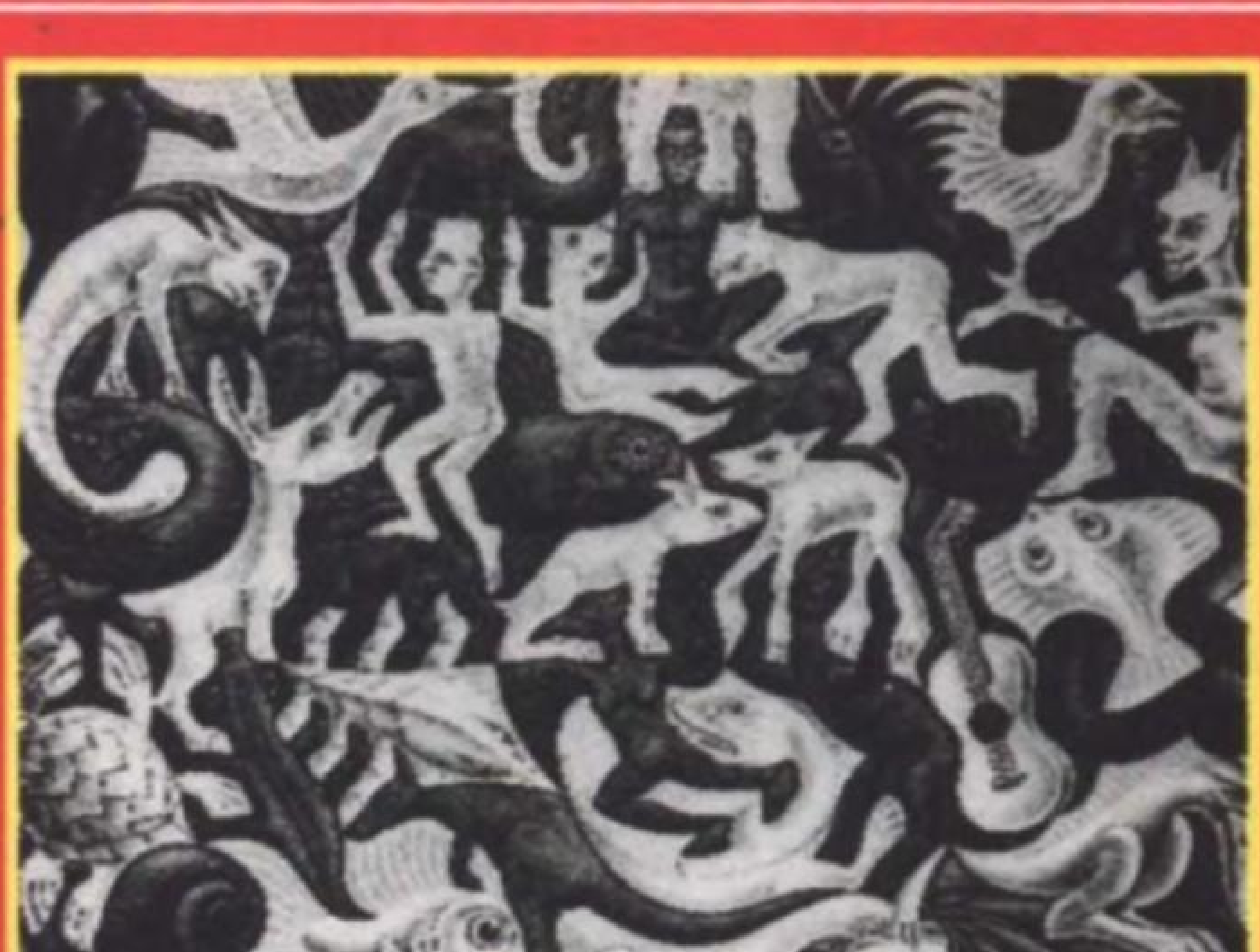
THE PULITZER PRIZE WINNER

CARL SAGAN

Coauthor of SHADOWS OF FORGOTTEN ANCESTORS

THE DRAGONS OF EDEN



SPECULATIONS ON THE EVOLUTION OF HUMAN INTELLIGENCE

"WILL LEAVE THE READER EXHILARATED AND TINGLING...A MASTERPIECE."
—*Chicago Tribune Book World*

THE DRAGONS OF EDEN

Speculations on the Evolution of Human Intelligence

Carl Sagan

BALLANTINE BOOKS · NEW YORK

A Ballantine Book
Published by The Random House Publishing Group

Published in the United States by Ballantine Books, an imprint of The Random House Publishing Group, a division of Random House, Inc., New York, and simultaneously in Canada by Random House of Canada Limited, Toronto.

www.ballantinebooks.com

Library of Congress Catalog Card Number: 76-53472

ISBN 0-345-34629-7

This edition published by arrangement with Random House, Inc.

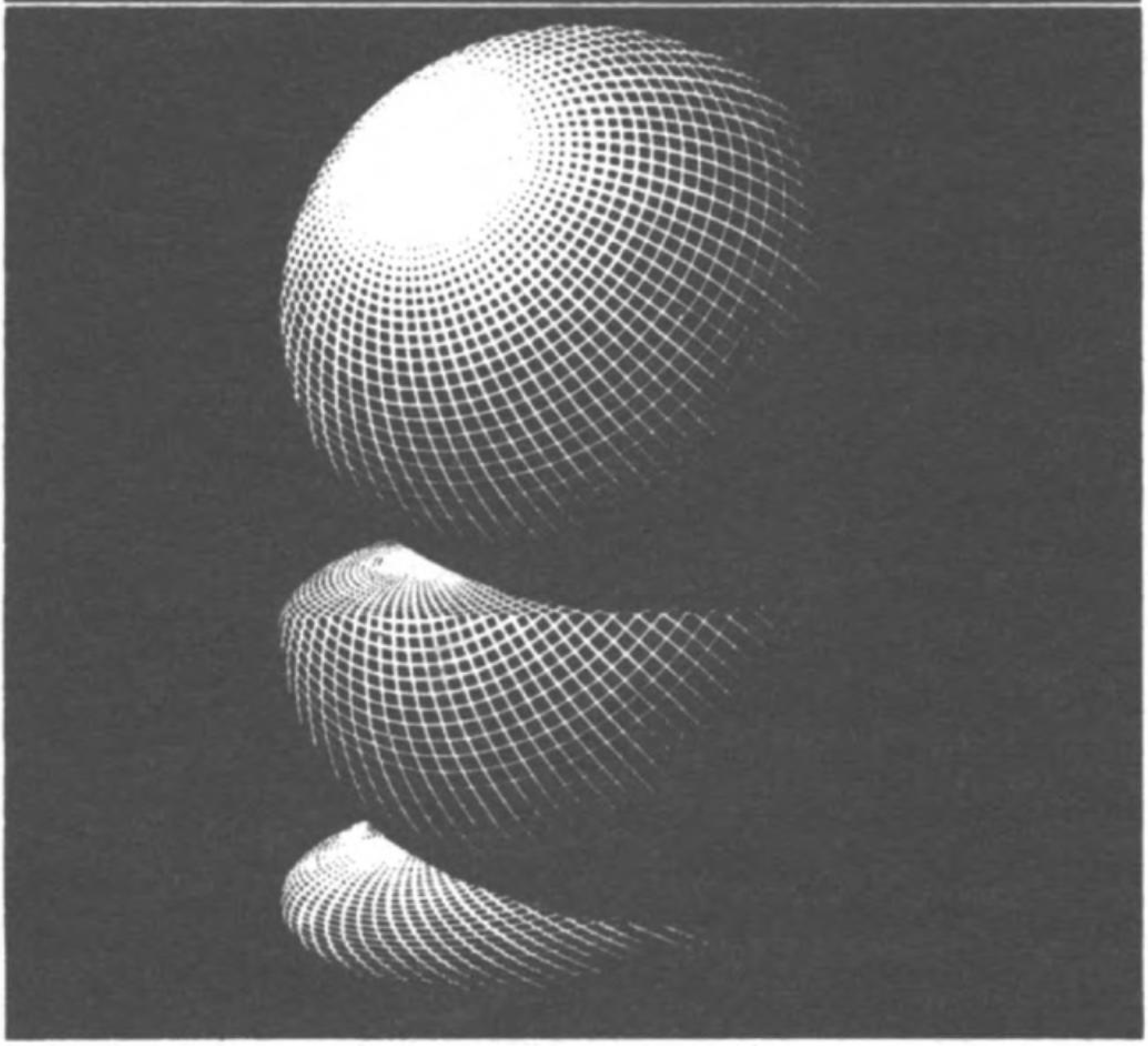
Manufactured in the United States of America

First Ballantine Books Edition: April 1978

OPM 49 48 47 46 45 44 43

Contents

Introduction



In good speaking, should not the mind of the speaker know the truth of the matter about which he is to speak?

PLATO
Phaedrus

I do not know where to find in any literature, whether ancient or modern, any adequate account of that nature with which I am acquainted. Mythology comes nearest to it of any.

HENRY DAVID THOREAU
The Journal

JACOB BRONOWSKI was one of a small group of men and women in any age who find all of human knowledge—the arts and sciences, philosophy and psychology—interesting and accessible. He was not confined to a single discipline, but ranged over the entire panorama of human learning. His book and television series, *The Ascent of Man*, are a superb teaching tool and a remarkable memorial; they are, in a way, an account of how human beings and human brains grew up together.

His last chapter/episode, called "The Long Childhood," describes the extended period of time—longer relative to our lifespan than for any other species—in which young humans are dependent on adults and exhibit immense plasticity—that is, the ability to learn from their environment and their culture. Most organisms on Earth depend on their genetic information, which is "prewired" into their nervous systems, to a much greater extent than they do on their extragenetic information, which is acquired during their lifetimes. For human beings, and indeed for all mammals, it is the other way around. While our behavior is still significantly controlled by our genetic inheritance, we have, through our brains, a much richer opportunity to blaze new behavioral and cultural pathways on short time scales. We have made a kind of bargain with nature: our children will be difficult to raise, but their capacity for new learning will greatly enhance the chances of survival of the human species. In addition, human beings have, in the most recent few tenths of a percent of our existence, invented not only extragenetic but also extrasomatic knowledge: information stored outside our bodies, of which writing is the most notable example.

The time scale for evolutionary or genetic change is very long. A characteristic period for the emergence of one advanced species from another is perhaps a hundred thousand years; and very often the difference in behavior between closely related species—say, lions and tigers—do not seem very great. An example of recent evolution of organ systems in humans is our toes. The big toe plays an important function in balance while walking; the other toes have much less obvious utility. They are clearly evolved from fingerlike appendages for grasping and swinging, like those of arboreal apes and monkeys. This evolution constitutes a respecialization—the adaptation of an organ system originally evolved for one function to another and quite different function—which required about ten million years to emerge. (The feet of the mountain gorilla have undergone a similar although quite independent evolution.)

But today we do not *have* ten million years to wait for the next advance. We live in a time when our world is changing at an unprecedented rate. While the changes are largely of our own making, they cannot be ignored. We must adjust and adapt and control, or we perish.

Only an extragenetic learning system can possibly cope with the swiftly changing circumstances that our species faces. Thus the recent rapid evolution of human intelligence is not only the cause of but also the only conceivable solution to the many serious problems that beset us. A better understanding of the nature and evolution of human intelligence just possibly might help us to deal intelligently with our unknown and perilous future.

I am interested in the evolution of intelligence for another reason as well. We now have at our command, for the first time in human history, a powerful tool—the large radio telescope—which is capable of communication over immense interstellar distances. We are just beginning to employ it in a halting and tentative manner, but with a perceptibly increasing pace, to determine whether other civilizations on unimaginably distant and exotic worlds may be sending radio messages to us. Both the existence of those other civilizations and the nature of the messages they may be sending depend on the universality of the process of evolution of intelligence that has occurred on Earth. Conceivably, some hints or insights helpful in the quest for extraterrestrial intelligence might be derived from an investigation of the evolution of terrestrial intelligence.

I was pleased and honored to deliver the first Jacob Bronowski Memorial Lecture in Natural Philosophy in November 1975, at the University of Toronto. In writing this book, I have expanded substantially the scope of that lecture, and have been in return provided with an exhilarating opportunity to learn something about subjects in which I am not expert. I found irresistible the temptation to synthesize some of what I learned into a coherent picture, and to tender some hypotheses on the nature and evolution of human intelligence that may be novel, or that at least have not been widely discussed.

The subject is a difficult one. While I have formal training in biology, and have worked for many years on the origin and early evolution of life, I have little formal education in, for example, the anatomy and physiology of the brain. Accordingly, I proffer the following ideas with a substantial degree of trepidation; I know very well that many of them are speculative and can be proved or disproved only on the anvil of experiment. At the very least, this inquiry has provided me with an opportunity to look into an entrancing subject; perhaps my remarks will stimulate others to look more deeply.

The great principle of biology—the one that, as far as we know, distinguishes the biological from the physical sciences—is evolution by natural selection, the brilliant discovery of Charles Darwin and Alfred Russel Wallace in the middle of the nineteenth century.* It is through natural selection, the preferential survival and replication of organisms that are by accident better adapted to their environments, that the elegance and beauty of contemporary life forms have emerged. The development of an organ system as complex as the brain must be inextricably tied to the earlier history of life, its fits and starts and dead ends, the tortuous adaptation of organisms to conditions that change once again, leaving the life form that once was supremely adapted again in danger of extinction. Evolution is adventitious and not foresighted. Only through the deaths of an immense number of slightly maladapted organisms are we, brains and all, here today.

Biology is more like history than it is like physics;

* Since the time of the famous Victorian debate between Bishop Wilberforce and T. H. Huxley, there has been a steady and notably unproductive barrage fired against the Darwin/Wallace ideas, often by those with doctrinal axes to grind. Evolution is a fact amply demonstrated by the fossil record and by contemporary molecular biology. Natural selection is a successful theory devised to explain the fact of evolution. For a very polite response to recent criticisms of natural selection, including the quaint view that it is a tautology ("Those who survive survive"), see the article by Gould (1976) listed in the references at the back of this book. Darwin was, of course, a man of his times and occasionally given—as in his remarks on the inhabitants of Tierra del Fuego quoted above—to self-congratulatory comparisons of Europeans with other peoples. In fact, human society in pretechnological times was much more like that of the compassionate, communal and cultured Bushman hunter-gatherers of the Kalahari Desert than the Fuegians Darwin, with some justification, derided. But the Darwinian insights—on the existence of evolution, on natural selection as its prime cause, and on the relevance of these concepts to the nature of human beings—are landmarks in the history of human inquiry, the more so because of the dogged resistance which such ideas evoked in Victorian England, as, to a lesser extent, they still do today.

the accidents and errors and lucky happenstances of the past powerfully prefigure the present. In approaching as difficult a biological problem as the nature and evolution of human intelligence, it seems to me at least prudent to give substantial weight to arguments derived from the evolution of the brain.

My fundamental premise about the brain is that its workings—what we sometimes call "mind"—are a consequence of its anatomy and physiology, and nothing more. "Mind" may be a consequence of the action of the components of the brain severally or collectively. Some processes may be a function of the brain as a whole. A few students of the subject seem to have concluded that, because they have been unable to isolate and localize all higher brain functions, no future generation of neuroanatomists will be able to achieve this objective. But absence of evidence is not evidence of absence. The entire recent history of biology shows that we are, to a remarkable degree, the results of the interactions of an extremely complex array of molecules; and the aspect of biology that was once considered its holy of holies, the nature of the genetic material, has now been fundamentally understood in terms of the chemistry of its constituent nucleic acids, DNA and RNA, and their operational agents, the proteins. There are many instances in science, and particularly in biology, where those closest to the intricacies of the subject have a more highly developed (and ultimately erroneous) sense of its intractability than those at some remove. On the other hand, those at too great a distance may, I am well aware, mistake ignorance for perspective. At any rate, both because of the clear trend in the recent history of biology and because there is not a shred of evidence to suport it, I will not in these pages entertain any hypotheses on what used to be called the mind-body dualism, the idea that inhabiting the matter of the body is something made of quite different stuff, called mind.

Part of the enjoyment and indeed delight of this subject is its contact with all areas of human endeavor, particularly with the possible interaction between insights obtained from brain physiology and insights obtained from human introspection. There is, fortunately, a long history of the latter, and in former times the richest, most intricate and most profound of these were called myths. "Myths," declared Salustius in the fourth century, "are things which never happened but always are." In the Platonic dialogues and *The Republic*, every time Socrates cranks up a myth—the parable of the cave, to take the most celebrated example—we know that we have arrived at something central.

I am not here employing the word "myth" in its present popular meaning of something widely believed and contrary to fact, but rather in its earlier sense, as a metaphor of some subtlety on a subject difficult to describe in any other way. Accordingly, I have interspersed in the discussion on the following pages occasional excursions into myths, ancient and modern. The title of the book itself comes from the unexpected aptness of several different myths, traditional and contemporary.

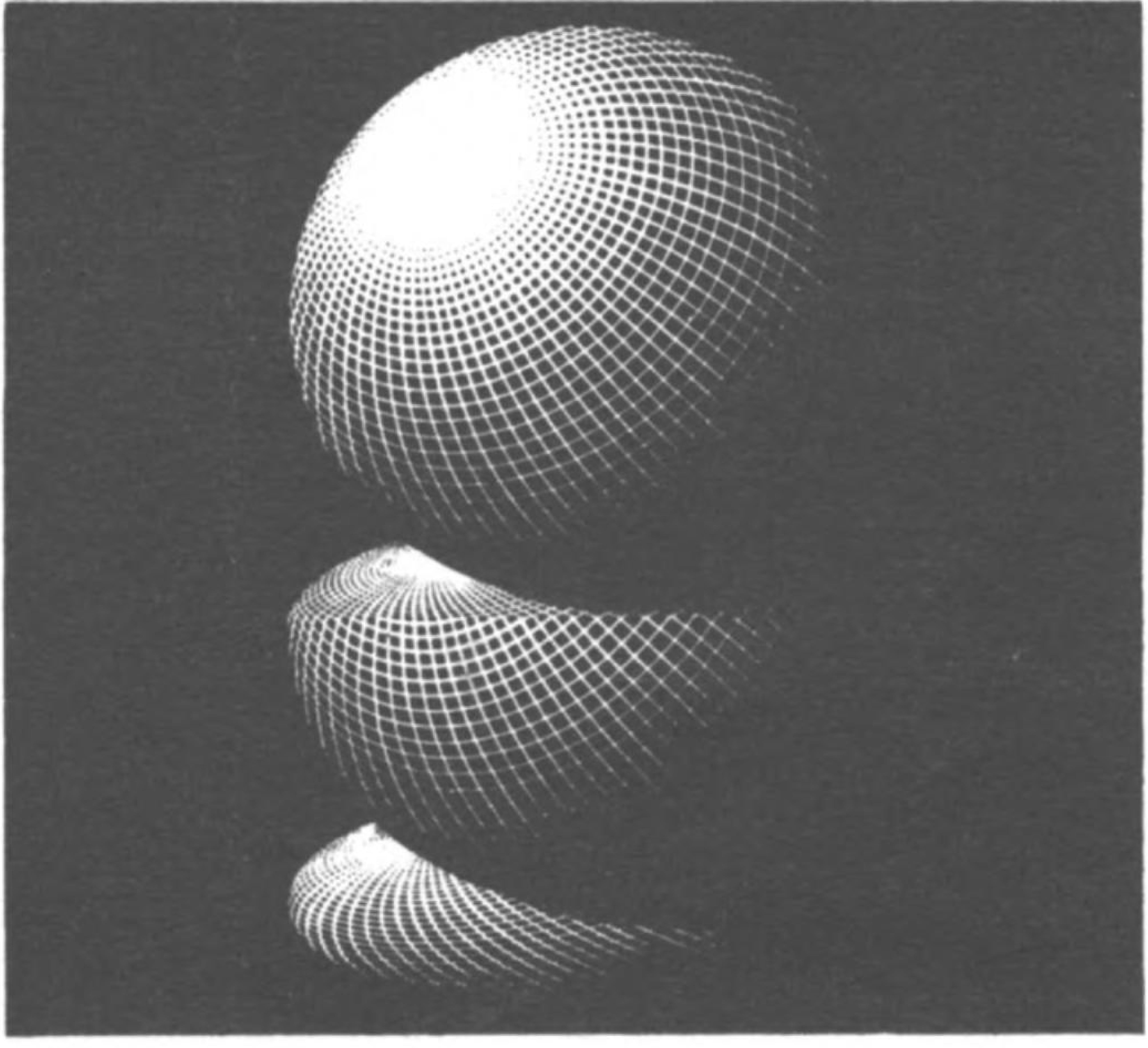
While I hope that some of my conclusions may be of interest to those whose profession is the study of human intelligence, I have written this book for the interested layman. Chapter 2 presents arguments of somewhat greater difficulty than the rest of this inquiry, but still, I hope, accessible with only a little effort. Thereafter, the book should be smooth sailing. Occasional technical terms are usually defined when first introduced, and are collected in the glossary. The figures and the glossary are additional tools to aid those with no formal background in science, although understanding my arguments and agreeing with them are not, I suspect, the same thing.

In 1754, Jean Jacques Rousseau, in the opening paragraph of his *Dissertation on the Origin and Foundation of the Inequity of Mankind,* wrote:

> Important as it may be, in order to judge rightly of the natural state of man, to consider him from his origin . . . I shall not follow his organization through its successive developments. . . . On this subject I could form none but vague and almost imaginary conjectures. Comparative anatomy has as yet made too little progress, and the observations of naturalists are too uncertain to afford an adequate basis for any solid reasoning.

Rousseau's cautions of more than two centuries ago are valid still. But there has been remarkable progress in investigating both comparative brain anatomy and animal and human behavior, which he correctly recognized as critical to the problem. It may not be premature today to attempt a preliminary synthesis.

1
THE COSMIC CALENDAR



What seest thou else
In the dark backward and abysm of
time?

WM. SHAKESPEARE
The Tempest

THE WORLD is very old, and human beings are very young. Significant events in our personal lives are measured in years or less; our lifetimes in decades; our family genealogies in centuries; and all of recorded history in millennia. But we have been preceded by an awesome vista of time, extending for prodigious periods into the past, about which we know little—both because there are no written records and because we have real difficulty in grasping the immensity of the intervals involved.

Yet we are able to date events in the remote past. Geological stratification and radioactive dating provide information on archaeological, palenotological and geological events; and astrophysical theory provides data on the ages of planetary surfaces, stars, and the Milky Way Galaxy, as well as an estimate of the time that has elapsed since that extraordinary event called the Big Bang—an explosion that involved all of the matter and energy in the present universe. The Big Bang may be the beginning of the universe, or it may be a discontinuity in which information about the earlier history of the universe was destroyed. But it is certainly the earliest event about which we have any record.

The most instructive way I know to express this cosmic chronology is to imagine the fifteen-billion-year lifetime of the universe (or at least its present incarnation since the Big Bang) compressed into the span of a single year. Then every billion years of Earth history would correspond to about twenty-four days of our cosmic year, and one second of that year to 475 real revolutions of the Earth about the sun. On pages 14 through 16 I present the cosmic chronology in three forms: a list of some representative pre-December dates; a calendar for the month of December; and a closer look at the late evening of New Year's Eve. On this scale, the events of our history books—even books that make significant efforts to deprovincialize the present—are so compressed that it is necessary to give a second-by-second recounting of the last seconds of the cosmic year. Even then, we find events listed as contemporary that we have been taught to consider as widely separated in time. In the history of life, an equally rich tapestry must have been woven in other periods—for example, between 10:02 and 10:03 on the morning of April 6th or September 16th. But we have detailed records only for the very end of the cosmic year.

The chronology corresponds to the best evidence now available. But some of it is rather shaky. No one would be astounded if, for example, it turns out that plants colonized the land in the Ordovician rather than the Silurian Period; or that segmented worms appeared earlier in the Precambrian Period than indicated. Also,

PRE-DECEMBER DATES

Big Bang	**January 1**
Origin of the Milky Way Galaxy	**May 1**
Origin of the solar system	**September 9**
Formation of the Earth	**September 14**
Origin of life on Earth	**~ September 25**
Formation of the oldest rocks known on Earth	**October 2**
Date of oldest fossils (bacteria and blue-green algae)	**October 9**
Invention of sex (by microorganisms)	**~ November 1**
Oldest fossil photosynthetic plants	**November 12**
Eukaryotes (first cells with nuclei) flourish	**November 15**

~ = *approximately*

COSMIC CALENDAR

DECEMBER

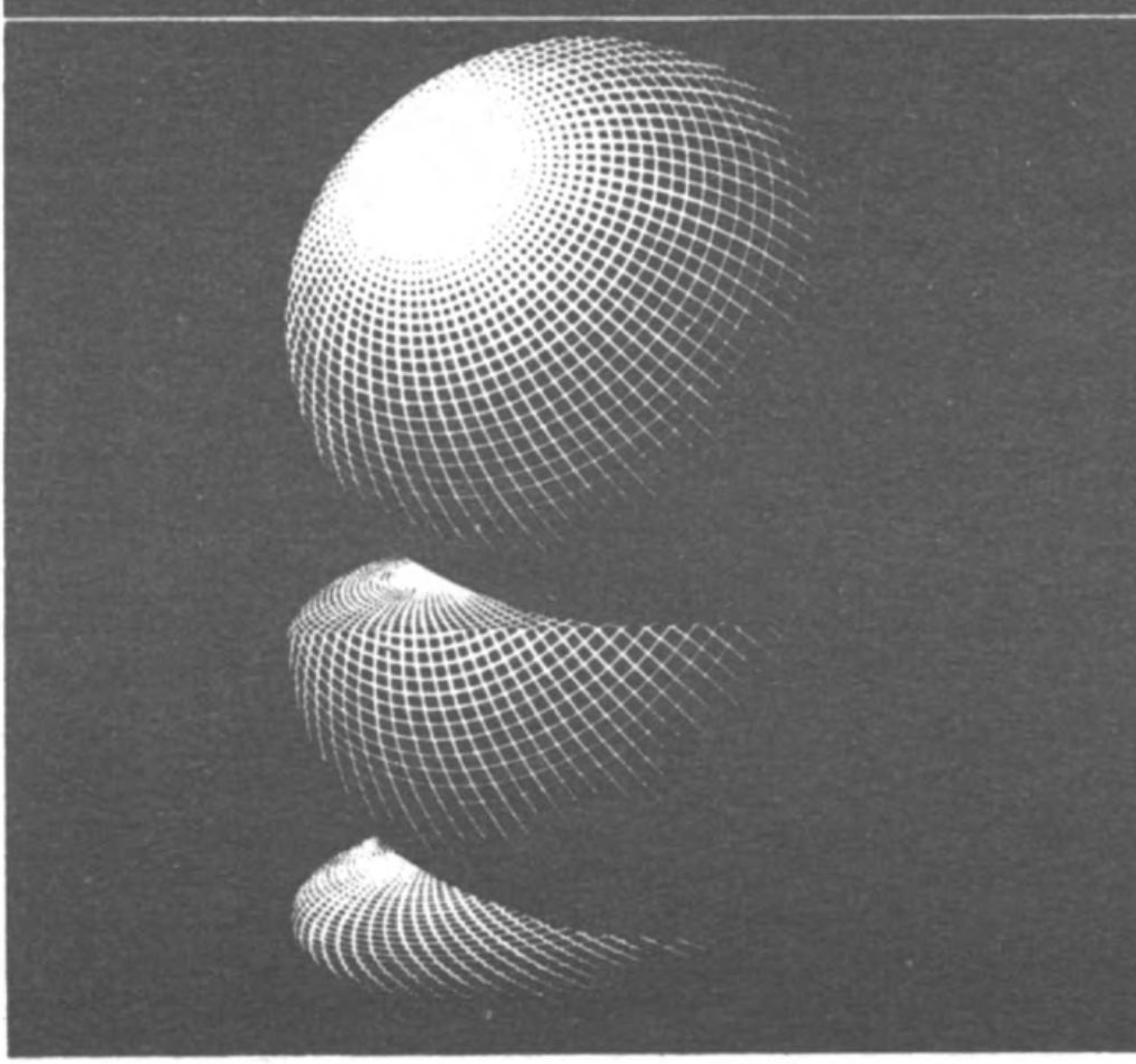
SUNDAY	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY
	1 Significant oxygen atmosphere begins to develop on Earth.	2	3	4	5 Extensive vulcanism and channel formation on Mars.	6
7	8	9	10	11	12	13
14	15	16 First worms.	17 Precambrian ends. Paleozoic Era and Cambrian Period begin. Invertebrates flourish.	18 First oceanic plankton. Trilobites flourish.	19 Ordovician Period. First fish, first vertebrates.	20 Silurian Period. First vascular plants. Plants begin colonization of land.
21 Devonian Period begins. First insects. Animals begin colonization of land.	22 First amphibians. First winged insects.	23 Carboniferous Period. First trees. First reptiles.	24 Permian Period begins. First dinosaurs.	25 Paleozoic Era ends. Mesozoic Era begins.	26 Triassic Period. First mammals.	27 Jurassic Period. First birds.
28 Cretaceous Period. First flowers. Dinosaurs become extinct.	29 Mesozoic Era ends. Cenozoic Era and Tertiary Period begin. First cetaceans. First primates.	30 Early evolution of frontal lobes in the brains of primates. First hominids. Giant mammals flourish.	31 End of the Pliocene Period. Quaternary (Pleistocene and Holocene) Period. First humans.			

DECEMBER 31	
Origin of *Proconsul* and *Ramapithecus*, probable ancestors of apes and men	~ 1:30 P.M.
First humans	~ 10:30 P.M.
Widespread use of stone tools	11:00 P.M.
Domestication of fire by Peking man	11:46 P.M.
Beginning of most recent glacial period	11:56 P.M.
Seafarers settle Australia	11:58 P.M.
Extensive cave painting in Europe	11:59 P.M.
Invention of agriculture	11:59:20 P.M.
Neolithic civilization; first cities	11:59:35 P.M.
First dynasties in Sumer, Ebla and Egypt; development of astronomy	11:59:50 P.M.
Invention of the alphabet; Akkadian Empire	11:59:51 P.M.
Hammurabic legal codes in Babylon; Middle Kingdom in Egypt	11:59:52 P.M.
Bronze metallurgy; Mycenaean culture; Trojan War; Olmec culture: invention of the compass	11:59:53 P.M.
Iron metallurgy; First Assyrian Empire; Kingdom of Israel; founding of Carthage by Phoenicia	11:59:54 P.M.
Asokan India; Ch'in Dynasty China; Periclean Athens; birth of Buddha	11:59:55 P.M.
Euclidean geometry; Archimedean physics; Ptolemaic astronomy; Roman Empire; birth of Christ	11:59:56 P.M.
Zero and decimals invented in Indian arithmetic; Rome falls; Moslem conquests	11:59:57 P.M.
Mayan civilization; Sung Dynasty China; Byzantine empire; Mongol invasion; Crusades	11:59:58 P.M.
Renaissance in Europe; voyages of discovery from Europe and from Ming Dynasty China; emergence of the experimental method in science	11:59:59 P.M.
Widespread development of science and technology; emergence of a global culture; acquisition of the means for self-destruction of the human species; first steps in spacecraft planetary exploration and the search for extraterrestrial intelligence	Now: The first second of New Year's Day

in the chronology of the last ten seconds of the cosmic year, it was obviously impossible for me to include all significant events; I hope I may be excused for not having explicitly mentioned advances in art, music and literature or the historically significant American, French, Russian and Chinese revolutions.

The construction of such tables and calendars is inevitably humbling. It is disconcerting to find that in such a cosmic year the Earth does not condense out of interstellar matter until early September; dinosaurs emerge on Christmas Eve; flowers arise on December 28th; and men and women originate at 10:30 P.M. on New Year's Eve. All of recorded history occupies the last ten seconds of December 31; and the time from the waning of the Middle Ages to the present occupies little more than one second. But because I have arranged it that way, the first cosmic year has just ended. And despite the insignificance of the instant we have so far occupied in cosmic time, it is clear that what happens on and near Earth at the beginning of the second cosmic year will depend very much on the scientific wisdom and the distinctly human sensitivity of mankind.

2
GENES AND BRAINS



What the hammer? What the chain?
In what furnace was thy brain?
What the anvil? What dread grasp
Dare its deadly terrors clasp?

WM. BLAKE
"The Tyger"

Of all animals, man has the largest brain in proportion to his size.

ARISTOTLE
The Parts of Animals

taxa. Many more taxa exist, of course, than are shown by the few points in the figure. But the curve is representative of the much denser array of points that would be necessary to characterize the tens of millions of separate taxa which have emerged during the history of life on our planet. The major taxa, which have evolved most recently, are by and large the most complicated.

Some notion of the complexity of an organism can be obtained merely by considering its behavior—that is, the number of different functions it is called upon to perform in its lifetime. But complexity can also be judged by the minimum information content in the organism's genetic material. A typical human chromosome has one very long DNA molecule wound into coils, so that the space it occupies is very much smaller than it would be if it were unraveled. This DNA molecule is composed of smaller building blocks, a little like the rungs and sides of a rope ladder. These blocks are called nucleotides and come in four varieties. The language of life, our hereditary information, is determined by the sequence of the four different sorts of nucleotides. We might say that the language of heredity is written in an alphabet of only four letters.

But the book of life is very rich; a typical chromosomal DNA molecule in a human being is composed of about five billion pairs of nucleotides. The genetic instructions of all the other taxa on Earth are written in the same language, with the same code book. Indeed, this shared genetic language is one line of evidence that all the organisms on Earth are descended from a single ancestor, a single instance of the origin of life some four billion years ago.

The information content of any message is usually described in units called bits, which is short for "binary digits." The simplest arithmetical scheme uses not ten digits (as we do because of the evolutionary accident that we have ten fingers) but only two, 0 and 1. Thus any sufficiently crisp question can be answered by a single binary digit—0 or 1, yes or no. If the genetic code were written in a language of two letters rather than four letters, the number of bits in a DNA molecule would equal twice the number of nucleotide pairs. But since there are four different kinds of nucleotides, the number of bits of information in DNA is four times the number of nucleotide pairs. Thus if a single chromosome has five billion (5×10^9) nucleotides, it contains twenty billion (2×10^{10}) bits of information. [A symbol such as 10^9 merely indicates a one followed by a certain number of zeroes—in this case, nine of them.]

How much information is twenty billion bits? What would be its equivalent, if it were written down in an ordinary printed book in a modern human language? Alphabetical human languages characteristically have twenty to forty letters plus one or two dozen numerals and punctuation marks; thus sixty-four alternative characters should suffice for most such languages. Since 2^6 equals 64 ($2 \times 2 \times 2 \times 2 \times 2 \times 2$), it should take no more than six bits to specify a given character. We can think of this being done by a sort of game of "Twenty Questions," in which each answer corresponds to the investment of a single bit to a yes/no question. Suppose the character in question is the letter J. We might specify it by the following procedure:

FIRST QUESTION: Is it a letter (0) or some other character (1)?
ANSWER: A letter (0).
SECOND QUESTION: Is it in the first half (0) or the second half of the alphabet (1)?
ANSWER: In the first half (0).
THIRD QUESTION: Of the thirteen letters in the first half of the alphabet, is it in the first seven (0) or the second six (1)?
ANSWER: In the second six (1).
FOURTH QUESTION: In the second six (H, I, J, K, L, M), is it in the first half (0) or the second

half (1)?

ANSWER: In the first half (0).

FIFTH QUESTION: Of these letters H, I, J, is it H (0) or is it one of I and J (1)?

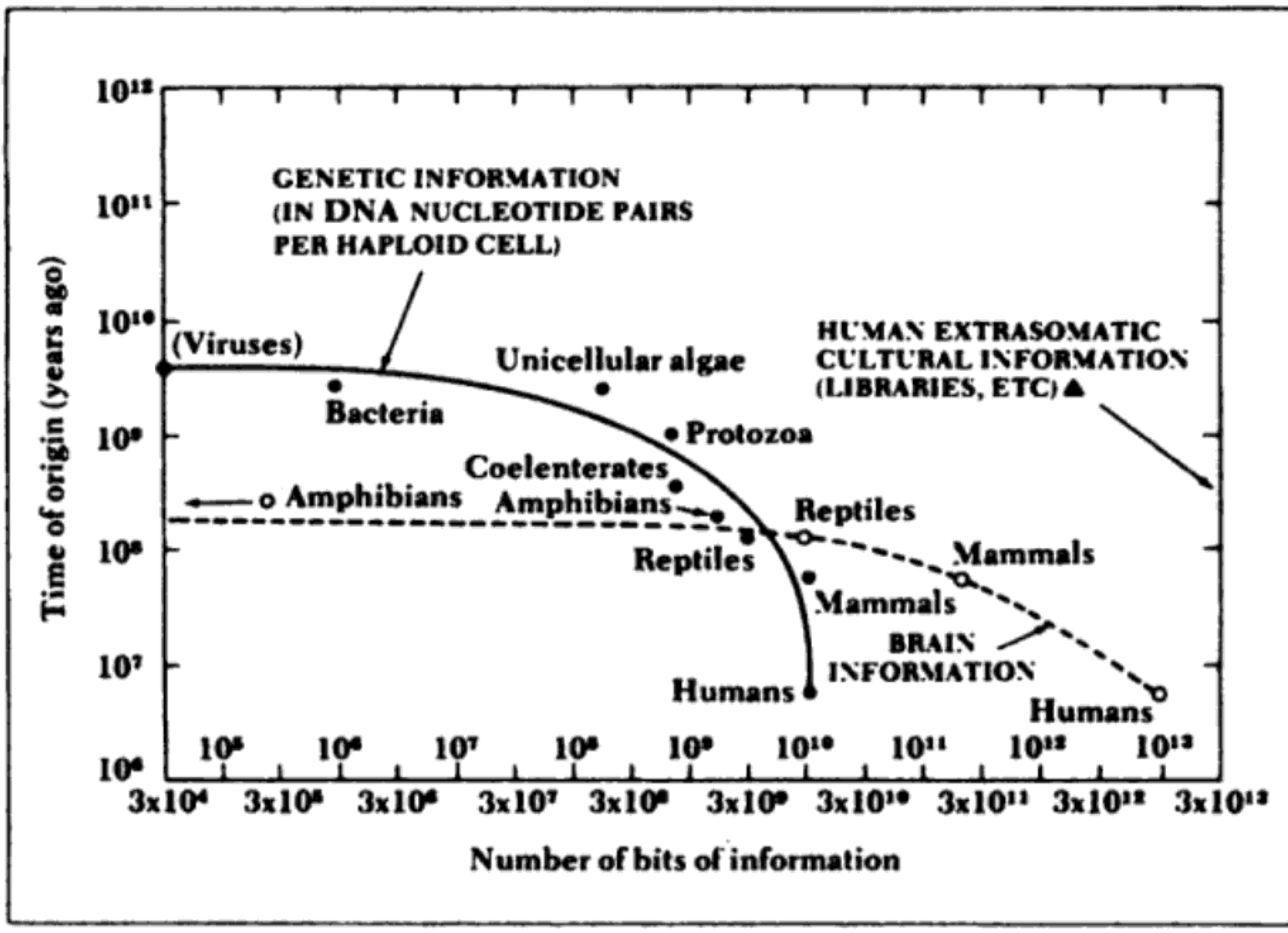
ANSWER: It is one of I and J (1).

SIXTH QUESTION: Is it I (0) or J (1)?

ANSWER: It is J (1).

Specifying the letter J is therefore equivalent to the binary message, 001011. But it required not twenty questions but six, and it is in this sense that only six bits are required to specify a given letter. Therefore twenty billion bits are the equivalent of about three billion letters ($2 \times 10^{10}/6 \cong 3 \times 10^9$). If there are approximately six letters in an average word, the information content of a human chromosome corresponds to about five hundred million words ($3 \times 10^9/6 = 5 \times 10^8$). If there are about three hundred words on an ordinary page of printed type, this corresponds to about two million pages ($5 \times 10^8/3 \times 10^2 \cong 2 \times 10^6$). If a typical book contains five hundred such pages, the information content of a single human chromosome corresponds to some four thousand volumes ($2 \times 10^6/5 \times 10^2 = 4 \times 10^3$). It is clear, then, that the sequence of rungs on our DNA ladders represents an enormous library of information. It is equally clear that so rich a library is required to specify as exquisitely constructed and intricately functioning an object as a human being. Simple organisms have less complexity and less to do, and therefore require a smaller amount of genetic information. The Viking landers that put down on Mars in 1976 each had preprogrammed instructions in their computers amounting to a few million bits. Thus Viking had slightly more "genetic information" than a bacterium, but significantly less than an alga.

The chart on page 26 also shows the minimum amount of genetic information in the DNA of various taxa. The amount shown for mammals is less than for



The evolution of information content in genes and brains during the history of life on Earth. The solid curve, which goes with the filled circles, represents the number of bits of information contained in the genes of various taxa, whose rough time of origin in the geological record is also shown. Because of variations in the amount of DNA per cell for certain taxa, only the minimum information content for a given taxon is shown, the data being taken from the work of Britten and Davidson (1969). The dashed curve, which goes with the open circles, is an approximate estimate of the evolution in the amount of information in the brains and nervous systems of these same organisms. The information in the brains of amphibians and still lower animals are off the left edge of the figure. The number of bits of information in the genetic material of viruses is shown, but it is not clear that viruses originated several billions of years ago. It is possible that viruses have evolved more recently, by loss of function, from bacteria or other more elaborate organisms. If the extrasomatic information of human beings were included (libraries, etc.), that point would be far off the lower right edge of the chart.

human beings, because most mammals have less genetic information than human beings do. Within certain taxa—for example, the amphibians—the amount of genetic information varies wildly from species to species, and it is thought that much of this DNA may be redundant or functionless. This is the reason that the chart displays the *minimum* amount of DNA for a given taxon.

We see from the chart that there was a striking improvement in the information content of organisms on Earth some three billion years ago, and a slow increase in the amount of genetic information thereafter. We also see that if more than some tens of billions (several times 10^{10}) of bits of information are necessary for human survival, extragenetic systems will have to provide them: the rate of development of genetic systems is so slow that no source of such additional biological information can be sought in the DNA.

The raw materials of evolution are mutations, inheritable changes in the particular nucleotide sequences that make up the hereditary instructions in the DNA molecule. Mutations are caused by radioactivity in the environment, by cosmic rays from space, or, as often happens, randomly—by spontaneous rearrangements of the nucleotides which statistically must occur every now and then. Chemical bonds spontaneously break. Mutations are also to some extent controlled by the organism itself. Organisms have the ability to repair certain classes of structural damage done to their DNA. There are, for example, molecules which patrol the DNA for damage; when a particularly egregious alteration in the DNA is discovered, it is snipped out by a kind of molecular scissors, and the DNA put right. But such repair is not and must not be perfectly efficient: mutations are required for evolution. A mutation in a DNA molecule within a chromosome of a skin cell in my index finger has no influence on heredity. Fingers are not involved, at least directly, in the propagation of the species. What counts are mutations in the gametes, demonstrated by Karl Lashley, a Harvard psychoneurologist, who surgically removed (extirpated) significant fractions of the cerebral cortex of rats without noticeably affecting their recollection of previously learned behavior on how to run mazes. From such experiments it is clear that the same memory must be localized in many different places in the brain, and we now know that some memories are funneled between the left and right cerebral hemispheres by a conduit called the corpus callosum.

Lashley also reported no apparent change in the general behavior of a rat when significant fractions—say, 10 percent—of its brain were removed. But no one asked the rat its opinion. To investigate this question properly would require a detailed study of rat social, foraging, and predator-evasion behavior. There are many conceivable behavioral changes resulting from such extirpations that might not be immediately obvious to the casual scientist but that might be of considerable significance to the rat—such as the amount of post-extirpation interest an attractive rat of the opposite sex now elicits, or the degree of disinterest now evinced by the presence of a stalking cat.*

It is sometimes argued that cuts or lesions in significant parts of the cerebral cortex in humans—as by bilateral prefrontal lobotomy or by an accident—have little effect on behavior. But some sorts of human behavior are not very apparent from the outside, or even from the inside. There are human perceptions and activities that may occur only rarely, such as creativity. The association of ideas involved in acts—even small ones—of creative genius seems to imply substantial investments of brain resources. These creative acts indeed characterize our entire civilization and mankind

---

* Incidentally, as a test of the influence of animated cartoons on American life, try rereading this paragraph with the word "rat" replaced everywhere by "mouse," and see if your sympathy for the surgically invaded and misunderstood beast suddenly increases.

as a species. Yet in many people they occur only rarely, and their absence may be missed by neither the brain-damaged subject nor the inquiring physician.

While substantial redundancy in brain function is inevitable, the strong equipotent hypothesis is almost certainly wrong, and most contemporary neurophysiologists have rejected it. On the other hand, a weaker equipotent hypothesis—holding, for example, that memory is a function of the cerebral cortex as a whole —is not so readily dismissable, although it is testable, as we shall see.

There is a popular contention that half or more of the brain is unused. From an evolutionary point of view this would be quite extraordinary: why should it have evolved if it had no function? But actually the statement is made on very little evidence. Again, it is deduced from the finding that many lesions of the brain, generally of the cerebral cortex, have no apparent effect on behavior. This view does not take into account (1) the possibility of redundant function; and (2) the fact that some human behavior is subtle. For example, lesions in the right hemisphere of the cerebral cortex may lead to impairments in thought and action, but in the nonverbal realm, which is, by definition, difficult for the patient or the physician to describe.

There is also considerable evidence for localization of brain function. Specific brain sites below the cerebral cortex have been found to be concerned with appetite, balance, thermal regulation, the circulation of the blood, precision movements and breathing. A classic study on higher brain function is the work of the Canadian neurosurgeon, Wilder Penfield, on the electrical stimulation of various parts of the cerebral cortex, generally in attempts to relieve symptoms of a disease such as psychomotor epilepsy. Patients reported a snatch of memory, a smell from the past, a sound or color trace—all elicited by a small electrical current at a particular site in the brain.

In a typical case, a patient might hear an orchestral composition in full detail when current flowed through Penfield's electrode to the patient's cortex, exposed after a craniotomy. If Penfield indicated to the patient —who typically is fully conscious during such procedures—that he was stimulating the cortex when he was not, invariably the patient would report no memory trace at that moment. But when, without notice, a current would flow through the electrode into the cortex, a memory trace would begin or continue. A patient might report a feeling tone, or a sense of familiarity, or a full retrieval of an experience of many years previous playing back in his mind, simultaneously but in no conflict with his awareness of being in an operating room conversing with a physician. While some patients described these flashbacks as "little dreams," they contained none of the characteristic symbolism of dream material. These experiences have been reported almost exclusively by epileptics, and it is possible, although it has by no means been demonstrated, that non-epileptics are, under similar circumstances, subject to comparable perceptual reminiscences.

In one case of electrical stimulation of the occipital lobe, which is concerned with vision, the patient reported seeing a fluttering butterfly of such compelling reality that he stretched out his hand from the operating table to catch it. In an identical experiment performed on an ape, the animal peered intently, as if at an object before him, made a swift catching motion with his right hand, and then examined, in apparent bewilderment, his empty fist.

Painless electrical stimulation of at least some human cerebral cortices elicits cascades of memories of particular events. But removal of the brain tissue in contact with the electrode does not erase the memory. It is difficult to resist the conclusion that at least in humans memories are stored somewhere in the cerebral cortex, waiting for the brain to retrieve them by electrical impulses—which, of course, are ordinarily generated within the brain itself.

If memory is a function of the cerebral cortex as a whole—a kind of dynamic reverberation or electrical standing wave pattern of the constituent parts, rather than stored statically in separate brain components—this would explain the survival of memory after significant brain damage. The evidence, however, points in the other direction: In experiments performed by the American neurophysiologist Ralph Gerard at the University of Michigan, hamsters were taught to run a simple maze and then chilled almost to the freezing point in a refrigerator, a kind of induced hibernation. The temperatures were so low that all detectable electrical activity in the animals' brains ceased. If the dynamic view of memory were true, the experiment should have wiped out all memory of successful maze-running. Instead, after thawing, the hamsters remembered. Memory seems to be localized in specific sites in the brain, and the survival of memories after massive brain lesions must be the result of redundant storage of static memory traces in various locales.

Penfield, extending the findings of previous researchers, also uncovered a remarkable localization of function in the motor cortex. Certain parts of the outer layers of our brain are responsible for sending signals to or receiving signals from specific parts of the body. A version of Penfield's maps of the sensory and motor cortices appear on pages 36 and 37. It reflects in an engaging way the relative importance of various parts of our body. The enormous amount of brain area committed to the fingers—particularly the thumb—and to the mouth and the organs of speech corresponds precisely to what in human physiology,