuron, set the output of this neuron = 1, otherwise set it to 0.

To Train the Neural Net

- Run repeated recognition trials on sample problems.
- After each trial, adjust the synaptic strengths of all the interneuronal connections to improve the performance of the neural net on this trial (see the discussion below on how to do this).
- Continue this training until the accuracy rate of the neural net is no longer improving (i.e., reaches an asymptote).

Key Design Decisions

In the simple schema above, the designer of this neural-net algorithm needs to determine at the outset:

- What the input numbers represent.
- The number of layers of neurons.
- The number of neurons in each layer. (Each layer does not necessarily need to have the same number of neurons.)
- The number of inputs to each neuron in each layer. The number of inputs (i.e., interneuronal connections) can also vary from neuron to neuron and from layer to layer.
- The actual "wiring" (i.e., the connections). For each neuron in each layer, this consists of a list of other neurons, the outputs of which constitute the

inputs to this neuron. This represents a key design area. There are a number of possible ways to do this:

(i) Wire the neural net randomly; or
(ii) Use an evolutionary algorithm (see below) to determine an optimal wiring; or
(iii) Use the system designer's best judgment in determining the wiring.

- The initial synaptic strengths (i.e., weights) of each connection. There are a number of possible ways to do this:

(i) Set the synaptic strengths to the same value; or
(ii) Set the synaptic strengths to different random values; or
(iii) Use an evolutionary algorithm to determine an optimal set of initial values; or
(iv) Use the system designer's best judgment in determining the initial values.

- The firing threshold of each neuron.
- The output. The output can be:

(i) the outputs of $layer_M$ of neurons; or
(ii) the output of a single output neuron, the inputs of which are the outputs of the neurons in $layer_M$; or
(iii) a function of (e.g., a sum of) the outputs of the neurons in $layer_M$; or
(iv) another function of neuron outputs in multiple layers.

- How the synaptic strengths of all the connections are adjusted during the training of this neural net. This is a key design decision and is the subject of a great deal of research and discussion. There are a number of possible ways to do this:

(i) For each recognition trial, increment or decrement each synaptic strength by a (generally small) fixed amount so that the neural net's output more closely matches the correct answer. One way to do this is to try both incrementing and decrementing and see which has the more desirable effect. This can be time-consuming, so other methods exist for making local decisions on whether to increment or decrement each synaptic strength.
(ii) Other statistical methods exist for modifying the synaptic strengths after each recognition trial so that the performance of the neural net on that trial more closely matches the correct answer.

Note that neural-net training will work even if the answers to the training trials are not all correct. This allows using real-world training data that may have an inherent error rate. One key to the success of a neural net–based recognition system is the amount of data used for training. Usually a very substantial amount is needed to obtain satisfactory results. Just like human students, the amount of time that a neural net spends learning its lessons is a key factor in its performance.

Variations

Many variations of the above are feasible:

- There are different ways of determining the topology. In particular, the interneuronal wiring can be set either randomly or using an evolutionary algorithm.
- There are different ways of setting the initial synaptic strengths.
- The inputs to the neurons in $layer_i$ do not necessarily need to come from the outputs of the neurons in $layer_{i-1}$. Alternatively, the inputs to the neurons in each layer can come from any lower layer or any layer.
- There are different ways to determine the final output.
- The method described above results in an "all or nothing" (1 or 0) firing called a nonlinearity. There are other nonlinear functions that can be used. Commonly a function is used that goes from 0 to 1 in a rapid but more gradual fashion. Also, the outputs can be numbers other than 0 and 1.
- The different methods for adjusting the synaptic strengths during training represent key design decisions.

The above schema describes a "synchronous" neural net, in which each recognition trial proceeds by computing the outputs of each layer, starting with $layer_0$ through $layer_M$. In a true parallel system, in which each neuron is operating independently of the others, the neurons can operate "asynchronously" (that is, independently). In an asynchronous approach, each neuron is constantly scanning its inputs and fires whenever the sum of its weighted inputs exceeds its threshold (or whatever its output function specifies).

173. See chapter 4 for a detailed discussion of brain reverse engineering. As one example of the progression, S. J. Thorpe writes: "We have really only just begun what will certainly be a long term project aimed at reverse engineering the primate visual system. For the moment, we have only explored some very simple architectures, involving essentially just feed-forward architectures involving a relatively small numbers of layers. . . . In the years to come, we will strive to incorporate as many of the computational tricks used by the primate and human visual system as possible. More to the point, it seems that by adopting the spiking neuron approach, it will soon be possible to develop sophisticated systems capable of simulating very large neuronal networks in real time." S. J. Thorpe et al., "Reverse Engineering of the Visual System Using Networks of Spiking Neurons," *Proceedings of the IEEE 2000 International Symposium on Circuits and Systems* IV (IEEE Press), pp. 405–8, http://www.sccn.ucsd.edu/~arno/mypapers/thorpe.pdf.

174. T. Schoenauer et al. write: "Over the past years a huge diversity of hardware for artificial neural networks (ANN) has been designed. . . . Today one can choose from a wide range of neural network hardware. Designs differ in terms of architectural approaches, such as neurochips, accelerator boards and multi-board neurocomputers, as well as concerning the purpose of the system, such as the ANN algorithm(s) and the system's versatility. . . . Digital neurohardware can be classified by the:[*sic*] system architecture, degree of parallelism, typical neural network partition per processor, inter-processor communication network and numerical representation." T. Schoenauer, A. Jahnke, U. Roth, and H. Klar, "Digital Neurohardware: Principles and Perspectives," in *Proc. Neuronale Netze in der Anwendung*—Neural Networks in Applications NN'98, Magdeburg, invited paper (February 1998): 101–6, http://bwrc.eecs.berkeley.edu/People/kcamera/neural/papers/schoenauer98digital.pdf. See also Yihua Liao, "Neural Networks in Hardware: A Survey" (2001), http://ailab.das.ucdavis.edu/~yihua/research/NNhardware.pdf.
175. Here is the basic schema for a genetic (evolutionary) algorithm. Many variations are possible, and the designer of the system needs to provide certain critical parameters and methods, detailed below.

THE EVOLUTIONARY ALGORITHM

Create N solution "creatures." Each one has:

- A genetic code: a sequence of numbers that characterize a possible solution to the problem. The numbers can represent critical parameters, steps to a solution, rules, etc.

For each generation of evolution, do the following:

- Do the following for each of the N solution creatures:

  (i) Apply this solution creature's solution (as represented by its genetic code) to the problem, or simulated environment.
  (ii) Rate the solution.

- Pick the L solution creatures with the highest ratings to survive into the next generation.
- Eliminate the (N − L) nonsurviving solution creatures.
- Create (N − L) new solution creatures from the L surviving solution creatures by:

  (i) Making copies of the L surviving creatures. Introduce small random variations into each copy; or
  (ii) Creating additional solution creatures by combining parts of the genetic code (using "sexual" reproduction, or otherwise combining portions of the chromosomes) from the L surviving creatures; or
  (iii) Doing a combination of (i) and (ii).

- Determine whether or not to continue evolving:

Improvement = (highest rating in this generation) – (highest rating in the previous generation).
If Improvement < Improvement Threshold, then we're done.

- The solution creature with the highest rating from the last generation of evolution has the best solution. Apply the solution defined by its genetic code to the problem.

Key Design Decisions

In the simple schema above, the designer needs to determine at the outset:

- Key parameters:
  N
  L
  Improvement threshold
- What the numbers in the genetic code represent and how the solution is computed from the genetic code.
- A method for determining the N solution creatures in the first generation. In general, these need only be "reasonable" attempts at a solution. If these first-generation solutions are too far afield, the evolutionary algorithm may have difficulty converging on a good solution. It is often worthwhile to create the initial solution creatures in such a way that they are reasonably diverse. This will help prevent the evolutionary process from just finding a "locally" optimal solution.
- How the solutions are rated.
- How the surviving solution creatures reproduce.

Variations

Many variations of the above are feasible. For example:

- There does not need to be a fixed number of surviving solution creatures (L) from each generation. The survival rule(s) can allow for a variable number of survivors.
- There does not need to be a fixed number of new solution creatures created in each generation (N − L). The procreation rules can be independent of the size of the population. Procreation can be related to survival, thereby allowing the fittest solution creatures to procreate the most.
- The decision as to whether or not to continue evolving can be varied. It can consider more than just the highest-rated solution creature from the most recent generation(s). It can also consider a trend that goes beyond just the last two generations.

176. Sam Williams, "When Machines Breed," August 12, 2004, http://www.salon.com/tech/feature/2004/08/12/evolvable_hardware/index_np.html.
177. Here is the basic scheme (algorithm description) of recursive search. Many varia-

tions are possible, and the designer of the system needs to provide certain critical parameters and methods, detailed below.

THE RECURSIVE ALGORITHM
Define a function (program) "Pick Best Next Step." The function returns a value of "SUCCESS" (we've solved the problem) or "FAILURE" (we didn't solve it). If it returns with a value of SUCCESS, then the function also returns the sequence of steps that solved the problem.

PICK BEST NEXT STEP does the following:

- Determine if the program can escape from continued recursion at this point. This bullet, and the next two bullets deal with this escape decision.

  First, determine if the problem has now been solved. Since this call to Pick Best Next Step probably came from the program calling itself, we may now have a satisfactory solution. Examples are:

(i) In the context of a game (for example, chess), the last move allows us to win (such as checkmate).
(ii) In the context of solving a mathematical theorem, the last step proves the theorem.
(iii) In the context of an artistic program (for example, a computer poet or composer), the last step matches the goals for the next word or note.

If the problem has been satisfactorily solved, the program returns with a value of "SUCCESS" and the sequence of steps that caused the success.

- If the problem has not been solved, determine if a solution is now hopeless. Examples are:

(i) In the context of a game (such as chess), this move causes us to lose (checkmate for the other side).
(ii) In the context of solving a mathematical theorem, this step violates the theorem.
(iii) In the context of an artistic creation, this step violates the goals for the next word or note.

If the solution at this point has been deemed hopeless, the program returns with a value of "FAILURE."

- If the problem has been neither solved nor deemed hopeless at this point of recursive expansion, determine whether or not the expansion should be abandoned anyway. This is a key aspect of the design and takes into consideration the limited amount of computer time we have to spend. Examples are:

(i) In the context of a game (such as chess), this move puts our side sufficiently "ahead" or "behind." Making this determination may not be straightforward and is the primary design decision. However, simple approaches (such as adding up piece values) can still provide good results. If the program determines that our side is sufficiently ahead, then Pick Best Next Step returns in a similar manner to a determination that our side has won (that is, with a value of "SUCCESS"). If the program determines that our side is sufficiently behind, then Pick Best Next Step returns in a similar manner to a determination that our side has lost (that is, with a value of "FAILURE").

(ii) In the context of solving a mathematical theorem, this step involves determining if the sequence of steps in the proof is unlikely to yield a proof. If so, then this path should be abandoned, and Pick Best Next Step returns in a similar manner to a determination that this step violates the theorem (that is, with a value of "FAILURE"). There is no "soft" equivalent of success. We can't return with a value of "SUCCESS" until we have actually solved the problem. That's the nature of math.

(iii) In the context of an artistic program (such as a computer poet or composer), this step involves determining if the sequence of steps (such as the words in a poem, notes in a song) is unlikely to satisfy the goals for the next step. If so, then this path should be abandoned, and Pick Best Next Step returns in a similar manner to a determination that this step violates the goals for the next step (that is, with a value of "FAILURE").

- If Pick Best Next Step has not returned (because the program has neither determined success nor failure nor made a determination that this path should be abandoned at this point), then we have not escaped from continued recursive expansion. In this case, we now generate a list of all possible next steps at this point. This is where the precise statement of the problem comes in:

(i) In the context of a game (such as chess), this involves generating all possible moves for "our" side for the current state of the board. This involves a straightforward codification of the rules of the game.

(ii) In the context of finding a proof for a mathematical theorem, this involves listing the possible axioms or previously proved theorems that can be applied at this point in the solution.

(iii) In the context of a cybernetic art program, this involves listing the possible words/notes/line segments that could be used at this point.

For each such possible next step:

(i) Create the hypothetical situation that would exist if this step were implemented. In a game, this means the hypothetical state of the board. In a mathematical proof, this means adding this step (for example, axiom) to the proof. In an art program, this means adding this word/note/line segment.
(ii) Now call Pick Best Next Step to examine this hypothetical situation. This is, of course, where the recursion comes in because the program is now calling itself.
(iii) If the above call to Pick Best Next Step returns with a value of "SUCCESS," then return from the call to Pick Best Next Step (that we are now in) also with a value of "SUCCESS." Otherwise consider the next possible step.

If all the possible next steps have been considered without finding a step that resulted in a return from the call to Pick Best Next Step with a value of "SUCCESS," then return from this call to Pick Best Next Step (that we are now in) with a value of "FAILURE."

End of PICK BEST NEXT STEP
If the original call to Pick Best Next Move returns with a value of "SUCCESS," it will also return the correct sequence of steps:

(i) In the context of a game, the first step in this sequence is the next move you should make.
(ii) In the context of a mathematical proof, the full sequence of steps is the proof.
(iii) In the context of a cybernetic art program, the sequence of steps is your work of art.

If the original call to Pick Best Next Step returns with a value of "FAILURE," then you need to go back to the drawing board.

Key Design Decisions
In the simple schema above, the designer of the recursive algorithm needs to determine the following at the outset:

- The key to a recursive algorithm is the determination in Pick Best Next Step of when to abandon the recursive expansion. This is easy when the program has achieved clear success (such as checkmate in chess or the requisite solution in a math or combinatorial problem) or clear failure. It is more difficult when a clear win or loss has not yet been achieved. Abandoning a line of inquiry before a well-defined outcome is necessary because otherwise the program might run for billions of years (or at least until the warranty on your computer runs out).
- The other primary requirement for the recursive algorithm is a straight-

forward codification of the problem. In a game like chess, that's easy. But in other situations, a clear definition of the problem is not always so easy to come by.

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179. Ben Goertzel: *The Structure of Intelligence* (New York: Springer-Verlag, 1993); *The Evolving Mind* (Gordon and Breach, 1993); *Chaotic Logic* (Plenum, 1994); *From Complexity to Creativity* (Plenum, 1997). For a link to Ben Goertzel's books and essays, see http://www.goertzel.org/work.html.
180. KurzweilAI.net (http://www.KurzweilAI.net) provides hundreds of articles by one hundred "big thinkers" and other features on "accelerating intelligence." The site offers a free daily or weekly newsletter on the latest developments in the areas covered by this book. To subscribe, enter your e-mail address (which is maintained in strict confidence and is not shared with anyone) on the home page.
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    Average atomic weight of carbon (adjusting for isotope ratios) = 12.011.

    Carbon in the biomass = 1.55×10^{22} grams / 12.011 = 1.3×10^{21} mols.

    $1.3 \times 10^{21} \times 6.02 \times 10^{23}$ (Avogadro's number) = 7.8×10^{44} carbon atoms.

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    2. Evaluate risk according to available science, not popular perception, and allow for common reasoning biases.
    3. Give precedence to ameliorating known and proven threats to human health and environmental quality over acting against hypothetical risks.
    4. Treat technological risks on the same basis as natural risks; avoid underweighting natural risks and overweighting human-technological risks. Fully account for the benefits of technological advances.
    5. Estimate the lost opportunities of abandoning a technology, and take into account the costs and risks of substituting other credible options, carefully considering widely distributed effects and follow-on effects.

6. Consider restrictive measures only if the potential impact of an activity has both significant probability and severity. In such cases, if the activity also generates benefits, discount the impacts according to the feasibility of adapting to the adverse effects. If measures to limit technological advance do appear justified, ensure that the extent of those measures is proportionate to the extent of the probable effects.
7. When choosing among measures to restrict technological innovation, prioritize decision criteria as follows: Give priority to risks to human and other intelligent life over risks to other species; give non-lethal threats to human health priority over threats limited to the environment (within reasonable limits); give priority to immediate threats over distant threats; prefer the measure with the highest expectation value by giving priority to more certain over less certain threats, and to irreversible or persistent impacts over transient impacts.

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41. Larry Thompson, "Human Gene Therapy: Harsh Lessons, High Hopes," *FDA Consumer Magazine* (September–October 2000), http://www.fda.gov/fdac/features/2000/500_gene.html.
42. Bill Joy, "Why the Future Doesn't Need Us."
43. The Foresight Guidelines (Foresight Institute, version 4.0, October 2004, http://www.foresight.org/guidelines/current.html) are designed to address the potential positive and negative consequences of nanotechnology. They are intended to inform citizens, companies, and governments, and provide specific guidelines to responsibly develop nanotechnology-based molecular manufacturing. The Foresight Guidelines were initially developed at the Institute Workshop on Molecular Nanotechnology Research Policy Guidelines, sponsored by the institute and the Institute for Molecular Manufacturing (IMM), February 19–21, 1999. Participants included James Bennett, Greg Burch, K. Eric Drexler, Neil Jacobstein, Tanya Jones, Ralph Merkle, Mark Miller, Ed Niehaus, Pat Parker, Christine Peterson, Glenn Reynolds, and Philippe Van Nedervelde. The guidelines have been updated several times.
44. Martine Rothblatt, CEO of United Therapeutics, has proposed replacing this moratorium with a regulatory regime in which a new International Xenotransplantation Authority inspects and approves pathogen-free herds of genetically engineered pigs as acceptable sources of xenografts. Rothblatt's solution also helps stamp out rogue xenograft surgeons by promising each country that joins the IXA, and helps to enforce the rules within its borders, a fair share of the pathogen-free xenografts for its own citizens suffering from organ failure. See Martine Roth-

blatt, "Your Life or Mine: Using Geoethics to Resolve the Conflict Between Public and Private Interests," in *Xenotransplantation* (Burlington, Vt.: Ashgate, 2004). Disclosure: I am on the board of directors of United Therapeutics.

45. See Singularity Institute, http://www.singinst.org. Also see note 30 above. Yudkowsky formed the Singularity Institute for Artificial Intelligence (SIAI) to develop "Friendly AI," intended to "create cognitive content, design features, and cognitive architectures that result in benevolence" before near-human or better-than-human AIs become possible. SIAI has developed The SIAI Guidelines on Friendly AI: "Friendly AI," http://www.singinst.org/friendly/. Ben Goertzel and his Artificial General Intelligence Research Institute have also examined issues related to developing friendly AI; his current focus is on developing the Novamente AI Engine, a set of learning algorithms and architectures. Peter Voss, founder of Adaptive A.I., Inc., has also collaborated on friendly-AI issues: http://adaptive ai.com/.
46. Integrated Fuel Cell Technologies, http://ifctech.com. Disclosure: The author is an early investor in and adviser to IFCT.
47. *New York Times,* September 23, 2003, editorial page.
48. The House Committee on Science of the U.S. House of Representatives held a hearing on April 9, 2003, to "examine the societal implications of nanotechnology and H.R. 766, the Nanotechnology Research and Development Act of 2002." See "Full Science Committee Hearing on the Societal Implications of Nanotechnology," http://www.house.gov/science/hearings/full03/index.htm, and "Hearing Transcript," http://commdocs.house.gov/committees/science/hsy86340.000/hsy86340_0f.htm. For Ray Kurzweil's testimony, see also http://www.KurzweilAI.net/meme/frame.html?main=/articles/art0556.html. Also see Amara D. Angelica, "Congressional Hearing Addresses Public Concerns About Nanotech," April 14, 2003, http://www.KurzweilAI.net/articles/art0558.html.

Chapter Nine: Response to Critics

1. Michael Denton, "Organism and Machine," in Jay W. Richards et al., *Are We Spiritual Machines? Ray Kurzweil vs. the Critics of Strong A.I.* (Seattle: Discovery Institute Press, 2002), http://www.KurzweilAI.net/meme/frame.html?main=/articles/art0502.html.
2. Jaron Lanier, "One Half of a Manifesto," *Edge* (September 25, 2000), http://www.edge.org/documents/archive/edge74.html.
3. Ibid.
4. See chapters 5 and 6 for examples of narrow AI now deeply embedded in our modern infrastructure.
5. Lanier, "One Half of a Manifesto."
6. An example is Kurzweil Voice, developed originally by Kurzweil Applied Intelligence.
7. Alan G. Ganek, "The Dawning of the Autonomic Computing Era," *IBM Systems*

Journal (March 2003), http://www.findarticles.com/p/articles/mi_m0ISJ/is_1_42/ai_98695283/print.

8. Arthur H. Watson and Thomas J. McCabe, "Structured Testing: A Testing Methodology Using the Cyclomatic Complexity Metric," NIST special publication 500–35, Computer Systems Laboratory, National Institute of Standards and Technology, 1996.
9. Mark A. Richards and Gary A. Shaw, "Chips, Architectures and Algorithms: Reflections on the Exponential Growth of Digital Signal Processing Capability," submitted to *IEEE Signal Processing,* December 2004.
10. Jon Bentley, "Programming Pearls," *Communications of the ACM* 27.11 (November 1984): 1087–92.
11. C. Eldering, M. L. Sylla, and J. A. Eisenach, "Is There a Moore's Law for Bandwidth," *IEEE Communications* (October 1999): 117–21.
12. J. W. Cooley and J. W. Tukey, "An Algorithm for the Machine Computation of Complex Fourier Series," *Mathematics of Computation* 19 (April 1965): 297–301.
13. There are an estimated 100 billion neurons with an estimated interneuronal connection "fan out" of about 1,000, so there are about 100 trillion (10^{14}) connections. Each connection requires at least 70 bits to store an ID for the two neurons at either end of the connection. So that's approximately 10^{16} bits. Even the uncompressed genome is about 6 billion bits (about 10^{10}), a ratio of at least 10^6: 1. See chapter 4.
14. Robert A. Freitas Jr., *Nanomedicine*, vol. I, *Basic Capabilities*, section 6.3.4.2, "Biological Chemomechanical Power Conversion" (Georgetown, Tex.: Landes Bioscience, 1999), pp. 147–48, http://www.nanomedicine.com/NMI/6.3.4.2.htm#p4; see illustration at http://www.nanomedicine.com/NMI/Figures/6.2.jpg.
15. Richard Dawkins, "Why Don't Animals Have Wheels?" *Sunday Times*, November 24, 1996, http://www.simonyi.ox.ac.uk/dawkins/WorldOfDawkins-archive/Dawkins/Work/Articles/1996-11-24wheels.shtml.
16. Thomas Ray, "Kurzweil's Turing Fallacy," in Richards et al., *Are We Spiritual Machines?*
17. Ibid.
18. Anthony J. Bell, "Levels and Loops: The Future of Artificial Intelligence and Neuroscience," *Philosophical Transactions of the Royal Society of London B* 354 (1999): 2013–20, http://www.cnl.salk.edu/~tony/ptrsl.pdf.
19. Ibid.
20. David Dewey, "Introduction to the Mandelbrot Set," http://www.ddewey.net/mandelbrot.
21. Christof Koch quoted in John Horgan, *The End of Science* (Reading, Mass.: Addison-Wesley, 1996).
22. Roger Penrose, *Shadows of the Mind: A Search for the Missing Science of Consciousness* (New York: Oxford University Press, 1996); Stuart Hameroff and Roger Penrose, "Orchestrated Objective Reduction of Quantum Coherence in Brain

Microtubules: The 'Orch OR' Model for Consciousness," *Mathematics and Computer Simulation* 40 (1996): 453–80, http://www.quantumconsciousness.org/penrosehameroff/orchOR.html.
23. Sander Olson, "Interview with Seth Lloyd," November 17, 2002, http://www.nanomagazine.com/i.php?id=2002_11_17.
24. Bell, "Levels and Loops."
25. See the exponential growth of computing graphs in chapter 2 (pp. 67, 70).
26. Alfred N. Whitehead and Bertrand Russell, *Principia Mathematica,* 3 vols. (Cambridge, U.K.: Cambridge University Press, 1910, 1912, 1913).
27. Gödel's incompleteness theorem first appeared in his "Uber formal unenscheiderbare Satze der *Principia Mathematica* und verwandter Systeme I," *Monatshefte für Mathematik und Physik* 38 (1931): 173–98.
28. Alan M. Turing, "On Computable Numbers with an Application to the Entscheidungsproblem," *Proceedings of the London Mathematical Society* 42 (1936): 230–65. The "Entscheidungsproblem" is the decision or halting problem—that is, how to determine ahead of time whether an algorithm will halt (come to a decision) or continue in an infinite loop.
29. Church's version appeared in Alonzo Church, "An Unsolvable Problem of Elementary Number Theory," *American Journal of Mathematics* 58 (1936): 345–63.
30. For an entertaining introductory account of some of the implications of the Church-Turing thesis, see Douglas R. Hofstadter, *Gödel, Escher, Bach: An Eternal Golden Braid* (New York: Basic Books, 1979).
31. The busy-beaver problem is one example of a large class of noncomputable functions, as seen in Tibor Rado, "On Noncomputable Functions," *Bell System Technical Journal* 41.3 (1962): 877–84.
32. Ray, "Kurzweil's Turing Fallacy."
33. Lanier, "One Half of a Manifesto."
34. A human, that is, who is not asleep and not in a coma and of sufficient development (that is, not a prebrain fetus) to be conscious.
35. John R. Searle, "I Married a Computer," in Richards et al., *Are We Spiritual Machines?*
36. John R. Searle, *The Rediscovery of the Mind* (Cambridge, Mass.: MIT Press, 1992).
37. Hans Moravec, Letter to the Editor, *New York Review of Books,* http://www.kurzweiltech.com/Searle/searle_response_letter.htm.
38. John Searle to Ray Kurzweil, December 15, 1998.
39. Lanier, "One Half of a Manifesto."
40. David Brooks, "Good News About Poverty," *New York Times* November 27, 2004, A35.
41. Hans Moravec, Letter to the Editor, *New York Review of Books,* http://www.kurzweiltech.com/Searle/searle_response_letter.htm.
42. Patrick Moore, "The Battle for Biotech Progress—GM Crops Are Good for the

Environment and Human Welfare," *Greenspirit* (February 2004), http://www.greenspirit.com/logbook.cfm?msid=62.

43. Joel Cutcher-Gershenfeld, private communication to Ray Kurzweil, February 2005.
44. William A. Dembski, "Kurzweil's Impoverished Spirituality," in Richards et al., *Are We Spiritual Machines?*
45. Denton, "Organism and Machine."

Epilogue

1. As quoted in James Gardner, "Selfish Biocosm," *Complexity* 5.3 (January–February 2000): 34–45.
2. In the function $y = 1/x$, if $x = 0$, then the function is literally undefined, but we can show that the value of y exceeds any finite number. We can transform $y = 1/x$ into $x = 1/y$ by flipping the nominator and denominator of both sides of the equation. So if we set y to a large finite number, then we can see that x becomes very small but not zero, no matter how big y gets. So the value of y in $y = 1/x$ can be seen to exceed any finite value for y if $x = 0$. Another way to express this is that we can exceed any possible finite value of y by setting x to be greater than 0 but smaller than 1 divided by that value.
3. With estimates of 10^{16} cps for functional simulation of the human brain (see chapter 3) and about 10^{10} (under ten billion) human brains, that's 10^{26} cps for all biological human brains. So 10^{90} cps exceeds this by a factor of 10^{64}. If we use the more conservative figure of 10^{19} cps, which I estimated was necessary to simulate each nonlinearity in each neuron component (dendrite, axon, and so on), we get a factor of 10^{61}. A trillion trillion trillion trillion trillion is 10^{60}.
4. See the estimates in the preceding note; 10^{42} cps exceeds this by a factor of ten thousand trillion (10^{16}).
5. Stephen Jay Gould, "Jove's Thunderbolts," *Natural History* 103.10 (October 1994): 6–12; chapter 13 in *Dinosaur in a Haystack: Reflections in Natural History* (New York: Harmony Books, 1995).