BY THEODORE MODIS

Complexity and change have grown at accelerating rates throughout history, but they may soon reach a turning point. A scientist and strategic analyst offers a way to quantify complexity as it accumulates via world-changing events.

THE LIMITS OF

"Punk eek," or punctuated equilibrium, is the generally accepted idea that biological evolution has not been a continuous, uniform process, but rather has undergone well-defined jumps, or growth spurts, with periods of relative stability in between. With these bursts of change come an increase in complexity.

These bursts of change and increased complexity have become more frequent with time, and society now experiences an exponential growth pattern for change. But there are reasons to believe that the rate of change may soon slow down and that our children will experience less change during their lives than we have.

If you stop and think of the events that significantly influenced human evolution over the eons, you will realize that they have tended to crowd together historically as we approach the present. The twentieth century alone features more turning points in the history of mankind than the previous five centuries put together. Similarly, the last 2,000 years have more to show than the previous 10,000 years, and so on. The rapid appearance of evolutionary turning points has rendered our lives increasingly complex. The exponential growth pattern of change is striking and presents a challenge to ordinary people unable to adequately cope with it.

If this exponential pattern continues, we will reach levels of change and complexity that border on the absurd. More and more significant events will occur in less and less time. We could soon witness a parade of milestones comparable to those of the entire twentieth century pass in front of our eyes within seconds—if we are capable of perceiving them at all.

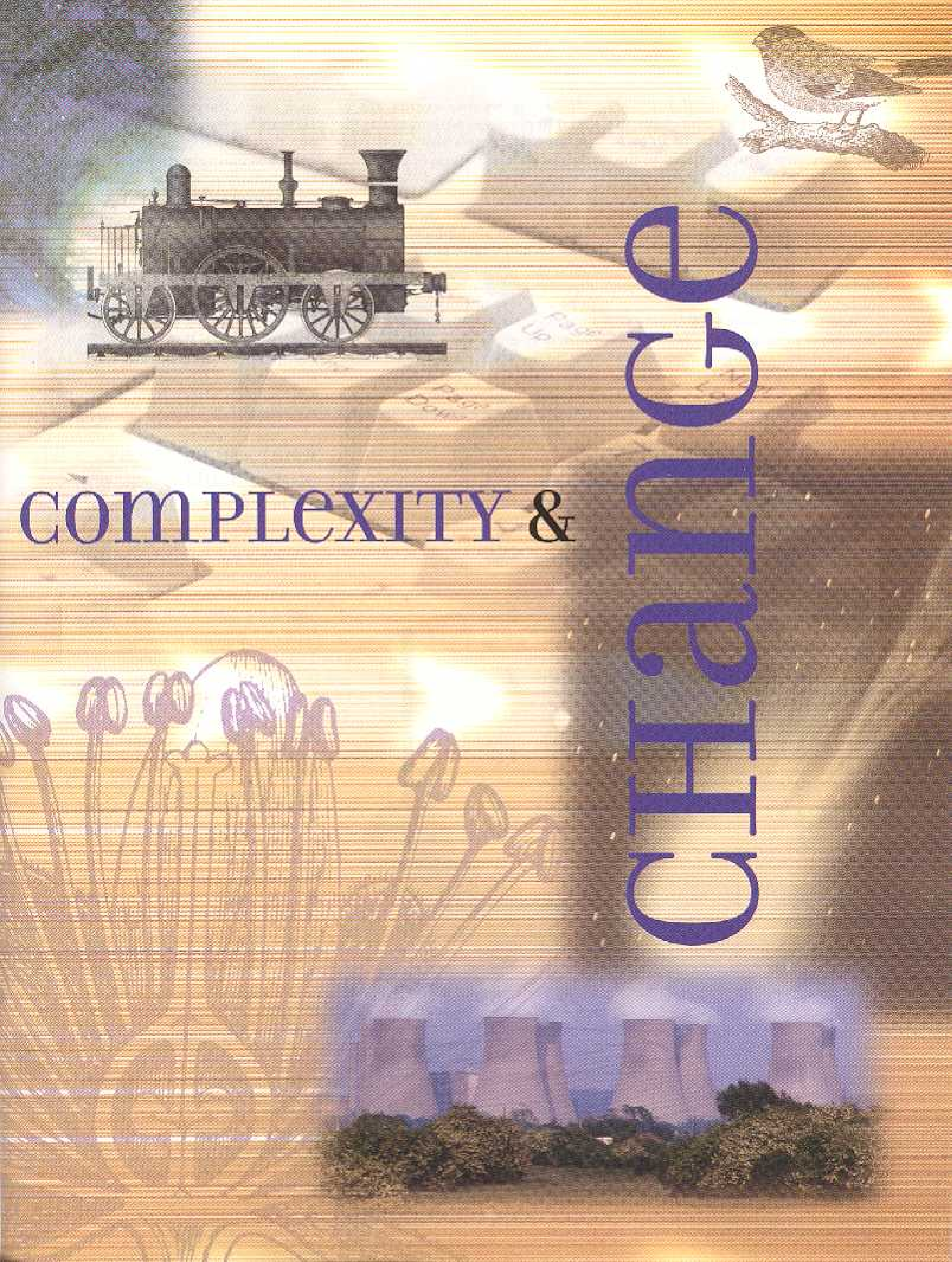
This impasse is intriguing and disturbing, and it warrants a closer examination of the explosive pattern of change. Change and complexity are intertwined. Complexity increases both when the rate of change increases and when the amount of things that are changing around us increases. Large amounts of change have appeared with every evolutionary jump of punk eek, when complexity also jumped. At every evolutionary turning point, be it the appearance of life on Earth, the acquisition of speech by *Homo sapiens*, or the invention of the printing press, the world's complexity increased by a certain amount. To quantify this amount we must be able to somehow *measure* complexity.

Evolution is a well-defined concept, but the term *complexity* remains today vague and unscientific. In his best-selling book *Out of Control*, Kevin Kelly concludes:

> How do we know one thing or process is more complex than another? Is a cucumber more complex than a Cadillac? Is a meadow more complex than a mammal brain? Is a zebra more complex than a national economy? I am aware of three or four mathematical definitions for complexity, none of them broadly useful in answering the type of questions I just asked.

Quantifying Complexity

It may yet be impossible to scientifically quantify the amount of complexity ingrained in the evolutionary steps of punk eek, but if we make certain assumptions, we could rate


COMPLEXITY &
CHANGE

the *relative* complexity that these steps contribute. It follows common sense that the importance of an evolutionary step is proportional to the amount of complexity it introduces. But an evolutionary step's importance is also proportional to the length of the ensuing stasis: The longer that the period of stability following a step is, the more importance we can attribute to that step historically:

Importance = Change in complexity x Duration of ensuing stasis

Therefore, among evolutionary steps that are of *equal* importance, we can rate their *relative* contribution to complexity according to their timing. (See Figure A.) The more they crowd together, the greater their complexity contribution. Thus it is possible to analyze quantitatively the complexity growth pattern of a set of equally important evolutionary milestones.

If two milestone events are of equal importance, we can assess the amount of complexity each contributes by the duration of the period of stasis that followed—a shorter stasis indicates more complexity.

The milestones in the history of the world that are topmost in significance certainly have large and therefore *comparable* importance. To a first approximation we can consider them to be of *equal* importance. We can then calculate the relative complexity contribution of each milestone; it will be inversely proportional to the time interval to the next milestone. By Pareto's rule—otherwise known as the 80/20 rule—the topmost significant milestones will be responsible for most of the world's complexity, and we can in a first pass ignore lesser events that took place in between.

A handful of most-important events must include the very first such event, the creation of the universe or big bang. But by extending our time horizon so far back, we span a seemingly disparate set of evolutionary processes—cosmological, geological, biological, sociological, and technological. There is no *a priori* reason that complexity grew according to the same law across all these processes. There are only indications from sets of milestones specific to each process that similar exponential patterns have been found everywhere. We need a set of milestones that covers the entire range to check whether the same growth law has been in effect from the very beginning.

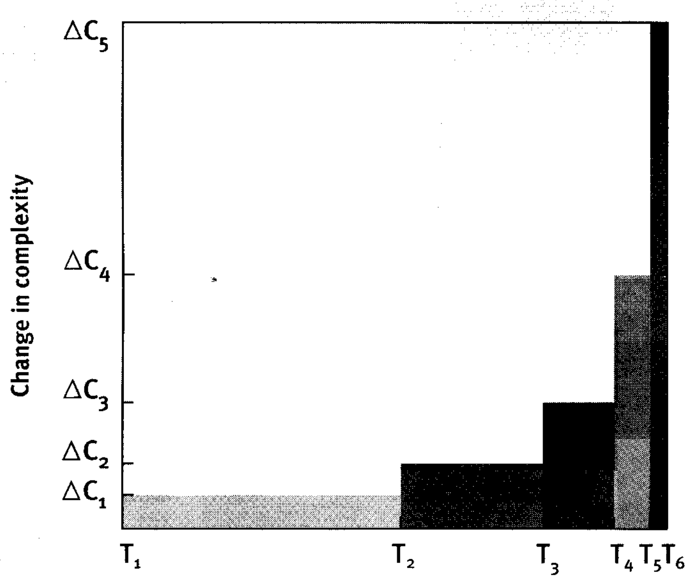


Figure A

Complexity compounds complexity. Milestone events occurring rapidly in succession will increase the amount of complexity added to the world at a faster rate. The area of each rectangle represents "Importance" and remains constant. Of two equally important milestones, the one with the shorter ensuing duration of stasis is the one that contributed more complexity. Thus, if we assume that the emergence of the first hominids (milestone 10—see Table 1 on page 29) and the invention of the steam engine (milestone 25) were equally "important," we can determine which one contributed more complexity by the duration of time until the next milestone event occurred. In this case, the steam engine added more complexity, with a stasis of just 125 years versus 12 million years following the first hominids.

What Are the Most Significant Milestones in History?

Answers to this question can be found in compilations of most-significant-milestones lists, a favorite intellectual pastime and object of diverse academic endeavors. A recent celebrated example is John Brockman's book *The Greatest Inventions of the Past 2,000 Years*. Others I have drawn from include lists compiled by the *National Geographic, Scientific American*, the *Encyclopaedia Britannica*, the American Museum of Natural History, and Carl Sagan's celebrated Cosmic Calendar, as well as individual scientists who responded directly to a questionnaire, including Nobel Prize–winning biochemist Paul D. Boyer.

Combining data from the most complete and reliable sets of milestones, I identified a total of 302 milestones spread over the last 20 billion years. They tend to coalesce in recent times, but also in clusters, as different authors may give different dates for the same event. The peak of each cluster serves as the "canonical" milestone date, and the spread around this peak is a measure of the uncertainty. I have identified a total of 28 canonical milestone dates up to the present time (which, for the sake of simplicity, I define as the year 2000). See Table 1, opposite.

Now we can study these 28 canon-
continued on page 30

TWENTY-EIGHT "CANONICAL" MILESTONES

TABLE 1 The 28 "canonical" milestones, listed in boldface, generally represent a cluster of many milestone events. The years given represent an average of all of the milestones contained in each cluster and are expressed in number of years before the present time (i.e., the year 2000).

1	**Big Bang** and associated processes: 15.5 billion years ago	15	**Domestication of fire, *Homo heidelbergensis*:** 325,000 years ago
2	**Origin of Milky Way,** first stars: 10 billion years ago	16	**Differentiation of human DNA types:** 200,000 years ago
3	**Origin of life on Earth,** formation of the solar system and the Earth, oldest rocks: 4 billion years ago	17	**Emergence of "modern humans,"** earliest burial of the dead: 105,700 years ago
4	**First eukaryotes,** invention of sex (by microorganisms), atmospheric oxygen, oldest photosynthetic plants, plate tectonics established: 2 billion years ago	18	**Rock art, protowriting:** 35,800 years ago
5	**First multicellular life** (sponges, seaweeds, protozoans): 1 billion years ago	19	**Invention of agriculture:** 19,200 years ago
6	**Cambrian explosion,** invertebrates, vertebrates, plants colonize land, first trees, reptiles, insects, amphibians: 430 million years ago	20	**Techniques for starting fire,** first cities: 11,000 years ago
7	**First mammals,** first birds, first dinosaurs, first use of tools: 210 million years ago	21	**Development of the wheel, writing,** archaic empires: 4,907 years ago
8	**First flowering plants,** oldest angiosperm fossil: 139 million years ago	22	**Democracy,** city-states, the Greeks, Buddha: 2,437 years ago
9	**Asteroid collision,** first primates, mass extinction (including dinosaurs): 54.6 million years ago	23	**Zero and decimals invented,** Rome falls, Moslem conquest: 1,440 years ago
10	**First hominids,** first humanoids: 28.5 million years ago	24	**Renaissance (printing press),** discovery of New World, the scientific method: 539 years ago
11	**First orangutan,** origin of proconsul: 16.5 million years ago	25	**Industrial revolution (steam engine),** political revolutions (France, USA): 225 years ago
12	**Chimpanzees and humans diverge,** earliest hominid bipedalism: 5.1 million years ago	26	**Modern physics,** radio, electricity, automobile, airplane: 100 years ago
13	**First stone tools,** first humans, Ice Age, *Homo erectus*, origin of spoken language: 2.2 million years ago	27	**DNA structure described, transistor invented, nuclear energy,** World War II, Cold War, Sputnik: 50 years ago
14	**Emergence of *Homo sapiens*:** 555,000 years ago	28	**Internet, human genome sequenced:** 5 years ago


HUBBLE SPACE TELESCOPE IMAGE / NASA


[illegible]


DON DAVIS / NASA

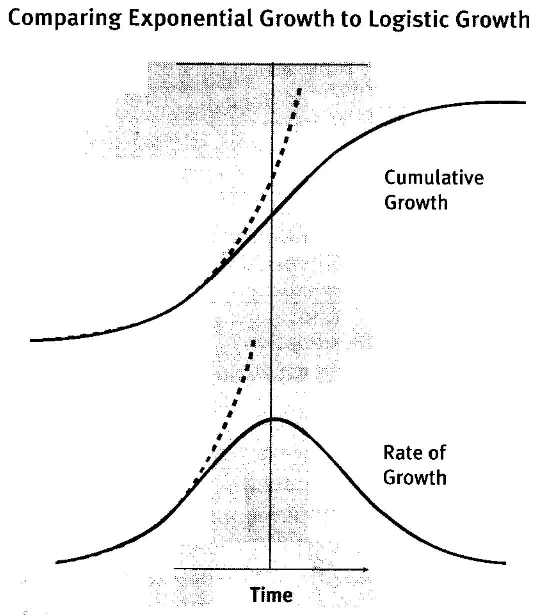


FIGURE B

Cumulative growth (e.g., a population) is shown on top. The rate of growth (increments per unit of time) is shown at the bottom. The question before us is whether change in complexity is exponential (dotted line) or logistic.

continued from page 28

ical milestone dates—history's most important growth spurts—to determine which law of growth, exponential or logistic, governs complexity, change, and our destiny.

THE BEGINNING OF EVERY S-CURVE IS EXPONENTIAL

The most natural of growth laws is the S-shaped, logistic curve, or S-curve. This pattern is characteristic of species population growing under Darwinian competition. For example, an S-curve pattern results when a pair of rabbits is left alone in a fenced-off range. If the average rabbit litter is taken as two, then we observe the rabbit population go through the successive stages of 2, 4, 8, 16, 32, 64, and so on—that is, exponential growth. There is a population explosion for a while. However, the food on their range is limited and can feed only a certain number of rabbits. As the population ap-

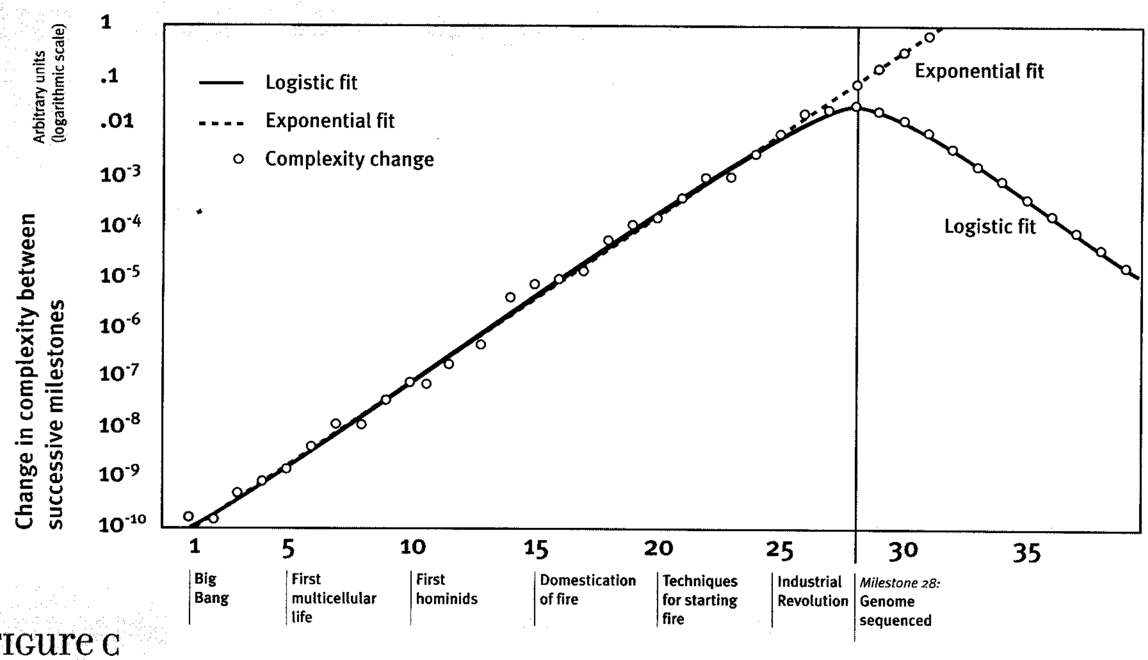


FIGURE C

Exponential and logistic fits to the data of the canonical milestone set. The vertical scale of arbitrary units is logarithmic (each point is 10 times larger than the next lower point), depicting the change in complexity at every milestone. The circles on the forecasted trends indicate the complexity change associated with future milestones. The vertical line between milestones 25 and 30 indicates the position of the most-recent milestone, for which we cannot yet determine a complexity contribution. If the next equally important milestone happens sooner rather than later, we will see complexity continuing to increase at an exponential growth rate. If it's delayed, complexity's growth will be slowing (logistic fit).

proaches this number, the growth rate must slow down. Eventually, the population stabilizes as the S-curve reaches a ceiling.

While growth in competition follows an S-shaped curve, its *rate* of growth follows a bell-shaped curve. The rate accelerates, peaks, then slows down. Originally used in biology, the bell curve illustrates that anything with life grows at a rate that crests halfway through the growth process and eventually subsides. In sharp contrast, the rate of growth of a *purely exponential* process follows an equally steep exponential pattern initially, but later, instead of subsiding, it explodes.

All S-curves begin exponentially, but no natural growth process remains exponential indefinitely. If we are indeed dealing with natural growth in competition, there will be a time when the initial explosive growth rate will begin slowing down and the exponential pattern will turn into an S-curve.

For the 28 canonical set of milestones, both exponential and logistic functions fit the data pattern, but the latter does a somewhat better job than the former. (See Figure C.)

According to the exponential law, the world's complexity should continue to increase at an increasing rate. In other words, evolutionary milestones should appear increasingly crowded: The next milestone should be in 13.4 years, the following one 6.3 years later, the one after that in 3 more years, the next in 1.4 years, and so on.

But if change and complexity follow the laws of natural growth—like the competitive behavior of rabbits in a fenced field—then we would see that complexity's rate of change has just reached a peak and will henceforth begin to decline. The midpoint of the logistic function is milestone number 27.89, which corresponds roughly to 1990, when complexity grew at the highest rate ever. From then onward, complexity's rate of change began decreasing, and future milestones will appear progressively less frequently. The next three milestones are due in intervals of 38, 45, and 69 years respectively.

For perspective, let us look at the three most-recent milestones.

TABLE 2

Forecasts for Complexity Change: How Soon till the Next Milestone?

Milestone Number	Logistic Fit Complexity Change*	Years	Exponential Fit Complexity Change*	Years
28	0.0265	38	0.0744	13.4
29	0.0223	45	0.1584	6.3
30	0.0146	69	0.3372	3.0
31	0.0081	124	0.7178	1.4
32	0.0041	245	1.5278	0.7
33	0.0020	508	3.2518	0.3
34	0.0009	1,078	6.9213	0.1
35	0.0004	2,315	14.7317	0.07
36	0.0002	5,000	31.3558	0.03
37	0.0001	10,800	66.7397	0.015

*In the same arbitrary units as Figure C.

Because an event's importance is inversely proportional to the period of ensuing stasis—a longer time between milestones—a slower rate of complexity growth means a longer lull to the next "punk eek" milestone (see Figure A).

The case can be made that both growth laws adequately describe the general pattern that complexity followed in its evolution. After all, the first half of the logistic function is very similar to an exponential function. The logistic rate of growth diverges significantly from an exponential during the second half of the life cycle, and the question becomes which law complexity will follow from now onward.

Present time is taken as year 2000:

- 5 years ago: Internet/human genome sequenced.
- 50 years ago: DNA/transistor/nuclear energy.
- 100 years ago: modern physics (radio, electricity, etc.)/automobile/airplane.

In other words, dates for world-shaking milestones like the above three should be expected around 2038, and then again around 2083 and 2152. Table 2 spells out the timing of future milestones as expected from the logistic and exponential growth laws determined by the above fits.

The Exponential Fiasco

The exponential pattern is so steep that around the year 2025 we would be witnessing the equivalent of all of the twentieth-century milestones in less than a week, and the rate of appearance of milestones would continue to increase. Sometime later, humans will become incapable of perceiving changes that take place in fractions of a second. Does it still make sense to talk in terms of change when no one perceives it?

A relatively young school of philosophical thought is built around the idea that life can be simulated in its entirety, including more-abstract notions such as consciousness, and that in some distant future computers will be able to do *everything* humans do and more. Computers are already capable of perceiving and exchanging information at rates much higher than those of humans. And it is expected that computers will still improve by much. It could be argued that machines will eventually take over control of the world if for no other reason than the fact that they would be able to handle the changes that are appearing at rates too fast for humans to perceive. The exponential growth pattern for the world's complexity could then be sustained, but for how long?

Not for too long, I am afraid. Machines, no matter how intelligent they become, will not be of help for too long. According to the exponential pattern, *all* of the change that will ever take place will have practically done so by 2028. In other words, people who will still be alive in 2028—i.e., the generation of people born in the mid-1940s or later—will be bystanders of all the change that can ever take place, even if they won't perceive most of it.

Alternatively, there may be something wrong with the question we are asking. Change growing indefinitely and exponentially may have no "physical" existence if it cannot be detected. The viable alternative suggested by Figure C—appropriately supported by a fit of slightly better quality—is that change would grow along an S-curve, whose life cycle is all ready halfway completed.

The Ultimate S-Curve

Figure C indicates that the evolution of complexity in the universe has been following a logistic growth pattern from the very beginning—the big bang. This is remarkable considering the vastness of the time scale, and also considering the fact that complexity resulted from very different evolutionary processes—planetary, biological, social, and technological. The S-curve has its inflection point—the time of the highest rate of change—around our own time. Considering the symmetry of the pattern, we can conclude that the end of the universe is roughly another 15 billion years away. Such a conclusion is not really at odds—considering the crudeness of its derivation—with recent scientific thinking. Despite new evidence that the universe may exist forever, there are widely accepted beliefs that our solar system will end some 5 billion years from now.

Two remarks are in order concerning the above S-curve analysis. First, the logistic function that usually has time as a variable now is expressed in terms of the consecutive milestone number, which effectively amounts to a logarithmic time scale. Our Euclidean conception of linear time does not seem appropriate for this kind of cosmic-scale evolution. Second, we are obviously adopting an anthropic approach here in the sense that we are overlooking how complexity may have evolved in other parts of the universe. Still, this analysis carries more weight than just the elegance and the simplicity of its formulation. The esteemed theoretical physicist John Wheeler has argued that the very validity of the laws of physics depends on the existence of consciousness. In a way, the human point of view is all that counts.

We Are Sitting on Top of the World

We saw earlier that the exponential growth pattern renders the present generation privileged by forecasting that all change possible will take place by 2028. But the life cycle of the S-curve also peaks during the lifetime of people born in the mid-1940s. In particular, it spells out that we are now traversing the only time period in the history of the universe in which 88 calendar years can witness changes coming from as many as three evolutionary milestones. We happen to be positioned at the world's prime. □

About the Author
Theodore Modis, formerly a researcher in high-energy physics at Brookhaven National Laboratories and at CERN, is a member of the faculty of the Duxx Graduate School in Business Leadership in Monterrey, Mexico. He has recently released a new, electronic edition of his first book, *Predictions: 10 Years Later,* in which he examines the outcomes of his forecasts.

His address is 2, rue Beau Site, Geneva 1203, Switzerland. E-mail tmodis@compuserve.com; Web site www.growth-dynamics.com.

The author thanks Nobel Prize–winning biochemist Paul D. Boyer and Eric L. Schwartz, professor of cognitive and neural systems at Boston University for their contributions. A longer version of this essay is available online at www.growth-dynamics.com.