THE CLASSIC BESTSELLER

CARL SAGAN

COSMOS

WITH A NEW FOREWORD BY

NEIL deGRASSE TYSON

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Neil deGrasse Tyson

Not everyone who successfully impacts the hearts and minds of one generation will carry that currency of influence into the generations that follow. The continued success of *Cosmos*, Carl Sagan's magnum opus, argues strongly for Carl's affability and intelligence. But it also reveals a hidden hunger in us all to learn about our place in the universe and embrace why that matters intellectually, culturally, and emotionally.

These properties distinguish the work of Carl Sagan and his collaborators from all other efforts to communicate science. Most good books in the genre teach you what to know in the author's field of expertise—what's hot, what's interesting—in clear and simple language. But rarely is that information shaped into knowledge. And even more rarely is that knowledge shaped into wonder, the foundation of a *Cosmos* perspective on the world. Dare I assert that *Cosmos* wielded this power in ways that profoundly influenced how we would observe, interpret, and conduct our lives?

One of the least noted facts about *Cosmos*, but perhaps its most significant gift to human culture, is how it repeatedly cross-pollinated traditional sciences—astronomy, biology, chemistry, and geology. When taken separately, each of these fields is noble and time-honored. But when taken together—when *Cosmos* wove them into a tapestry of insight on our place in the universe—their juxtaposition became potent and indelible. *Cosmos* was early, if not first, in this endeavor. In the decades that followed its publication, we would see the rise of hybrid fields of study such as astrobiology, astro-particle physics, astro-chemistry, planetary geology—some still donning their hyphens.

But the publication and bestselling success of *Cosmos* accomplished much more than this. The book's treatment of scientific topics was persistently blended with other traditional fields of study, such as history, anthropology, art, and philosophy, to reveal for the first time how and why readers should embrace all the ways that science matters in our culture.

At the time, there was nothing fresher, more uplifting, or more empowering than the themes and messages of *Cosmos*. Perhaps for the first time in any medium, the person teaching you science—Carl Sagan—cared about the tangled mental roadways that can rob a person of rational thought. His motif was to speak with you, not lecture at you. With that level of pedagogical comfort, millions of people around the world invited his television image into their living rooms and his printed words into their reading chairs.

When *Cosmos* first arrived in 1980, the arms race of the Cold War was fading, but nonetheless continued to hold hostage the world's nations with a nuclear arsenal of destructive powers derived from the minds of physicists. But exploration was not without hope. NASA had already landed Viking on Mars, seven years after we walked on the moon. And the twin Voyager space probes continued their fly-by tour of the Jovian planets, on their way out of the solar system altogether. All headline news. But much more was to come. The space shuttle had not yet flown. The International Space Station existed only on paper. The Hubble Space Telescope was eleven years from launch. The first exoplanets—worlds orbiting suns other than our own—were fifteen years from detection. The World Wide Web was still a decade away from becoming a household utility, democratizing access to cosmic discoveries. And dozens more space missions would launch and arrive at their respective destinations.

In a field that moves as rapidly as astrophysics, one would think it impossible to write a timeless tract on it. But within *Cosmos* you're never focused on the bleeding edge of science. That comes and goes. You're instead treated to what the epic adventure of scientific inquiry means to Earth, to our species—to you. And that recipe works at any time, in any place, for any generation.

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FOREWORD

Ann Druyan

I once stood on the shores of the cosmic ocean with Carl Sagan.

Thirty-five years ago we shivered in the sunshine on the wind-whipped Monterey cliffs of northern California's Pacific coast with our co-writer, astronomer Steven Soter, and a small television crew. It was a struggle to wrangle the wildly flapping two-foot-long galley pages of this book while trying to keep hold of the cardboard cue cards that Steve and I had prepared for Carl for the television show. (The book and its original 1980 companion television series were created simultaneously in a three-year-long frenzy, although each contains passages and sequences not found in the other.) The pages of script and manuscript were one of a kind back in those relatively low-tech days. With every gust coming off the light-dazzled waves, the pages threatened to take flight and blow out to sea like the dandelion puffballs Carl kept releasing to the cosmos.

The scenes we wrote and shot that day became the opening of the show and the first words of the book: "The cosmos is all that is or ever was or ever will be."

We were consciously going for a biblical cadence, words that would scope out the ambitious territorial range of our explorations in space and time. Beginning the saga of 40,000 generations of searchers on one tiny world trying to find their bearings in the cosmos required nothing less than an epic flourish.

It became the "Welcome aboard" to a personal voyage on the ship of the imagination, one that nearly a billion people have taken, and still take, in great numbers, in virtually every language spoken on our "pale blue dot." Ever since the fall of 1980, in both its manifestations, *Cosmos* has carried multitudes to the outermost reaches of our understanding of the universe, to places unimaginably small and incomprehensibly vast.

Some religious fundamentalists found that first line offensive. To them it was a shot across their bow that Carl was out to steal their thunder. They were on to something. As with everything Carl wrote, the science of *Cosmos* is solid, with big red rhetorical flags warning the reader when the author ventures into the speculative. (And thirty-five years later, how astonishingly prophetic have been most of Carl's conjectures on everything from climate change on Earth, the ambiguities of the Viking lander's findings on Mars, to his dreams of what might await us on Saturn's moon, Titan.) But Carl didn't stop there.

The universe revealed by the relentless error-correcting mechanism of science was to him infinitely preferable to the untested assumptions of traditional belief. For Carl, the "spiritual" had to be rooted in natural reality. He cherished those ideas about the cosmos that remained after the most rigorous experiment and observation. Scientific insight made him *feel* something, a soaring sensation, a recognition that he could only compare to falling in love. And as he used to say: "When you're in love, you want to tell the world."

This is the big, wide-open, welcoming embrace of *Cosmos*, as far from the clock-watching slow-death tedium of too many a science class as Titan is from Earth. It's about being unafraid to take the findings of science to *heart*.

Cosmos is for many that first encounter with the universe that you thought was foreclosed to you because you couldn't do the math, or you live in a place where there are no scientists to invite you in. Carl wanted everyone to come on this voyage; to experience the power of the scientific perspective and the wonders it reveals. His secret was to recapture the person he was before he understood the concept and then retrace his own *thought steps* toward comprehension. It worked. He inspired legions to study, teach, and do science.

The U.S. Library of Congress has recently designated *Cosmos* one of the eighty-eight books "that shaped America."

It's a roster that includes such earth-shaking works as Thomas Paine's *Common Sense*, Herman Melville's *Moby Dick*, Harriet Beecher Stowe's *Uncle Tom's Cabin*, and Jack Kerouac's *On the Road*. They're listed in chronological order and the very first one, published in 1751 (decades before the concept of a constitutional government by, for, and of the people, crystallized), is also a science book. It's by another who believed that democracy requires an informed public of responsible decision-makers. The list begins with Benjamin Franklin's *Experiments and Observations on Electricity*. That book and this one are passionate acts of citizenship by two scientists who wanted science to belong to all of us.

This spring I returned for the first time to the shores of the cosmic ocean. I was there with another television crew to shoot the opening scenes of the new *Cosmos* series. Our host, astrophysicist Neil deGrasse Tyson, is one of the many scientists whose young lives were touched by Carl. I am happy to report that the terrain is as unspoiled, gorgeous, and inspiring as it was the first time.

As I looked out at the glittering waters of the Pacific I was seeing for Carl. He knew that it's not for any one generation to see the completed picture. That's the point. The picture is never completed. There is always so much more that remains to be discovered.

Welcome aboard. It's time, once again, to set sail for the stars.

Ann Druyan served as creative director of NASA's Voyager Interstellar Message and was Carl Sagan's co-writer on *Cosmos*, as well as co-creator of the motion picture *Contact* and many other works. She is an executive producer and writer of *Cosmos: A SpaceTime Odyssey*, the television sequel coming in 2014 on Fox. Ms. Druyan was married to Dr. Sagan until his death. The asteroids named after them are in perpetual wedding-ring orbit around the Sun.

INTRODUCTION

> The time will come when diligent research over long periods will bring to light things which now lie hidden. A single lifetime, even though entirely devoted to the sky, would not be enough for the investigation of so vast a subject ... And so this knowledge will be unfolded only through long successive ages. There will come a time when our descendants will be amazed that we did not know things that are so plain to them ... Many discoveries are reserved for ages still to come, when memory of us will have been effaced. Our universe is a sorry little affair unless it has in it something for every age to investigate ... Nature does not reveal her mysteries once and for all.
>
> —Seneca, *Natural Questions*,
> Book 7, first century

In ancient times, in everyday speech and custom, the most mundane happenings were connected with the grandest cosmic events. A charming example is an incantation against the worm which the Assyrians of 1000 B.C. imagined to cause toothaches. It begins with the origin of the universe and ends with a cure for toothache:

After Anu had created the heaven,
And the heaven had created the earth,
And the earth had created the rivers,
And the rivers had created the canals,
And the canals had created the morass,
And the morass had created the worm,
The worm went before Shamash, weeping,
His tears flowing before Ea:
"What wilt thou give me for my food,
What wilt thou give me for my drink?"

"I will give thee the dried fig
And the apricot."
"What are these to me? The dried fig
And the apricot!
Lift me up, and among the teeth
And the gums let me dwell!..."
Because thou hast said this, O worm,
May Ea smite thee with the might of
His hand!
(Incantation against toothache.)
Its treatment: Second-grade beer ... and oil thou shalt mix together;
The incantation thou shalt recite three times thereon and shalt put the medicine upon the tooth.

Our ancestors were eager to understand the world but had not quite stumbled upon the method. They imagined a small, quaint, tidy universe in which the dominant forces were gods like Anu, Ea, and Shamash. In that universe humans played an important if not a central role. We were intimately bound up with the rest of nature. The treatment of toothache with second-rate beer was tied to the deepest cosmological mysteries.

Today we have discovered a powerful and elegant way to understand the universe, a method called science; it has revealed to us a universe so ancient and so vast that human affairs seem at first sight to be of little consequence. We have grown distant from the Cosmos. It has seemed remote and irrelevant to everyday concerns. But science has found not only that the universe has a reeling and ecstatic grandeur, not only that it is accessible to human understanding, but also that we are, in a very real and profound sense, a part of that Cosmos, born from it, our fate deeply connected with it. The most basic human events and the most trivial trace back to the universe and its origins. This book is devoted to the exploration of that cosmic perspective.

In the summer and fall of 1976, as a member of the Viking

Lander Imaging Flight Team, I was engaged, with a hundred of my scientific colleagues, in the exploration of the planet Mars. For the first time in human history we had landed two space vehicles on the surface of another world. The results, described more fully in Chapter 5, were spectacular, the historical significance of the mission utterly apparent. And yet the general public was learning almost nothing of these great happenings. The press was largely inattentive; television ignored the mission almost altogether. When it became clear that a definitive answer on whether there is life on Mars would not be forthcoming, interest dwindled still further. There was little tolerance for ambiguity. When we found the sky of Mars to be a kind of pinkish-yellow rather than the blue which had erroneously first been reported, the announcement was greeted by a chorus of good-natured boos from the assembled reporters—they wanted Mars to be, even in this respect, like the Earth. They believed that their audiences would be progressively disinterested as Mars was revealed to be less and less like the Earth. And yet the Martian landscapes are staggering, the vistas breathtaking. I was positive from my own experience that an enormous global interest exists in the exploration of the planets and in many kindred scientific topics—the origin of life, the Earth, and the Cosmos, the search for extraterrestrial intelligence, our connection with the universe. And I was certain that this interest could be excited through that most powerful communications medium, television.

My feelings were shared by B. Gentry Lee, the Viking Data Analysis and Mission Planning Director. We decided, gamely, to do something about the problem ourselves. Lee proposed that we form a production company devoted to the communication of science in an engaging and accessible way. In the following months we were approached on a number of projects. But by far the most interesting was an inquiry tendered by KCET, the Public Broadcasting Service's outlet in Los Angeles. Eventually, we jointly agreed to produce a thirteen-part television series oriented toward astronomy but with a very broad human perspective. It was to be aimed at popular audiences, to be visually and musically stunning, and to engage the heart as well as the mind. We talked with underwriters, hired an executive producer, and found ourselves embarked on a three-year project called *Cosmos*. At this writing it has an estimated worldwide viewing audience of over 200 million people, or almost 5 percent of the human population of the planet Earth. It is dedicated to the proposition that the public is far more intelligent than it has generally been given credit for; that the deepest scientific questions on the nature and origin of the world excite the interests and passions of enormous numbers of people. The present epoch is a major crossroads for our civilization and perhaps for our species. Whatever road we take, our fate is indissolubly bound up with science. It is essential as a matter of simple survival for us to understand science. In addition, science is a delight; evolution has arranged that we take pleasure in understanding—those who understand are more likely to survive. The *Cosmos* television series and this book represent a hopeful experiment in communicating some of the ideas, methods and joys of science.

The book and the television series evolved together. In some sense each is based on the other. Many illustrations in this book are based on the striking visuals prepared for the television series. But books and television series have somewhat different audiences and admit differing approaches. One of the great virtues of a book is that it is possible for the reader to return repeatedly to obscure or difficult passages; this is only beginning to become possible, with the development of videotape and video-disc technology, for television. There is much more freedom for the author in choosing the range and depth of topics for a chapter in a book than for the procrustean fifty-eight minutes, thirty seconds of a noncommercial television program. This book goes more deeply into many topics than does the television series. There are topics discussed in the book which are not treated in the television series and vice versa. For example, explicit representations of the Cosmic Calendar, featured in the television series, do not appear here —in part because the Cosmic Calendar is discussed in my book *The Dragons of Eden;* likewise, I do not here discuss the life of Robert Goddard in much detail, because there is a chapter in *Broca's Brain* devoted to him. But each episode of the television series follows fairly closely the corresponding chapter of this book; and I like to think that the pleasure of each will be enhanced by reference to the other. Only a few of the more than 250 full-color illustrations in the hardbound and trade paperback editions of *Cosmos* could be accommodated in this edition, but all illustrations necessary to understand the text are included.

For clarity, I have in a number of cases introduced an idea more than once—the first time lightly, and with deeper passes on subsequent appearances. This occurs, for example, in the introduction to cosmic objects in Chapter 1, which are examined in greater detail later on; or in the discussion of mutations, enzymes and nucleic acids in Chapter 2. In a few cases, concepts are presented out of historical order. For example, the ideas of the ancient Greek scientists are presented in Chapter 7, well after the discussion of Johannes Kepler in Chapter 3. But I believe an appreciation of the Greeks can best be provided after we see what they barely missed achieving.

Because science is inseparable from the rest of the human endeavor, it cannot be discussed without making contact, sometimes glancing, sometimes head-on, with a number of social, political, religious and philosophical issues. Even in the filming of a television series on science, the worldwide devotion to military activities becomes intrusive. Simulating the exploration of Mars in the Mohave Desert with a full-scale version of the Viking Lander, we were repeatedly interrupted by the United States Air Force, performing bombing runs in a nearby test range. In Alexandria, Egypt, from nine to eleven A.M. every morning, our hotel was the subject of practice strafing runs by the Egyptian Air Force. In Samos, Greece, permission to film anywhere was withheld until the very last moment because of NATO maneuvers and what was clearly the construction of a warren of underground and hillside emplacements for artillery and tanks. In Czechoslovakia the use of walkie-talkies for organizing the filming logistics on a rural road attracted the attention of a Czech Air Force fighter, which circled overhead until reassured in Czech that no threat to national security was being perpetrated. In Greece, Egypt and Czechoslovakia our film crews were accompanied everywhere by agents of the state security apparatus. Preliminary inquiries about filming in Kaluga, U.S.S.R., for a proposed discussion of the life of the Russian pioneer of astronautics Konstantin Tsiolkovsky were discouraged—because, as we later discovered, trials of dissidents were to be conducted there. Our camera crews met innumerable kindnesses in every country we visited; but the global military presence, the fear in the hearts of the nations, was everywhere. The experience confirmed my resolve to treat, when relevant, social questions both in the series and in the book.

Science is an ongoing process. It never ends. There is no single ultimate truth to be achieved, after which all the scientists can retire. And because this is so, the world is far more interesting, both for the scientists and for the millions of people in every nation who, while not professional scientists, are deeply interested in the methods and findings of science. So, while there is little in the *Cosmos* book that has become obsolete since its first publication, there have been many significant new findings.

The Voyager 1 and 2 spacecraft encountered the Saturn system and uncovered a host of wonders concerning the planet, its intricate ring system, and its swarm of attendant satellites. Perhaps most interesting of these is Titan, which is now known to have an atmosphere rather like that of the primitive Earth, a dense haze layer composed of complex organic molecules, and perhaps a surface ocean of liquid hydrocarbons. A range of observations have recently been made of rings of debris surrounding young stars. These rings may be in the process of coagulating into new planetary systems, and suggest that planets may be overwhelmingly abundant among the stars of the Milky Way galaxy. Life has been found unexpectedly nibbling on sulfur compounds in very high temperature vents on the Earth's ocean floor. New evidence has accumulated suggesting that comets are periodically sprayed into the inner solar system, triggering the extinction of many species on Earth. Great regions of intergalactic space have been uncovered that seemingly are depleted in galaxies. New and important components of the universe bearing on the question of its ultimate fate have been suggested.

And the pace of discovery continues. Spacecraft of Japan, of the European Space Agency, and of the Soviet Union are scheduled to intercept Halley's Comet in 1986. The U.S. Space Telescope, the largest orbiting observatory ever attempted, is scheduled to be launched before the end of the decade. Important opportunities for spacecraft missions to Mars, to other comets, to asteroids, and to Titan are emerging. The U.S. *Galileo* spacecraft, scheduled to arrive in the Jupiter system in 1988, is designed to drop the first entry probe into the atmosphere of one of the giant planets. And there is a somber side to the pace of scientific discovery as well: recent work suggests that in the aftermath of a nuclear war the resulting soot and dust lofted high into the atmosphere would darken and freeze the Earth, producing an unprecedented catastrophe even for nations on which not a single bomb has fallen. Our technology is increasingly permitting us to explore the wonders of the Cosmos and to reduce the Earth to chaos. We are privileged to live in, and if we are lucky to influence, one of the most critical epochs in the history of the human species.

On a project of this magnitude it is impossible to thank everyone who has made a contribution. However, I would like to acknowledge, especially, B. Gentry Lee; the *Cosmos* production staff, including the senior producers Geoffrey Haines-Stiles and David Kennard and the executive producer Adrian Malone; the artists Jon Lomberg (who played a critical role in the original design and organization of the *Cosmos* visuals), John Allison, Adolf Schaller, Rick Sternbach, Don Davis, Brown, and Anne Norcia; consultants Donald Goldsmith, Owen Gingerich, Paul Fox, and Diane Ackerman; Cameron Beck; the KCET management, particularly Greg Andorfer, who first carried KCET's proposal to us, Chuck Allen, William Lamb, and James Loper; and the underwriters and co-producers of the *Cosmos* television series, including the Atlantic Richfield Company, the Corporation for Public Broadcasting, the Arthur Vining Davis Foundations, the Alfred P. Sloan Foundation, the British Broadcasting Corporation, and Polytel International. Others who helped in clarifying matters of fact or approach are listed at the back of the book. The final responsibility for the content of the book is, however, of course mine. I thank the staff at Random House, particularly my editor, Anne Freedgood, for their capable work and their patience when the deadlines for the television series and the book seemed to be in conflict. I owe a special debt of gratitude to Shirley Arden, my Executive Assistant, for typing the early drafts of this book and ushering the later drafts through all stages of production with her usual cheerful competence. This is only one of many ways in which the *Cosmos* project is deeply indebted to her. I am more grateful than I can say to the administration of Cornell University for granting me a two-year leave of absence to pursue this project, to my colleagues and students there, and to my colleagues at NASA, JPL and on the Voyager Imaging Team.

My greatest debt for the writing of *Cosmos* is owed to Ann Druyan and Steven Soter, my co-writers in the television series. They made fundamental and frequent contributions to the basic ideas and their connections, to the overall intellectual structure of the episodes, and to the felicity of style. I am deeply grateful for their vigorous critical readings of early versions of this book, their constructive and creative suggestions for revision through many drafts, and their major contributions to the television script which in many ways influenced the content of this book. The delight I found in our many discussions is one of my chief rewards from the *Cosmos* project.

Ithaca and Los Angeles
May 1980
and July 1984

CHAPTER I

THE SHORES OF THE COSMIC OCEAN

> The first men to be created and formed were called the Sorcerer of Fatal Laughter, the Sorcerer of Night, Unkempt, and the Black Sorcerer ... They were endowed with intelligence, they succeeded in knowing all that there is in the world. When they looked, instantly they saw all that is around them, and they contemplated in turn the arc of heaven and the round face of the earth ... [Then the Creator said]: "They know all ... what shall we do with them now? Let their sight reach only to that which is near; let them see only a little of the face of the earth!... Are they not by nature simple creatures of our making? Must they also be gods?"
>
> —The Popol Vuh of the Quiché Maya

> The known is finite, the unknown infinite; intellectually we stand on an islet in the midst of an illimitable ocean of inexplicability. Our business in every generation is to reclaim a little more land.
>
> —T. H. Huxley, 1887

The Cosmos is all that is or ever was or ever will be. Our feeblest contemplations of the Cosmos stir us—there is a tingling in the spine, a catch in the voice, a faint sensation, as if a distant memory, of falling from a height. We know we are approaching the greatest of mysteries.

The size and age of the Cosmos are beyond ordinary human understanding. Lost somewhere between immensity and eternity is our tiny planetary home. In a cosmic perspective, most human concerns seem insignificant, even petty. And yet our species is young and curious and brave and shows much promise. In the last few millennia we have made the most astonishing and unexpected discoveries about the Cosmos and our place within it, explorations that are exhilarating to consider. They remind us that humans have evolved to wonder, that understanding is a joy, that knowledge is prerequisite to survival. I believe our future depends on how well we know this Cosmos in which we float like a mote of dust in the morning sky.

Those explorations required skepticism and imagination both. Imagination will often carry us to worlds that never were. But without it, we go nowhere. Skepticism enables us to distinguish fancy from fact, to test our speculations. The Cosmos is rich beyond measure—in elegant facts, in exquisite interrelationships, in the subtle machinery of awe.

The surface of the Earth is the shore of the cosmic ocean. From it we have learned most of what we know. Recently, we have waded a little out to sea, enough to dampen our toes or, at most, wet our ankles. The water seems inviting. The ocean calls. Some part of our being knows this is from where we came. We long to return. These aspirations are not, I think, irreverent, although they may trouble whatever gods may be.

The dimensions of the Cosmos are so large that using familiar units of distance, such as meters or miles, chosen for their utility on Earth, would make little sense. Instead, we measure distance with the speed of light. In one second a beam of light travels 186,000 miles, nearly 300,000 kilometers or seven times around the Earth. In eight minutes it will travel from the Sun to the Earth. We can say the Sun is eight light-minutes away. In a year, it crosses nearly ten trillion kilometers, about six trillion miles, of intervening space. That unit of length, the distance light goes in a year, is called a light-year. It measures not time but distances—enormous distances.

The Earth is a place. It is by no means the only place. It is not even a typical place. No planet or star or galaxy can be typical, because the Cosmos is mostly empty. The only typical place is within the vast, cold, universal vacuum, the everlasting night of intergalactic space, a place so strange and desolate that, by comparison, planets and stars and galaxies seem achingly rare and lovely. If we were randomly inserted into the Cosmos, the chance that we would find ourselves on or near a planet would be less than one in a billion trillion trillion* (10^{33}, a one followed by 33 zeroes). In everyday life such odds are called compelling. Worlds are precious.

From an intergalactic vantage point we would see, strewn like sea froth on the waves of space, innumerable faint, wispy tendrils of light. These are the galaxies. Some are solitary wanderers; most inhabit communal clusters, huddling together, drifting endlessly in the great cosmic dark. Before us is the Cosmos on the grandest scale we know. We are in the realm of the nebulae, eight billion light-years from Earth, halfway to the edge of the known universe.

A galaxy is composed of gas and dust and stars—billions upon billions of stars. Every star may be a sun to someone. Within a galaxy are stars and worlds and, it may be, a proliferation of living things and intelligent beings and spacefaring civilizations. But from afar, a galaxy reminds me more of a collection of lovely found objects—seashells, perhaps, or corals, the productions of Nature laboring for aeons in the cosmic ocean.

There are some hundred billion (10^{11}) galaxies, each with, on the average, a hundred billion stars. In all the galaxies, there are perhaps as many planets as stars, $10^{11} \times 10^{11} = 10^{22}$, ten billion trillion. In the face of such overpowering numbers, what is the likelihood that only one ordinary star, the Sun, is accompanied by an inhabited planet? Why should we, tucked away in some forgotten corner of the Cosmos, be so fortunate? To me, it seems far more likely that the universe is brimming over with life. But we humans do not yet know. We are just beginning our explorations. From eight billion light-years away we are hard pressed to find even the cluster in which our Milky Way Galaxy is embedded, much less the Sun or the Earth. The only planet we are sure is inhabited is a tiny speck of rock and metal, shining feebly by reflected sunlight, and at this distance utterly lost.

But presently our journey takes us to what astronomers on Earth like to call the Local Group of galaxies. Several million of the inner solar system. There is, for example, the red planet Mars, with soaring volcanoes, great rift valleys, enormous planet-wide sandstorms, and, just possibly, some simple forms of life. All the planets orbit the Sun, the nearest star, an inferno of hydrogen and helium gas engaged in thermonuclear reactions, flooding the solar system with light.

Finally, at the end of all our wanderings, we return to our tiny, fragile, blue-white world, lost in a cosmic ocean vast beyond our most courageous imaginings. It is a world among an immensity of others. It may be significant only for us. The Earth is our home, our parent. Our kind of life arose and evolved here. The human species is coming of age here. It is on this world that we developed our passion for exploring the Cosmos, and it is here that we are, in some pain and with no guarantees, working out our destiny.

Welcome to the planet Earth—a place of blue nitrogen skies, oceans of liquid water, cool forests and soft meadows, a world positively rippling with life. In the cosmic perspective it is, as I have said, poignantly beautiful and rare; but it is also, for the moment, unique. In all our journeying through space and time, it is, so far, the only world on which we know with certainty that the matter of the Cosmos has become alive and aware. There must be many such worlds scattered through space, but our search for them begins here, with the accumulated wisdom of the men and women of our species, garnered at great cost over a million years. We are privileged to live among brilliant and passionately inquisitive people, and in a time when the search for knowledge is generally prized. Human beings, born ultimately of the stars and now for a while inhabiting a world called Earth, have begun their long voyage home.

The discovery that the Earth is a *little* world was made, as so many important human discoveries were, in the ancient Near East, in a time some humans call the third century B.C., in the greatest metropolis of the age, the Egyptian city of Alexandria. Here there lived a man named Eratosthenes. One of his envious contemporaries called him "Beta," the second letter of the Greek alphabet, because, he said, Eratosthenes was second best in the world in everything. But it seems clear that in almost everything Eratosthenes was "Alpha." He was an astronomer, historian, geographer, philosopher, poet, theater critic and mathematician. The titles of the books he wrote range from *Astronomy* to *On Freedom from Pain*. He was also the director of the great library of Alexandria, where one day he read in a papyrus book that in the southern frontier outpost of Syene, near the first cataract of the Nile, at noon on June 21 vertical sticks cast no shadows. On the summer solstice, the longest day of the year, as the hours crept toward midday, the shadows of temple columns grew shorter. At noon, they were gone. A reflection of the Sun could then be seen in the water at the bottom of a deep well. The Sun was directly overhead.

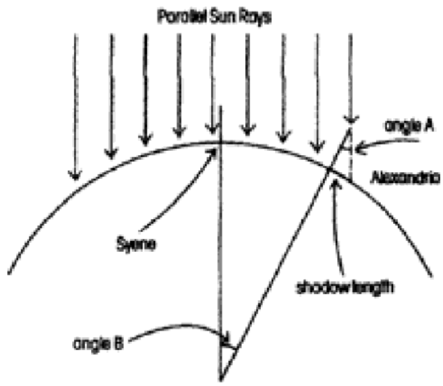
It was an observation that someone else might easily have ignored. Sticks, shadows, reflections in wells, the position of the Sun—of what possible importance could such simple everyday matters be? But Eratosthenes was a scientist, and his musings on these commonplaces changed the world; in a way, they made the world. Eratosthenes had the presence of mind to do an experiment, actually to observe whether in Alexandria vertical sticks cast shadows near noon on June 21. And, he discovered, sticks do.

Eratosthenes asked himself how, at the same moment, a stick in Syene could cast no shadow and a stick in Alexandria, far to the north, could cast a pronounced shadow. Consider a map of ancient Egypt with two vertical sticks of equal length, one stuck in Alexandria, the other in Syene. Suppose that, at a certain moment, each stick casts no shadow at all. This is perfectly easy to understand—provided the Earth is flat. The Sun would then be directly overhead. If the two sticks cast shadows of equal length, that also would make sense on a flat Earth: the Sun's rays would then be inclined at the same angle to the two sticks. But how could it be that at the same instant there was no shadow at Syene and a substantial shadow at Alexandria?

The only possible answer, he saw, was that the surface of the Earth is curved. Not only that: the greater the curvature, the greater the difference in the shadow lengths. The Sun is so far away that its rays are parallel when they reach the Earth. Sticks placed at different angles to the Sun's rays cast shadows of different lengths. For the observed difference in the shadow lengths, the distance between Alexandria and Syene had to be about seven degrees along the surface of the Earth; that is, if you imagine the sticks extending down to the center of the Earth, they would there intersect at an angle of seven degrees. Seven degrees is something like one-fiftieth of three hundred and sixty degrees, the full circumference of the Earth. Eratosthenes knew that the distance between Alexandria and Syene was approximately 800 kilometers, because he hired a man to pace it out. Eight hundred kilometers times 50 is 40,000 kilometers: so that must be the circumference of the Earth.*

This is the right answer. Eratosthenes' only tools were sticks, eyes, feet and brains, plus a taste for experiment. With them he deduced the circumference of the Earth with an error of only a few percent, a remarkable achievement for 2,200 years ago. He was the first person accurately to measure the size of a planet.

The Mediterranean world at that time was famous for seafaring. Alexandria was the greatest seaport on the planet. Once you knew the Earth to be a sphere of modest diameter, would you not be tempted to make voyages of exploration, to seek out undiscovered lands, perhaps even to attempt to sail around the planet? Four hundred years before Eratosthenes, Africa had been circumnavigated by a Phoenician fleet in the employ of the Egyptian Pharaoh Necho. They set sail, probably in frail open boats, from the Red Sea, turned down the east coast of Africa up into the Atlantic, returning through the Mediterranean. This epic journey took three years, about as long as a modern Voyager spacecraft takes to fly from Earth to Saturn.



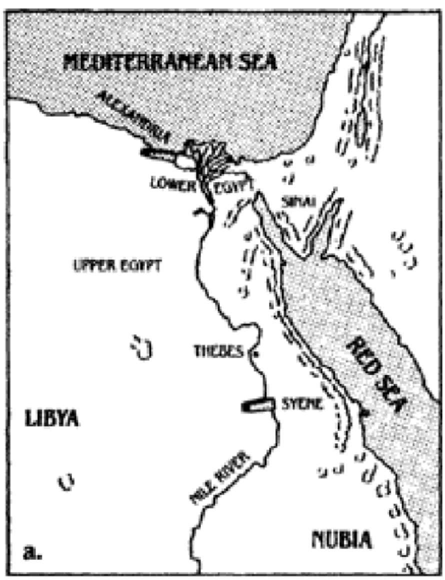
From the shadow length in Alexandria, the angle A can be measured. But from simple geometry ("if two parallel straight lines are transected by a third line, the alternate interior angles are equal"), angle B equals angle A. So by measuring the shadow length in Alexandria, Eratosthenes concluded that Syene was A = B = 7° away on the circumference of the Earth.

After Eratosthenes' discovery, many great voyages were attempted by brave and venturesome sailors. Their ships were tiny. They had only rudimentary navigational instruments. They used dead reckoning and followed coastlines as far as they could. In an unknown ocean they could determine their latitude, but not their longitude, by observing, night after night, the position of the constellations with respect to the horizon. The familiar constellations must have been reassuring in the midst of an unexplored ocean. The stars are the friends of explorers, then with seagoing ships on Earth and now with spacefaring ships in the sky. After Eratosthenes, some may have tried, but not until the time of Magellan did anyone succeed in circumnavigating the Earth. What tales of daring and adventure must earlier have been recounted as sailors and navigators, practical men of the world, gambled their lives on the mathematics of a scientist from Alexandria?

In Eratosthenes' time, globes were constructed portraying the Earth as viewed from space; they were essentially correct in the well-explored Mediterranean but became more and more inaccurate the farther they strayed from home. Our present knowledge of the Cosmos shares this disagreeable but inevitable feature. In the first century, the Alexandrian geographer Strabo wrote:

> Those who have returned from an attempt to circumnavigate the Earth do not say they have been prevented by an opposing continent, for the sea remained perfectly open, but, rather, through want of resolution and scarcity of provision.... Eratosthenes says that if the extent of the Atlantic Ocean were not an obstacle, we might easily pass by sea from Iberia to India.... It is quite possible that in the temperate zone there may be one or two habitable Earths.... Indeed, if [this other part of the world] is inhabited, it is not inhabited by men such as exist in our parts, and we should have to regard it as another inhabited world.

Humans were beginning to venture, in almost every sense that matters, to other worlds.



This p.: A flat map of ancient Egypt; when the sun is directly overhead, vertical obelisks cast no shadows in Alexandria or Syene. Next p., left: When the sun is not directly overhead, shadows of equal length are cast. But (next p., right) when the map is curved, the sun can be overhead in Syene and not in Alexandria; no shadow is then cast in Syene, while a pronounced shadow is cast in Alexandria.

The subsequent exploration of the Earth was a worldwide of commerce, culture and learning. It was graced with broad avenues thirty meters wide, elegant architecture and statuary, Alexander's monumental tomb, and an enormous lighthouse, the Pharos, one of the seven wonders of the ancient world.

But the greatest marvel of Alexandria was the library and its associated museum (literally, an institution devoted to the specialties of the Nine Muses). Of that legendary library, the most that survives today is a dank and forgotten cellar of the Serapeum, the library annex, once a temple and later reconsecrated to knowledge. A few moldering shelves may be its only physical remains. Yet this place was once the brain and glory of the greatest city on the planet, the first true research institute in the history of the world. The scholars of the library studied the entire Cosmos. *Cosmos* is a Greek word for the order of the universe. It is, in a way, the opposite of *Chaos*. It implies the deep interconnectedness of all things. It conveys awe for the intricate and subtle way in which the universe is put together. Here was a community of scholars, exploring physics, literature, medicine, astronomy, geography, philosophy, mathematics, biology, and engineering. Science and scholarship had come of age. Genius flourished there. The Alexandrian Library is where we humans first collected, seriously and systematically, the knowledge of the world.

In addition to Eratosthenes, there was the astronomer Hipparchus, who mapped the constellations and estimated the brightness of the stars; Euclid, who brilliantly systematized geometry and told his king, struggling over a difficult mathematical problem, "There is no royal road to geometry"; Dionysius of Thrace, the man who defined the parts of speech and did for the study of language what Euclid did for geometry; Herophilus, the physiologist who firmly established that the brain rather than the heart is the seat of intelligence; Heron of Alexandria, inventor of gear trains and steam engines and the author of *Automata*, the first book on robots; Apollonius of Perga, the mathematician who demonstrated the forms of the conic sections* —ellipse, parabola and hyperbola—the curves, as we now know, followed in their orbits by the planets, the comets and the stars; Archimedes, the greatest mechanical genius until Leonardo da Vinci; and the astronomer and geographer Ptolemy, who compiled much of what is today the pseudoscience of astrology: his Earth-centered universe held sway for 1,500 years, a reminder that intellectual capacity is no guarantee against being dead wrong. And among those great men was a great woman, Hypatia, mathematician and astronomer, the last light of the library, whose martyrdom was bound up with the destruction of the library seven centuries after its founding, a story to which we will return.

The Greek Kings of Egypt who succeeded Alexander were serious about learning. For centuries, they supported research and maintained in the library a working environment for the best minds of the age. It contained ten large research halls, each devoted to a separate subject; fountains and colonnades; botanical gardens; a zoo; dissecting rooms; an observatory; and a great dining hall where, at leisure, was conducted the critical discussion of ideas.

The heart of the library was its collection of books. The organizers combed all the cultures and languages of the world. They sent agents abroad to buy up libraries. Commercial ships docking in Alexandria were searched by the police—not for contraband, but for books. The scrolls were borrowed, copied and then returned to their owners. Accurate numbers are difficult to estimate, but it seems probable that the Library contained half a million volumes, each a handwritten papyrus scroll. What happened to all those books? The classical civilization that created them disintegrated, and the library itself was deliberately destroyed. Only a small fraction of its works survived, along with a few pathetic scattered fragments. And how tantalizing those bits and pieces are! We know, for example, that there was on the library shelves a book by the astronomer Aristarchus of Samos, who argued that the Earth is one of the planets, which like them orbits the Sun, and that the stars are enormously far away. Each of these conclusions is entirely correct, but we had to wait nearly two thousand years for their rediscovery. If we multiply by a hundred thousand our sense of loss for this work of Aristarchus, we begin to appreciate the grandeur of the achievement of classical civilization and the tragedy of its destruction.

We have far surpassed the science known to the ancient world. But there are irreparable gaps in our historical knowledge. Imagine what mysteries about our past could be solved with a borrower's card to the Alexandrian Library. We know of a three-volume history of the world, now lost, by a Babylonian priest named Berossus. The first volume dealt with the interval from the Creation to the Flood, a period he took to be 432,000 years or about a hundred times longer than the Old Testament chronology. I wonder what was in it.

The ancients knew that the world is very old. They sought to look into the distant past. We now know that the Cosmos is far older than they ever imagined. We have examined the universe in space and seen that we live on a mote of dust circling a humdrum star in the remotest corner of an obscure galaxy. And if we are a speck in the immensity of space, we also occupy an instant in the expanse of ages. We know now that our universe—or at least its most recent incarnation—is some fifteen or twenty billion years old. This is the time since a remarkable explosive event called the Big Bang. At the beginning of this universe, there were no galaxies, stars or planets, no life or civilizations, merely a uniform, radiant fireball filling all of space. The passage from the Chaos of the Big Bang to the Cosmos that we are beginning to know is the most awesome transformation of matter and energy that we have been privileged to glimpse. And until we find more intelligent beings elsewhere, we are ourselves the most spectacular of all the transformations—the remote descendants of the Big Bang, dedicated to understanding and further transforming the Cosmos from which we spring.

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*We use the American scientific convention for large numbers: one billion = 1,000,000,000 = 10^9; one trillion = 1,000,000,000,000 = 10^{12}, etc. The exponent counts the number of zeroes after the one.

*Or if you like to measure things in miles, the distance between Alexandria and Syene is about 500 miles, and 500 miles × 50 = 25,000 miles.

*So called because they can be produced by slicing through a cone at various angles. Eighteen centuries later, the writings of Apellecios on conic sections would be employed by Johannes Kepler in understanding for the first time the movement of the planets.

CHAPTER II

ONE VOICE IN THE COSMIC FUGUE

> Probably all the organic beings which have ever lived on this earth have descended from some one primordial form, into which life was first breathed.... There is grandeur in this view of life ... that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved.
>
> —Charles Darwin, *The Origin of Species*, 1859

All my life I have wondered about the possibility of life elsewhere. What would it be like? Of what would it be made? All living things on our planet are constructed of organic molecules—complex microscopic architectures in which the carbon atom plays a central role. There was once a time before life, when the Earth was barren and utterly desolate. Our world is now overflowing with life. How did it come about? How, in the absence of life, were carbon-based organic molecules made? How did the first living things arise? How did life evolve to produce beings as elaborate and complex as we, able to explore the mystery of our own origins?

And on the countless other planets that may circle other suns, is there life also? Is extraterrestrial life, if it exists, based on the same organic molecules as life on Earth? Do the beings of other worlds look much like life on Earth? Or are they stunningly different—other adaptations to other environments? What else is possible? The nature of life on Earth and the search for life elsewhere are two sides of the same question—the search for who we are.

In the great dark between the stars there are clouds of gas returned to the sea in commemoration of the doleful events at Danno-ura.

This legend raises a lovely problem. How does it come about that the face of a warrior is incised on the carapace of a crab? The answer seems to be that humans made the face. The patterns on the crab's shell are inherited. But among crabs, as among people, there are many different hereditary lines. Suppose that, by chance, among the distant ancestors of this crab, one arose with a pattern that resembled, even slightly, a human face. Even before the battle of Danno-ura, fishermen may have been reluctant to eat such a crab. In throwing it back, they set in motion an evolutionary process: If you are a crab and your carapace is ordinary, the humans will eat you. Your line will leave fewer descendants. If your carapace looks a little like a face, they will throw you back. You will leave more descendants. Crabs had a substantial investment in the patterns on their carapaces. As the generations passed, of crabs and fishermen alike, the crabs with patterns that most resembled a samurai face survived preferentially until eventually there was produced not just a human face, not just a Japanese face, but the visage of a fierce and scowling samurai. All this has nothing to do with what the crabs *want*. Selection is imposed from the outside. The more you look like a samurai, the better are your chances of survival. Eventually, there come to be a great many samurai crabs.

This process is called artificial selection. In the case of the Heike crab it was effected more or less unconsciously by the fishermen, and certainly without any serious contemplation by the crabs. But humans have deliberately selected which plants and animals shall live and which shall die for thousands of years. We are surrounded from babyhood by familiar farm and domestic animals, fruits and trees and vegetables. Where do they come from? Were they once free-living in the wild and then induced to adopt a less strenuous life on the farm? No, the truth is quite different. They are, most of them, made by us.

Ten thousand years ago, there were no dairy cows or ferret hounds or large ears of corn. When we domesticated the ancestors of these plants and animals—sometimes creatures who looked quite different—we controlled their breeding. We made sure that certain varieties, having properties we consider desirable, preferentially reproduced. When we wanted a dog to help us care for sheep, we selected breeds that were intelligent, obedient and had some pre-existing talent to herd, which is useful for animals who hunt in packs. The enormous distended udders of dairy cattle are the result of a human interest in milk and cheese. Our corn, or maize, has been bred for ten thousand generations to be more tasty and nutritious than its scrawny ancestors; indeed, it is so changed that it cannot even reproduce without human intervention.

The essence of artificial selection—for a Heike crab, a dog, a cow or an ear of corn—is this: Many physical and behavioral traits of plants and animals are inherited. They breed true. Humans, for whatever reason, encourage the reproduction of some varieties and discourage the reproduction of others. The variety selected for preferentially reproduces; it eventually becomes abundant; the variety selected against becomes rare and perhaps extinct.

But if humans can make new varieties of plants and animals, must not nature do so also? This related process is called natural selection. That life has changed fundamentally over the aeons is entirely clear from the alterations we have made in the beasts and vegetables during the short tenure of humans on Earth, and from the fossil evidence. The fossil record speaks to us unambiguously of creatures that once were present in enormous numbers and that have now vanished utterly.* Far more species have become extinct in the history of the Earth than exist today; they are the terminated experiments of evolution.

The genetic changes induced by domestication have occurred very rapidly. The rabbit was not domesticated until early medieval times (it was bred by French monks in the belief that newborn bunnies were fish and therefore exempt from the prohibitions against eating meat on certain days in the Church calendar); coffee in the fifteenth century; the sugar beet in the nineteenth century; and the mink is still in the earliest stages of domestication. In less than ten thousand years, domestication has increased the weight of wool grown by sheep from less than one kilogram of rough hairs to ten or twenty kilograms of uniform, fine down; or the volume of milk given by cattle during a lactation period from a few hundred to a million cubic centimeters. If artificial selection can make such major changes in so short a period of time, what must natural selection, working over billions of years, be capable of? The answer is all the beauty and diversity of the biological world. Evolution is a fact, not a theory.

That the mechanism of evolution is natural selection is the great discovery associated with the names of Charles Darwin and Alfred Russel Wallace. More than a century ago, they stressed that nature is prolific, that many more animals and plants are born than can possibly survive and that therefore the environment selects those varieties which are, by accident, better suited for survival. Mutations—sudden changes in heredity—breed true. They provide the raw material of evolution. The environment selects those few mutations that enhance survival, resulting in a series of slow transformations of one lifeform into another, the origin of new species.*

Darwin's words in *The Origin of Species* were:

> Man does not actually produce variability; he only unintentionally exposes organic beings to new conditions of life, and then Nature acts on the organisation, and causes variability. But man can and does select the variations given to him by Nature, and thus accumulate them in any desired manner. He thus adapts animals and plants for his own benefit or pleasure. He may do this methodically, or he may do it unconsciously by preserving the individuals most useful to him at the time, without any thought of altering the breed. … There is no obvious reason why the principles which have acted so efficiently under domestication should not have acted under Nature.… More individuals are born than can possibly survive.… The slightest advantage in one being, of any age or during any season, over those with which it comes into competition, or better adaptation in however slight a degree to the surrounding physical

conditions, will turn the balance.

T. H. Huxley, the most effective nineteenth-century defender and popularizer of evolution, wrote that the publications of Darwin and Wallace were a "flash of light, which to a man who has lost himself in a dark night, suddenly reveals a road which, whether it takes him straight home or not, certainly goes his way.... My reflection, when I first made myself master of the central idea of the 'Origin of Species,' was, 'How extremely stupid not to have thought of that!' I suppose that Columbus' companions said much the same.... The facts of variability, of the struggle for existence, of adaptation to conditions, were notorious enough; but none of us had suspected that the road to the heart of the species problem lay through them, until Darwin and Wallace dispelled the darkness."

Many people were scandalized—some still are—at both ideas, evolution and natural selection. Our ancestors looked at the elegance of life on Earth, at how appropriate the structures of organisms are to their functions, and saw evidence for a Great Designer. The simplest one-celled organism is a far more complex machine than the finest pocket watch. And yet pocket watches do not spontaneously self-assemble, or evolve, in slow stages, on their own, from, say, grandfather clocks. A watch implies a watchmaker. There seemed to be no way in which atoms and molecules could somehow spontaneously fall together to create organisms of such awesome complexity and subtle functioning as grace every region of the Earth. That each living thing was specially designed, that one species did not become another, were notions perfectly consistent with what our ancestors with their limited historical records knew about life. The idea that every organism was meticulously constructed by a Great Designer provided a significance and order to nature and an importance to human beings that we crave still. A Designer is a natural, appealing and altogether human explanation of the biological world. But, as Darwin and Wallace showed, there is another way, equally appealing, equally human, and far more compelling: natural selection, which makes the music of life more beautiful as the aeons pass.

The fossil evidence could be consistent with the idea of a Great Designer; perhaps some species are destroyed when the Designer becomes dissatisfied with them, and new experiments are attempted on an improved design. But this notion is a little disconcerting. Each plant and animal is exquisitely made; should not a supremely competent Designer have been able to make the intended variety from the start? The fossil record implies trial and error, an inability to anticipate the future, features inconsistent with an efficient Great Designer (although not with a Designer of a more remote and indirect temperament).

When I was a college undergraduate in the early 1950's, I was fortunate enough to work in the laboratory of H. J. Muller, a great geneticist and the man who discovered that radiation produces mutations. Muller was the person who first called my attention to the Heike crab as an example of artificial selection. To learn the practical side of genetics, I spent many months working with fruit flies, *Drosophila melanogaster* (which means the black-bodied dew-lover)—tiny benign beings with two wings and big eyes. We kept them in pint milk bottles. We would cross two varieties to see what new forms emerged from the rearrangement of the parental genes, and from natural and induced mutations. The females would deposit their eggs on a kind of molasses the technicians placed inside the bottles; the bottles were stoppered; and we would wait two weeks for the fertilized eggs to become larvae, the larvae pupae, and the pupae to emerge as new adult fruit flies.

One day I was looking through a low-power binocular microscope at a newly arrived batch of adult *Drosophila* immobilized with a little ether, and was busily separating the different varieties with a camel's-hair brush. To my astonishment, I came upon something very different: not a small variation such as red eyes instead of white, or neck bristles instead of no neck bristles. This was another, and very well-functioning, kind of creature with much more prominent wings and long feathery antennae. Fate had